Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model

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ABSTRACT

Underwater noise of whale-watching boats was recorded in the popular killer whale watching region of southern British Columbia and northwestern Washington State. A software sound propagation and impact assessment model was applied to estimate zones around whale-watching boats, where boat noise was audible to killer whales, where it interfered with their communication, where it caused behavioral avoidance and where it possibly caused hearing loss. Boat source levels ranged from 145 to 169 dB re 1µPa @ 1m, increasing with speed. The noise of fast boats was modeled to be audible to killer whales over 16 km, to mask killer whale calls over 14 km, to elicit a behavioral response over 200 m, and to cause a temporary threshold shift (TTS) in hearing of 5 dB after 30-50 min within 450 m. For boats cruising at slow speeds, the predicted ranges were 1 km for audibility and masking, 50 m for behavioral responses and 20 m for TTS. Superposed noise levels of a number of boats circulating around or following the whales were close to the critical level assumed to cause a permanent hearing loss over prolonged exposure. These data should be useful in developing whale-watching regulations. This study also gave lower estimates of killer whale call source levels of 105-124 dB re 1µPa.

Keywords: whale-watching, boat noise, killer whale, orcinus orca, audibility, disturbance, responsiveness, masking, hearing loss

Over the past few decades, whale watching has become an important tourist industry in many regions[1]. Whale watching has substituted economically for more environmentally harmful activities, it has increased public awareness of marine mammals, and it has offered scientists a "platform" to study whales. However, at some level of activity whale watching may be detrimental to the whales. Duffus and Dearden (1993) discuss economical and ecological benefits and costs of whale watching and present a management framework. Around the globe, whale watching workshops have taken place with the goal of setting up guidelines for regulating whale watching (e.g. Whale Watching Workshop of the International Whaling Commission, Australia 2000; Workshop on the Scientific Aspects of Managing Whale Watching, Italy 1996[2]; Workshop to Review and Evaluate Whale Watching Programs and Management Needs, USA 1988[3]).

The effects of whale-watching on marine mammals have previously been studied by observing behavioral responses of whales to the presence of whale-watching boats. Such responses include avoidance of boats (Blane and Jaakson 1994; Watkins 1986; Beach and Weinrich 1989) as well as attraction (Blane and Jaakson 1994; Jones and Swartz 1984; Watkins 1986), shortened surfacing (Blane and Jaakson 1994; Gordon *et al*. 1992), longer dives (Blane and Jaakson 1994), and interruption and termination of feeding and travelling behavior (Blane and Jaakson 1994). Richardson *et al*. (1995) reviewed reactions of marine mammals to ships and boats in general, including whale watching vessels. Schevill (1968) indicated that it is not the mere presence of the boat, but its noise evoking the reaction. In the current study, underwater noise of whale-watching boats was measured and acoustic impact was modeled.

The study site was Juan de Fuca Strait and Haro Strait in southern British Columbia and northwestern Washington. This area is frequented by various marine mammals including harbor seal (*Phoca vitulina*), Dall's porpoise (*Phocoenoides dalli*), harbor porpoise (*Phocoena phocoena*), and the primary target of the wildlife watching industry: the killer whale (*Orcinus orca*). In April 1999, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) listed the resident community of killer whales in British Columbia as threatened, because this population has not recovered from the historical impacts of shootings and captures in 1940-1970. The southern resident community has steadily declined in recent years, numbering 99 animals in 1995 and dropping to 83 animals by the end of 1999 (Ford *et al*. 2000). The lack of recovery is not fully understood but may include 1) chemical pollution indicated by high levels of immunotoxic chemicals in the animals' bodies (Ross *et al*. 2000), 2) a reduction in prey (salmon) availability (Nehlsen *et al*. 1991, Slaney *et al*. 1996), and 3) noise pollution. The southern resident killer whale community lives in a busy, hence noisy, commercial shipping lane and in the last several decades has been exposed to high and increasing numbers of commercial and private whale-watching boats. Between 1995 and 1999, maximum numbers of 60-70 motorboats were noted at the same place and time. (On top of these, up to 40 kayaks were observed.) Mean numbers of motorboats following a group of whales through Haro Strait were 14 (1995), 19.5 (1996), 28.5 (1997), 22 (1998) and 21.5 (1999) from mid-May through

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[1] Hoyt, E. 2000. Whale Watching 2000: Worldwide Tourism Numbers, Expenditures, and Expanding Socioeconomic Benefits. 157 pp. Available from International Fund for Animal Welfare IFAW, 411 Main Street, Yarmouthport, MA 02675-1822 USA.

[2] IFAW, Tethys Research Institute and Europe Conservation. 1996. Report of the workshop on the scientific aspects of managing whale watching, Montecastello di Vibio, Italy, 30th March - 4th April 1995. 40 pp. Available from IFAW, Warren Court, Park Rd., Crowborough, East Sussex TN6 2GA, United Kingdom.

[3] Atkins, N., and S.L. Swartz (eds.). 1988. Proceedings of the workshop to review and evaluate whale watching programs and management needs, November 14-16, 1988, Monterey CA. 53 pp. Available from Center for Marine Conservation, 600-1725 DeSales St. NW, Washington, DC 20036 USA.

August[4]. The objective of the current study was the development of a model to predict zones of acoustic impact around whale-watching boats and to aid in the establishment of whale-watching regulations.

METHODS

Field experiments

The study was conducted in Haro Strait (Fig. 1) using the Fisheries & Oceans Canada biological research vessel *Clupea* and the Canadian Coast Guard search and rescue liferaft *Skua*. From June 1 - 4, 1999, underwater sound recordings were taken outside Victoria harbor near Brotchie Ledge. Here, all the whale-watching boats passed by on their way into Haro Strait at speeds of 40-60 km/h (22-32 knots). The first tour operators left Victoria at 8:30AM returning 3 h later. Tours ran repeatedly until after 6 PM. Every boat was recorded 4-6 times per day. Whale-watching boats were identified using binoculars and photographs. The speed of the boats was measured with a radar gun from Kustom Signals Inc., model Falcon 55E0483, with an accuracy of 1 km/h. The distance at which the boats passed by the hydrophones was measured by radar from the research vessel. Underwater noise recording began as soon as a whale-watch boat was sighted. Recordings lasted 10-15 sec.

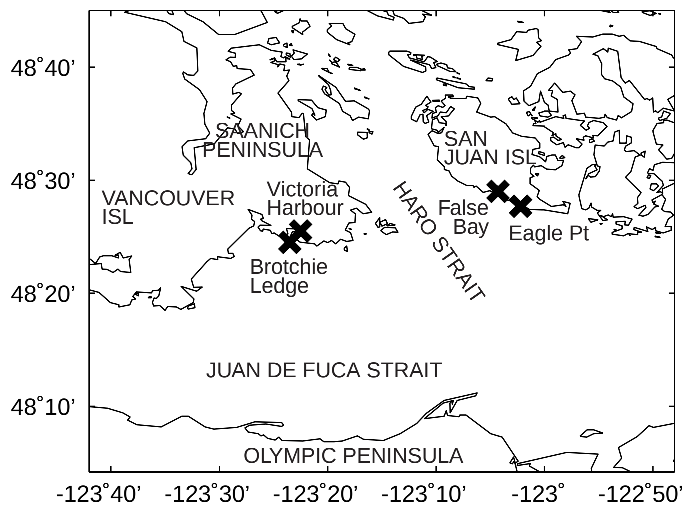

Figure 1: Map of the study site in southern British Columbia and northwestern Washington state.

On June 8 - 10 and August 30, 1999, the study was conducted in Haro Strait along the west coast of San Juan Island. Using the same method as above, we recorded 1) underwater noise of single whale-watching boats at slow speeds, 2) superposed underwater noise of a number of whale-watching boats around the whales, 3) sounds made by the resident killer whale population, and 4) ambient noise in the absence of whale-watching boats. At both locations, we also took CTD casts (conductivity / salinity, temperature, depth / pressure profiles) every 2-3 h to measure physical oceanography properties required for later sound propagation modeling. We maintained a log of all the measured and

[4] Personal communication from Dr. Richard W. Osborne, Whale Museum, Friday Harbor, Washington State, USA, 22 September 2000.

observed data including our GPS position, weather condition, and other factors potentially affecting the recorded sound such as large ferries or tankers passing by at a distance.

Hydrophones were of type ITC4123 with a bandwidth of 50Hz - 25kHz and custom-built pre-amplifiers. Two hydrophones were lowered to different depths between 5 and 15 m. Sound from both channels was anti-aliased with a high-frequency cut-off at 21 kHz and recorded directly onto PC hard drives with 16 bit resolution and a sampling frequency of 44100 Hz per channel. The system response was flat (within 3 dB) between 100 Hz and 21 kHz.

Sound propagation modeling

The sound propagation model used for data analysis was developed for environmental assessments of underwater noise impacts on marine mammals (Erbe and Farmer 2000a). The model is based on ray theory (Jensen *et al.* 1994), including absorption loss by the sediment, and frequency-dependent absorption by ocean water. Rays are traced in two dimensions through an ocean environment described by its bathymetry, sound speed profiles (which could change with range), and bottom sediment.

In 1996, Haro Strait was the site of a large physical oceanography experiment in a collaboration of the Massachusetts Institute of Technology, the Woods Hole Oceanographic Institution, the Institute of Ocean Sciences, the University of Victoria, Harvard University and the Office of Naval Research. In the western, central and steep regions of Haro Strait, the bottom was shown to be rock with no sediment. Towards the eastern and shallower areas of the Strait, grab samples revealed increasing sediment content with decreasing grain size from pebbles to coarse sand, then fine sand, then clays (Chapman *et al.* 1997). We found that killer whales mostly stayed in 40-70 m deep water along the relatively steep slope of western San Juan Island. Particularly in the early afternoon, at the peak of the whale watching activity, killer whales were mostly observed south of False Bay and north of Eagle Point. At this location, the physical properties of coarse sand (Hamilton 1980) were chosen for sediment modeling. Just outside Victoria harbor, the sediment was modeled as sand. I augmented my own CTD casts with those collected during the Haro Strait 1996 experiment at the same times of day and locations to get a smoothed mean sound speed profile.

Given a source spectrum of the underwater noise, the output of the sound propagation model is a matrix of received sound pressure levels and a matrix of received sound spectra as a function of range and depth. The analysis is done in adjacent 12^{th} octave bands with center frequencies ranging from 100 Hz to 20.3 kHz. Table 1 gives a complete list of center frequencies for all the 93 bands used.

Table 1. Center frequencies (Hz) of adjacent 12th octave bands.

	octave number							
	1	2	3	4	5	6	7	8
12th octaves	100	200	400	800	1600	3200	6400	12800
	106	212	424	848	1695	3390	6781	13561
	112	224	449	898	1796	3592	7184	14368
	119	238	476	951	1903	3805	7611	15222
	126	252	504	1008	2016	4032	8063	16127
	133	267	534	1068	2136	4271	8543	17086
	141	283	566	1131	2263	4525	9051	18102
	150	300	599	1199	2397	4795	9589	19178
	159	317	635	1270	2540	5080	10159	20319
	168	336	673	1345	2691	5382	10763	
	178	356	713	1425	2851	5702	11404	
	189	378	755	1510	3020	6041	12082	

Noise impact modeling

Zone of audibility

The zone of audibility predicts over what ranges and depths the noise is audible to a marine mammal species. For its computation, the model requires an audiogram of the target species. This is a measurement of pure tone detection thresholds at a number of frequencies. The model further requires knowledge of the width of the critical bands (Moore 1997) of the animal's auditory filter. As a third input, the model asks for a typical spectrum of ambient noise for the location of interest. The audibility model uses the received sound spectra of the sound propagation model as a function of range and depth and integrates the received energy into adjacent frequency bands of the width of the animal's critical bands. The resulting band levels are then compared to the animal's audiogram and to band levels of the ambient noise, also integrated into critical bands. If all of the received band levels of the boat noise are less than either the audiogram levels or the ambient noise levels at the corresponding frequencies, then the boat is considered inaudible.

Zone of masking

The zone of masking predicts over what ranges and depths the boat noise might obscure communication sounds of the target marine mammal species. For its computation, the model requires one or more animal communication sounds to be masked. Masking will depend on the loudness of the signal. The louder the signal, the less likely it is to be masked. The extent of the zone of masking is greatest when the signal is quietest, i.e., just recognizable in the absence of the masking noise. This worst-case scenario is modeled here. Band levels of the animal call are computed for the animal's critical bands. They are compared to the animal audiogram and ambient noise band levels. The call spectrum levels are then lowered such that the call is just recognizable in the absence of boat noise and in the presence of quiet ambient noise at sea state (SS) 1/2 (Fig. 2). The call is assumed to be just recognizable when the major spectral components at 4.7 and 5.8 kHz are audible. A study with a trained beluga whale (*Delphinapterus leucas*, Erbe 2000, Fig. 4) showed that while gradually decreasing the level of a call, the call remained recognizable to the whale as long as the major frequency components remained audible, even though some spectral peaks were already masked.

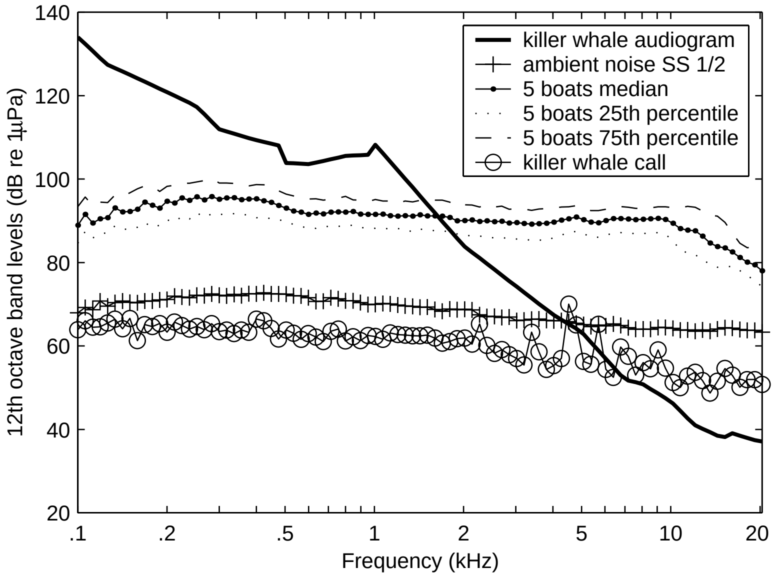

Figure 2: 12th octave band levels of ambient noise without boats at a sea state (SS) of 1/2, median levels of 5 (minimum 2, maximum 8) whale-watching boats within 400 m and percentiles, and a killer whale call lowered to a level where it is just recognizable in the absence of boats at SS 1/2.

At each range and depth, band levels of the received noise are compared to those of the signal at the level plotted in Fig. 2. If both the major peaks of the call are above the 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 call following Fletcher's (1940) equal-power-assumption. The assumption was corroborated with behavioral auditory experiments involving a beluga whale (Erbe and Farmer 1998, Erbe 2000). In the real world, masking 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. My simplified model ignores directional hearing and thus simulates the worst case.

Zone of responsiveness

The zone of responsiveness predicts over what ranges animals are likely to react to the boat noise. The reaction threshold may depend on a variety of factors, such as the received noise level, the bandwidth of the boat noise, the boat-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. There are no data in the literature on what noise characteristics cause behavioral reactions in killer whales. In the case of other marine mammals, often a broadband sound pressure level of 120 dB re 1µPa is used as a threshold of responsiveness (Richardson *et al.* 1995). The model of responsiveness takes the matrix of received sound pressure levels as a function of depth and range from the sound propagation model and wherever the entries are greater than 120 dB, a reaction might occur. Computed ranges are compared to observed killer whale behavior during this and other studies.

Zone of hearing damage

The zone of hearing damage predicts over what ranges and depths a temporary or permanent hearing loss can occur. Au *et al*. (1999) exposed a bottlenose dolphin (*Tursiops truncatus*) to octave band noise between 5 and 10 kHz for 30-50 min. 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.

Octave band noise levels of the whale-watching boats recorded in this study were generally less than 96 dB above audibility a few meters from the vessel. There is no data on TTS in quieter noise for delphinids yet. I therefore tried to extrapolate Au *et al*.'s results to lower noise levels based on tendencies found in terrestrial mammals. In humans and other terrestrial mammals maximum TTS occurred approximately half an octave to one octave above the center frequency of the noise band (Yost 1994, Clark 1991). Schlundt *et al*. (2000) confirmed this for bottlenose dolphins in a study of masked temporary threshold shift (MTTS - in background noise) after exposure to pure tones. With the fatiguing stimulus at 3 kHz, they measured a MTTS of 7 dB at 3 kHz, 16 dB at 4.5 kHz (half an octave above the noise frequency) and 17 dB at 6 kHz (one octave above the noise frequency). Unfortunately, Au *et al*. (1999) didn't measure above the center frequency of their noise. Based on Schlundt's data in this frequency range, I assumed that Au's TTS was 10 dB higher an octave above the center frequency, yielding a TTS of 22-28 dB. In humans, TTS grows slowly as a function of sound pressure level (SPL) in quiet noise, and faster in louder noise. In detail, 0.5 dB TTS occurs per 1 dB SPL as long as TTS < 10 dB. For louder noise, causing TTS > 10 dB, 1 dB TTS occurs per 1 dB SPL (Kryter 1985). Although this relationship has not yet been confirmed in delphinids, it is used here to scale down Au's TTS data: A TTS of 10 dB (instead of 22-28 dB) is expected from a reduction of exposure level by 12-18 dB. Another 10 dB reduction of exposure level is expected to reduce TTS from 10 dB down to 5 dB. Therefore, an exposure to 68-74 dB octave band level above audibility is assumed to cause 5 dB TTS in delphinids after 30-50 min. This compares with the range of TTS data for pinnipeds. Kastak *et al.* (1999) observed a TTS of about 5 dB after 20 min of exposure to octave band noise 60-75 dB above the normal center-frequency thresholds (at frequencies between 100 Hz and 2 kHz) in a harbor seal, two California sea lions (*Zalophus californianus*) and one northern elephant seal (*Mirounga angustirostris*).

There is no data on permanent hearing loss due to repeated and prolonged noise exposure in marine 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 yr 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 routine predicting TTS and PTS takes all three data sets into account. Octave band levels of the underwater noise of interest are calculated at a series of frequencies. If these are more than 96 dB above the center-frequency thresholds in killer whales, a TTS of at least 12-18 dB is modeled to occur after 30-50 min. If they are more than 68 dB above sensitivity, a TTS of 5 dB is possible after 30-50 min. For PTS, broadband sensation levels are computed. Equal-loudness contours have not been measured in killer whales. In general, they roughly follow the audiogram. Therefore, the killer whale audiogram is subtracted from the critical band levels of the industrial noise. Then energy is integrated over all frequencies. If the resulting orca-weighted level is greater than 60 "dBorca", a PTS of 2-5 dB is considered possible after decades of daily exposure.

Statistical analyses were performed using MathWorks software (MathWorks Inc. 1999). The regression R^2-statistic (correlation), the F-statistic (for the hypothesis test that all the regression coefficients are 0) and the P-value associated with this F-statistic were computed. The degrees of freedom for the F-statistic are subscripted.

RESULTS

Killer whale audiogram and critical bands

There are no data on killer whale critical bands (CB) in the literature. There is only one reference for critical band measurements in odontocetes. In a bottlenose dolphin above 30 kHz, critical bands were about a 3rd 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 (*Pseudorca crassidens*, Thomas *et al*. 1990). Using Fletcher's (1940) equal-power-assumption, critical bandwidths were estimated as $CB = 10^{CR/10}$. For odontocetes, these were on average a 12th of an octave wide (Erbe *et al*. 1999). Center frequencies of adjacent 12th octave bands used in the following analysis are listed in Table 1.

Hall and Johnson (1972) measured a behavioral audiogram of a killer whale that might have had impaired high-frequency hearing. This conclusion is based on a comparison of this data with the behavioral response and auditory brainstem response (ABR) audiograms of two killer whales measured by Szymanski *et al*. (1999), and the audiograms of other delphinids (Richardson *et al.* 1995, for review). As Szymanski *et al*. discuss, the ABR audiogram provides a suprathreshold estimate only. Therefore, I took their behavioral data at frequencies where both behavioral and ABR responses existed, and augmented the audiogram with ABR data, where only ABR responses were reported. The resulting audiogram is shown in Fig. 3. There is no data on low-frequency hearing thresholds in killer whales. Other odontocete species tested in the range of 100 Hz to 1 kHz are beluga whales (White *et al.* 1978, Awbrey *et al*. 1988, Johnson *et al.* 1989, Erbe and Farmer 1998), a bottlenose dolphin (Johnson 1967) and a Pacific white-sided dolphin (*Lagenorhynchus obliquidens*, Tremel *et al*. 1998). Fig. 3 shows the mean beluga audiogram, the bottlenose dolphin and the Pacific white-sided dolphin audiogram below 1 kHz. I took the mean of these, representing an estimate of low-frequency odontocete hearing. This was used to augment Szymanski *et al.*'s audiogram below 1 kHz and Hall and Johnson's audiogram below 500 Hz. The insensitive high-frequency response above 30 kHz of Hall and Johnson's animal was ignored. Finally, I interpolated both killer whale audiograms for the center-frequencies of adjacent 12th octave bands and took the mean. The thickened line in Fig.3 represents the killer whale audiogram used for the following analysis.

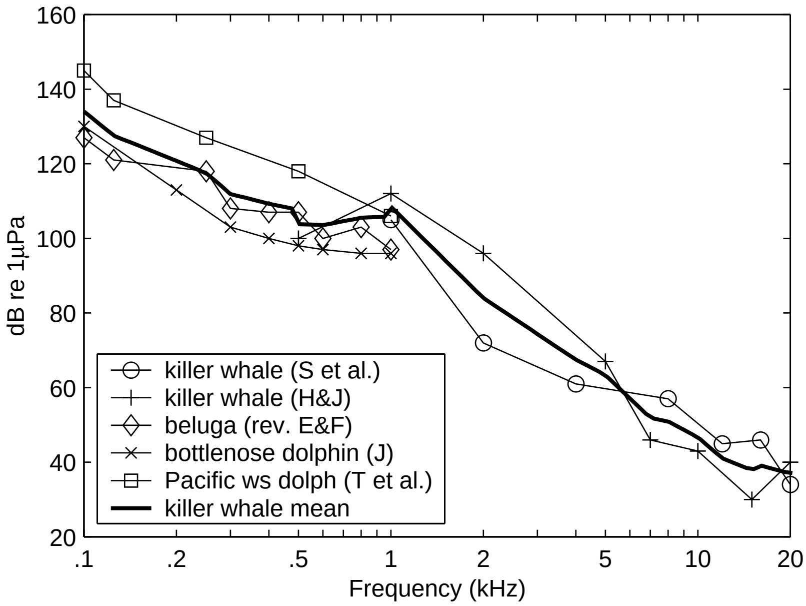

Figure 3: Odontocete audiograms used to calculate the mean killer whale audiogram after Szymanski *et al*. 1999, Hall and Johnson 1972, review by Erbe and Farmer 1998, Johnson 1967, Tremel *et al*. 1998.

Underwater noise signatures of boats

Recordings of a variety of whale watching zodiacs and non-inflatable motorboats were obtained. Using the sound propagation model described above, I calculated source levels (from 100 Hz to 20 kHz) and source spectra from all recordings. In general, source levels (*SL*) increased with increasing speed (*v*) (Figs. 4, 5) in accordance with other studies (Ross 1976). For large vessels (merchant cargo and passenger ships), the relationship is logarithmic: $SL \propto \log(v)$, (Ross 1976). For small boats, this is the first published study. I performed a linear regression using a least squares fit on *SL* versus log(*v*) (Figs. 4, 5).

For zodiacs (Fig. 4), the corresponding regression statistics were: R^2 = 0.48, $F_{1,11}$ =10.1, P = 0.009 for company A; R^2 = 0.04, $F_{1,13}$ = 0.6, P = 0.47 for company B; R^2 = 0.19, $F_{1,5}$ =1.2, P = 0.32 for company C; R^2 = 0.90, $F_{1,8}$ = 75.0, $P < 0.0001$ for company D; R^2 = 0.53, $F_{1,2}$ = 2.3, P = 0.27 for company E. With the exception of company D, the relationships between sound and speed were poor, which I attribute to uncertainties in the speed measurements. Often, boats passed by at a large distance of 200-400 m, in which case the radar gun measured the speed at an angle. As the vectorial projection of the velocity vector is shorter than the velocity, speed readings were lower than the actual speed. The radar gun operator tried to estimate the projection angle by eye at the time of the measurements. However, an uncertainty of 10 degrees can easily result in a speed error of 10-15 km/h.

Zodiacs had twin 150 hp, twin 175 hp, twin 225 hp and single 260 hp engines. Young and Miller (1960) compared noise from a 7.5 hp and an 18 hp outboard motor and found that the larger motor was noisier than the smaller motor at the same speeds. I could confirm this for the two models within the same series, Evinrude 175 hp and Evinrude 225 hp. For a comparison across different series and brands, more information on the motor and propulsor is needed. It is worth noting that company D, using sterndrives on their zodiacs, appears quieter than the other companies at all speeds.

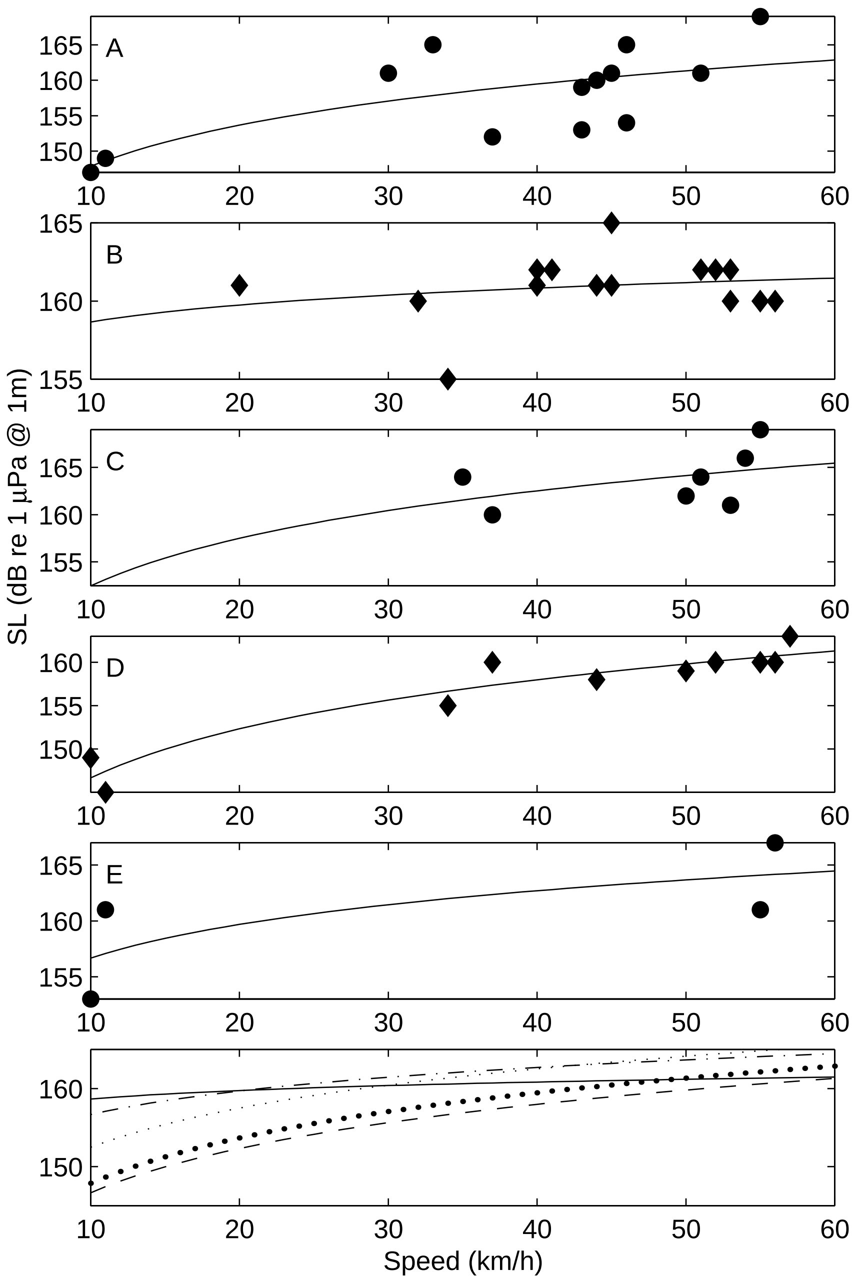

Figure 4: Zodiac source levels (*SL*) versus speed (*v*), and regression lines for *SL* ∝ log(*v*). Company A: twin 175 hp Evinrude outboard (OB), B: twin 150 hp Mariner OB, C: twin 150 hp Yamaha OB, D: single 260 hp Volvo sterndrive, E: twin 225 hp Evinrude OB. The last plot is a summary of regression lines (A: •••, B: —, C: …, D: ---, E: -.-).

Most rigid-hull motorboats were using inboards or sterndrives. It was thus impossible for us to tell what brand and power engine they used. Recordings therefore had to be classified by boat type. We obtained fewer recordings of these boats than of zodiacs. The regression statistics for a least-squares fit of *SL* to log(*v*) were (Fig. 5): R^2 = 0.06, $F_{1,1}$ = 0.1, P = 0.85 for company A; R^2 = 0.002, $F_{1,3}$ = 0.005, P = 0.95 for company B; R^2 = 0.84, $F_{1,3}$ = 15.4, P = 0.029 for company C; R^2 = 0.996, $F_{1,1}$ = 254.6, P = 0.039 for company D; R^2 = 0.98, $F_{1,1}$ = 53.9, P = 0.086 for company E; R^2 = 0.67, $F_{1,1}$ = 2.0, P = 0.39 for company F; R^2 = 0.24, $F_{1,1}$ = 0.3, P = 0.67 for company G; R^2 = 0.24, $F_{1,1}$ = 0.3, P =

0.67 for company H. For company E, source levels apparently decreased with speed (Fig. 5). I doubt this was the case and attribute this to the uncertainty in speed measurements. On average, zodiacs were slightly louder than motorboats at the same speed. At high speeds of around 50 km/h, zodiacs exhibited source levels about 162 dB re 1 μPa @ 1m. Motorboats averaged about 159 dB re 1 μPa @ 1m. We did not obtain rigid-hull motorboat recordings at slow speeds.

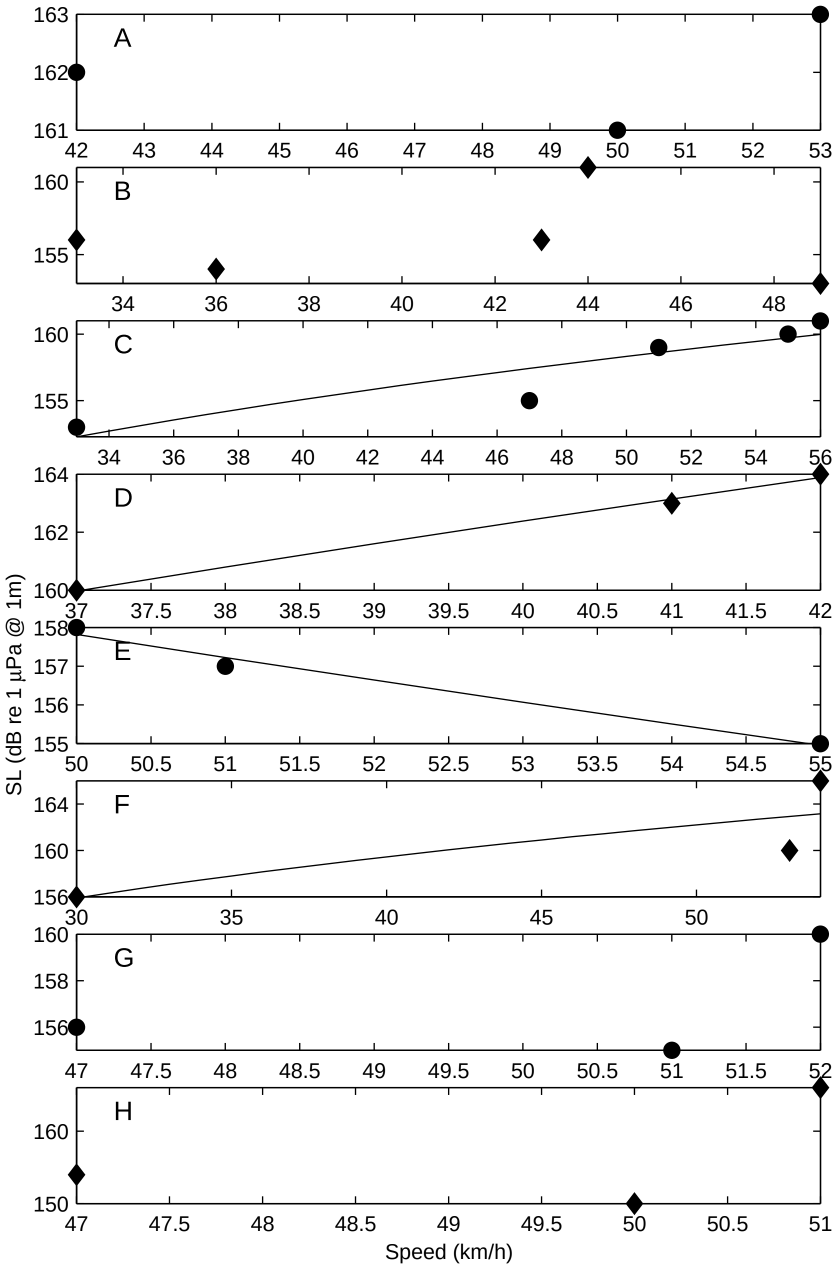

Figure 5: Source levels (*SL*) versus speed (*v*) for non-inflatable motorboats. Regression lines for $SL \propto \log(v)$ are shown only where the slope was significantly different from 0. A: racer, B: aluminum catamaran, C: alu. cruiser, D: alu. cat., E: alu. cruiser, F: racer, G: cruiser, H: yacht.

For the noise impact analysis, I chose two representative zodiac samples, company B at 51 km/h and company E at 10 km/h (Fig. 6). Cavitating propellers exhibit pure tones (and their harmonics) at low frequencies. The lowest tone corresponds to the rotational speed of the propeller and is caused by the most strongly cavitating blade (Lourens and du Preez 1998). The blade rate frequency is the product of this and the number of blades. The maximum rpm at full throttle of the current outboard motors lay between 5000-6000. All motors had either 3 or 4 blades. Therefore, pure tones between 100 Hz and 1 kHz were common. At low speeds, propeller cavitation noise might not be the prime component (Ross 1976); wave splashing and engine noise are usually audible as well. At higher speeds, body-cavitation and on-surface bouncing noise exist but are likely dominated by propeller cavitation noise. I did not attempt to identify the contributions of these individual components within the total noise spectrum.

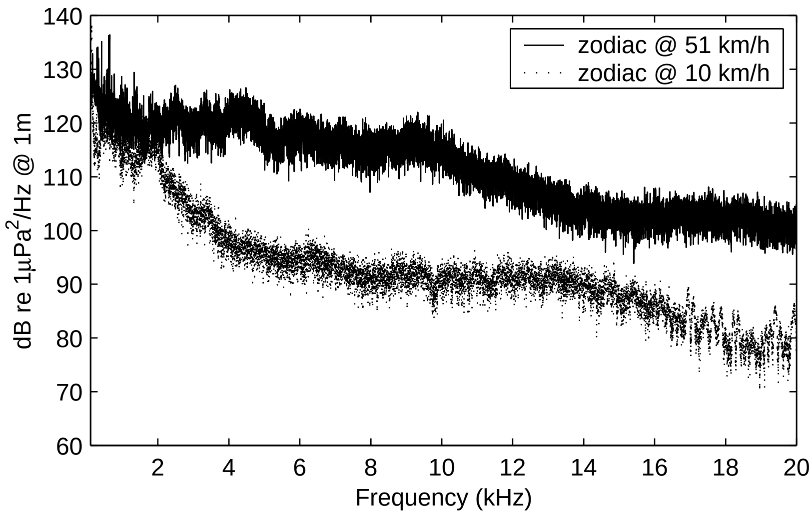

Figure 6: Source power density spectra of a slow zodiac from company E and a fast zodiac from company B, used for the impact analysis.

Ambient noise

Fig. 2 shows 12th octave band levels of ambient noise in the absence of whale watching boats in Haro Strait off San Juan Island on calm days. Spectrum density levels had slopes of -5 dB re $1\mu Pa^2/Hz$ per octave, which corresponded well with the Knudsen (1948) curves for sea state (SS) 1/2. In the presence of an average of 5 (minimum 2, maximum 8) whale-watching boats (any combination of zodiacs and non-inflatable motorboats) operating within 400 m of the hydrophone, noise levels were considerably louder than ambient. Median 12th octave band levels as well as the 25th and 75th percentiles are shown (Fig. 2). The 75th percentiles are about 10-13 dB higher than the 25th percentiles. This range can be attributed to two factors. First, in some of the recordings SS was as high as 2, which can raise ambient noise levels by 10 dB (Knudsen *et al.* 1948). Second, we did not know how many boats were actually cruising at low speed or idling or had their engines switched off. We found that most tour boats idled, particularly larger motorboats when observing the whales. However, some of the operators provided headphones coupled to underwater hydrophones so that customers could listen to the whales. These boats switched their engines off completely while floating around the whales.

Killer whale calls

We recorded a variety of killer whale calls from J-pod (Ford *et al.* 2000) in Haro Strait. These included burst-pulse sounds, whistles and echolocation click trains. The vast majority of sounds presented as constant-frequency (constant-wavelength CW) calls with harmonics in spectrogram analysis with 12 ms time-resolution and 86 Hz frequency-resolution. One such call that was heard often and clearly was chosen for the analysis of masking (Fig. 7). This call seemed to correspond to Ford's (1991) S1-type and Hoelzel and Osborne's (1986) Call Number 1, both recorded from the same population. The end-syllables in this call ranged from fairly quiet and short, as in the sample chosen here, to very pronounced, as in Ford's S1-spectrogram. Fig. 2 shows the predicted minimum level of recognizability of this call in the absence of boats and in the presence of SS 1/2 wind-and-wave noise. By analogy to masked hearing experiments with a beluga whale (Erbe 2000), this level was chosen such that the two major peaks of the call at 4.7 and 5.8 kHz just surpassed the background noise.

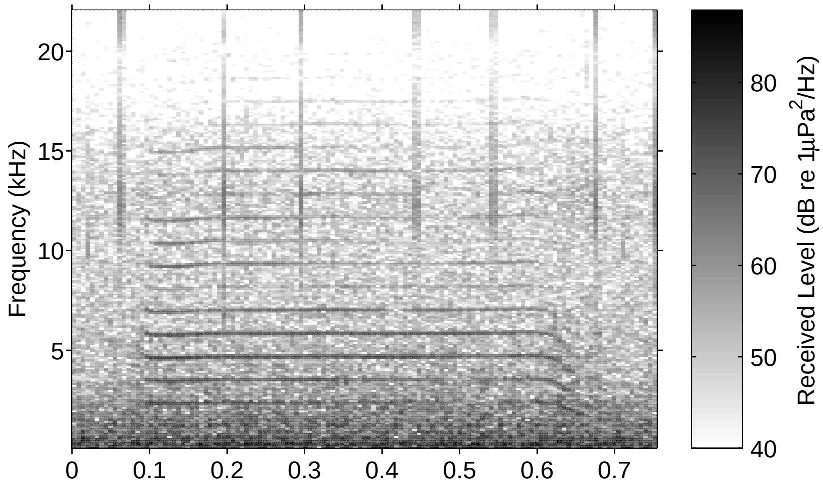

Figure 7: Spectrogram of the killer whale call chosen for the modeling of masking. Sampling frequency 44100 Hz, time resolution 12 ms.

Received broadband sound pressure levels of all recorded burst-pulse calls ranged between 105 and 124 dB re 1µPa. At the time of recording, we usually spotted animals within 100 m. The actual distance between the calling animal and the hydrophone was not known. Therefore, the received levels must be regarded as lower estimates of killer whale call source levels.

Sound propagation modeling

The sound propagation model and the subsequent impact assessment model were applied to the shallow waters along the west coast of San Juan island. In the early afternoon, at the peak of the whale-watching day, we found most whales just south of False Bay and north of Eagle Point in up to 70 m deep water. Fig. 8 shows the average measured sound speed profile and the modeled transmission loss for this area and time. Samples were computed every 10 m from 10 m to 50 m, then every 50 m up to 1 km range, then every km up to 22 km range.

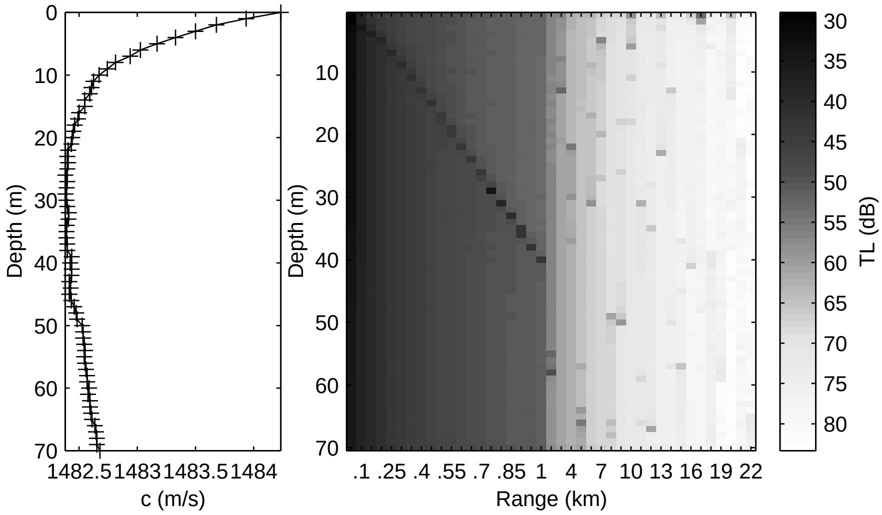

Figure 8: Sound speed profile (SSP) west of San Juan Island and modeled transmission loss (TL). Note the sudden change in scale of the x-axis. Samples were printed every 50 m between 50 m and 1 km, then every 1 km up to 22 km.

Noise impact modeling

Zones of impact around a zodiac of company B with twin 150 hp Mariner outboard motors going at a high speed of 51 km/h are shown in Fig. 9. The source level of this boat was 162 dB re 1µPa; its source power density spectrum was shown in Fig. 6. The model estimated that this boat would be audible to killer whales in Haro Strait over ranges of about 16 km (Fig. 9a) before blending in with ambient noise due to wind and waves at a modeled SS of 1/2. At higher wind speed, hence higher SS, this boat would be audible over shorter distances. This same boat would mask the killer whale call chosen to the point of unrecognizability over ranges of 14 km (Fig. 9b). The model predicted that this boat elicit a behavioral response in killer whales over ranges of 200 m (Fig. 9c).

Using the hearing loss data from Au *et al.* (1999), the boat could cause a TTS of 12-18 dB if a whale spent 30-50 min within 10 m range and depth (Fig. 9d). Based on the scaled-down TTS levels from Au *et al.* (1999), a TTS of 5 dB was modeled if a killer whale spent 30-50 min within 450 m range (Fig. 9e). If even lower sensation levels, as the ones measured by Kastak *et al.*(1999) in pinnipeds, can cause a TTS in killer whales, then a TTS of 4.8 dB could be expected if a killer whale stayed within 1 km of the boat for 20 min. If an animal was exposed to this boat noise within 1 km range continuously for 8 h per day, 5 d a week, for 50 yr, a PTS of 2-5 dB could be expected based on Kryter's (1985) data for humans.

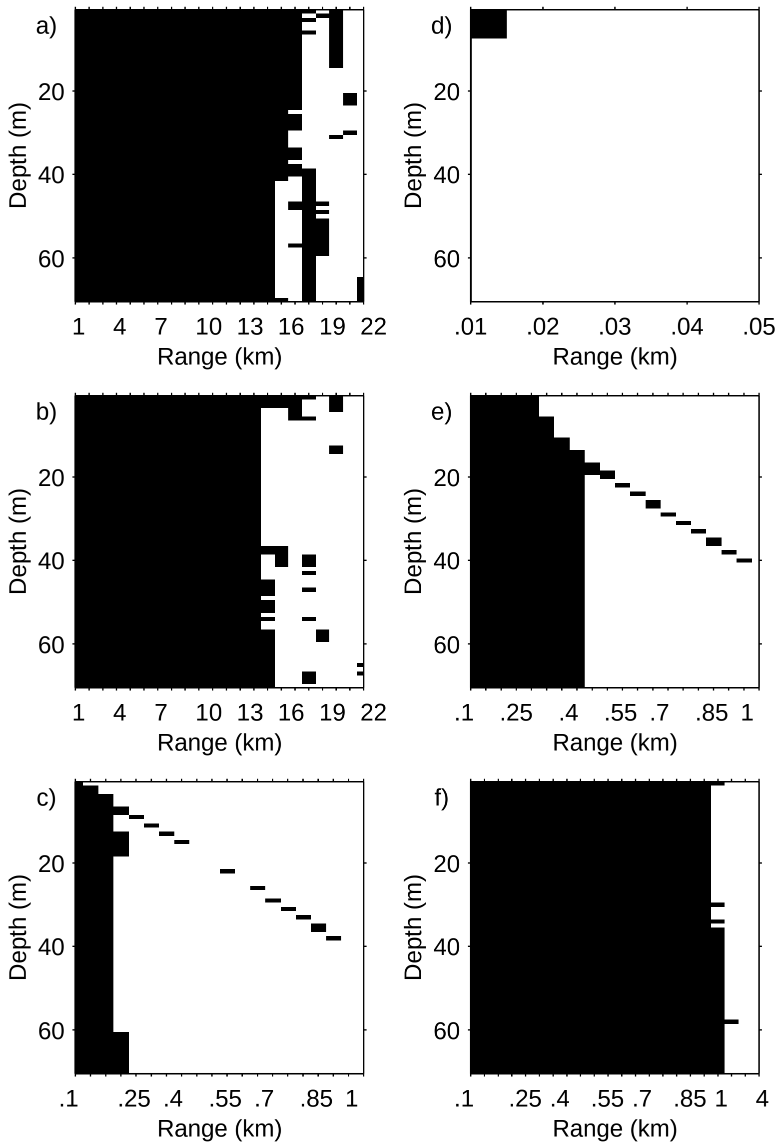

Figure 9: Zones of impact around a whale-watching zodiac with twin 150 hp outboard motors (company B) going at a speed of 51 km/h: a) audibility, b) masking, c) responsiveness, d) TTS 12-18 dB, e) TTS 5 dB, f) PTS 2-5 dB. Note the changing scales on the x-axes. Impact was modeled every 1m in depth and every 10 m in range up to 50 m range, then every 50 m up to 1 km range, then every 1 km.

Fig. 10 shows the modeled impact around a zodiac of company E, with twin 225 hp Evinrude outboard motors cruising at a slow speed of 10 km/h, at which many boats circle around and follow the whales. Audibility (Fig. 10a) and interference with killer whale calls (Fig. 10b) were modeled over 1 km range. A behavioral response was expected over only 50 m (Fig. 10c). There was no danger of as large a TTS as measured by Au *et al*. (1999) (Fig. 10d). A TTS of 5 dB scaled down from Au's data was modeled if a whale spent 30-50 min within 50 m depth to 20 m range (Fig. 10e). If Kastak's *et al*. (1999) pinniped data can be applied to killer whales, a TTS of 4.8 dB was modeled within 50 m range of the boat. A PTS of 2-5 dB was predicted to occur within 40 m depth at close ranges and 50 m range at low depth (Fig. 10f) after long and repeated exposure, based on human data (Kryter 1985).

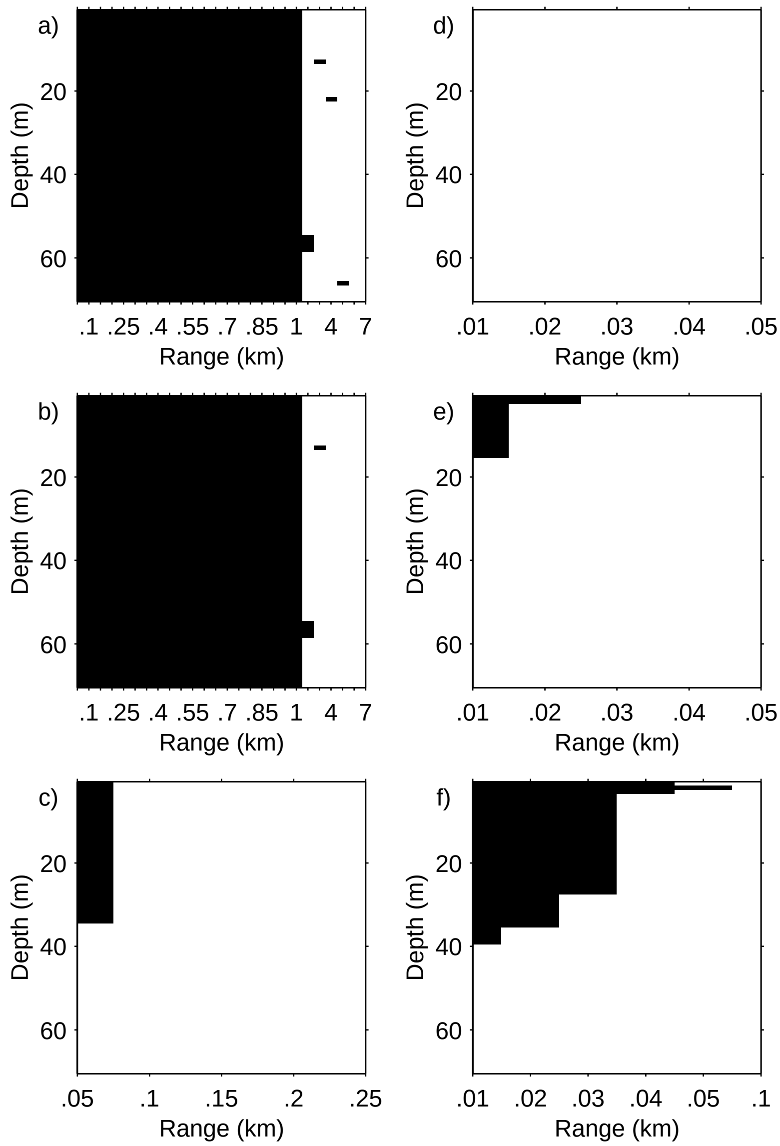

Figure 10: Zones of impact around a whale watching zodiac with twin 225 hp outboard motors (company E) cruising at a speed of 10 km/h: a) audibility, b) masking, c) responsiveness, d) TTS 12-18 dB, e) TTS 5 dB, f) PTS 2-5 dB. Note the changing x-scales as in Fig. 9.

Hearing loss models were also run for the median of noise levels in the presence of 5 boats (Fig. 2) within 400 m. Levels were not high enough for Au's TTS of 12-18 dB and just below the threshold for a TTS of 5 dB. The broadband sensation level was about 56 dBorca, which was just below the 60 dBorca threshold for Kryter's PTS of 2-5 dB. Clearly there is audible energy above the 20 kHz recorded (Fig. 2). Therefore, I extended the killer whale audiogram to higher frequencies by the minimum of the behavioral and electrophysiological data measured by Szymanski *et al*. (1999) (Fig. 11). A linear regression was performed on the 12th octave band levels of the 5-boat noise between 12 and 20 kHz. With the regression line, the 5-boat noise levels were extrapolated up to 100 kHz (Fig. 11). Given that the killer whale audiogram becomes less sensitive above 20 kHz and the noise drops rapidly, the audible energy above 20 kHz only adds 1 dB to the 56 dBorca in the case of 5 boats (Fig. 11).

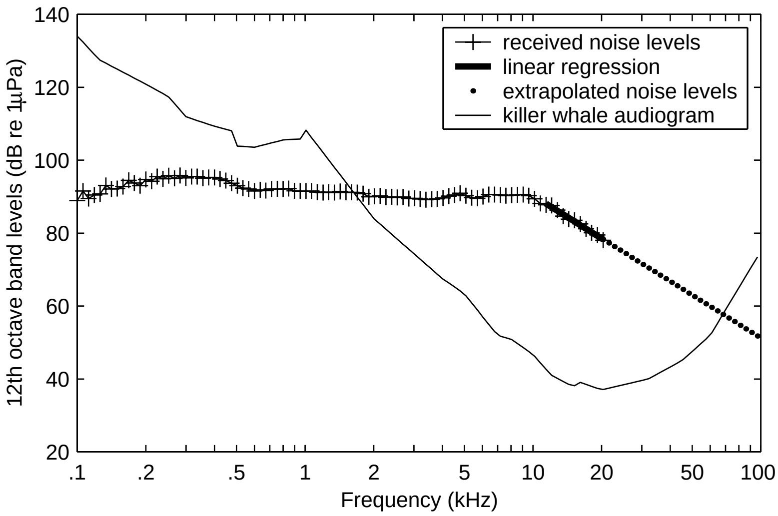

Figure 11: Killer whale audiogram, and underwater noise in the presence of 5 boats extrapolated to 100 kHz from a linear regression of levels between 12 and 20 kHz.

DISCUSSION

Underwater noise of whale-watching boats was recorded in the killer whale habitat of southern British Columbia and northwestern Washington State. Using a sound propagation model and acoustic impact assessment models, ranges over which boat noise 1) was audible to killer whales, 2) interfered with killer whale communication sounds, 3) caused a behavioral response and 4) could cause a temporary or permanent hearing loss were predicted. Ambient background noise plays a role in the range over which a boat is audible before it blends in with the background noise. It also is important for the zone of masking, which will be greatest at quietest background noise. Relatively quiet wind-and-wave noise at a SS of ½ was included in the model, thus representing a "worst-case" scenario, leading to conservative suggestions for whale-watching guidelines.

Audibility and masking

The predicted zone of masking was only slightly smaller than the zone of audibility. In other words, even the quietest noise masked a faint signal. The reason for this is that call and noise occupied the same frequency bands. If the call had different frequency-content, then the animal would be able to detect the call in louder noise and the zone of masking would be smaller (as in the case of Erbe and Farmer 2000b). The extent of the zone of masking obviously also depends on the loudness of the call; two communicating animals close together will be less affected by masking noise than two animals further apart. I only presented the latter case, i.e., the maximum zone of masking here. In a different study, I plotted zones of masking as a function of both the animal-boat and the animal-animal distance (Erbe 1997). Masking further depends on the directional hearing abilities of the animal. Only the worst case was considered in this study, where the masking boat noise and the animal call to be detected come out of the same direction.

I only modeled the interference of boat noise with a killer whale communication call. Similarly, the masking of environmental sounds, e.g. of surf, could be analyzed to assess whether an animal's ability to navigate away from shore is impeded. With more high-frequency recordings of boat noise, the masking of echolocation sounds for finding prey and navigation could be modeled.

Responsiveness

According to this model, a behavioral reaction should be observed over 200 m from fast boats and 50 m from slow boats. Kruse (1991) studied the interactions between northern resident killer whales and boats in Johnstone Strait, British Columbia. She linked behavioral reactions to boats within 400 m. Whales swam away from boats, at speeds greater than those of undisturbed whales, and swimming speed increased with the number of boats present. Williams (1999) found behavioral changes in northern residents within 100 m distance from boats (corresponding to whale-watching guidelines in Johnstone Strait). Whales employed different avoidance strategies depending on their sex, the number of boats (single vs. multiple) and distance. We often saw boats as close as 50 m and less to the whales, which implies that the southern residents did not show avoidance behavior at longer ranges. Explanations for this could be a habituation to boats or a decrease in auditory sensitivity due to temporary or permanent hearing loss. However, our observations were crude without controls or pre- and post-exposure observations.

The biological significance of behavioral responses is still unknown. If, e.g., feeding is disturbed, will animals simply go somewhere else to feed, or do they incur a reduced energy intake? Does whale-watching impact mating or nursing behavior? So far no long-term study (monitoring e.g. reproductive rate, mortality, habitat avoidance etc.) has been able to isolate whale-watching effects from other environmental effects, such as El Nino climate change or prey availability.

Hearing loss

It is unlikely that one animal will stay within 450 m of a single whale watching boat travelling at high speed for 30-50 min as required for a temporary threshold shift (TTS) in hearing of 5 dB based on scaled-down noise levels from Au *et al*.'s data (1999). However, during the busy tourist season, an animal could be exposed to continuous boat noise at those levels originating from a number of passing boats. Reducing speed in killer whale habitat where animals can be expected within a few hundred meters helps to lower noise levels.

On various occasions, we observed whales within 50 m and less of stationary or slowly cruising boats. A TTS of 5 dB was modeled after 30-50 min within 20m of one boat. Hearing is expected to recover to normal within 24 h if the animal manages to avoid boats thereafter. For a permanent loss (PTS) of 2-5 dB based on Kryter's (1985) data, animals would have to stay within 50 m of one boat for 8 h/d, 5 d/wk, for up to 50 yr. The real threat for TTS and PTS comes from the number of whale-watching boats in this area.

Noise levels measured in the presence of 5 boats within 400 m were just below the critical sensation level causing a PTS in human ears (Kryter 1985) after 50 yr of 8 h/d, 5 d/wk exposure. During the peak of the whale-watching season, whales find themselves surrounded by boats for 8-10 h/d, 7 d/wk. Between 1995 and 1999, the mean number of motorboats following a group of whales through Haro Strait from mid-May through August was 21, peak numbers were 60-70 motorboats. Whale watching has been popular in this area since the 1970s. For the last few years, tour operators have offered whale watching all year round. During the winter months, however, whale watching decreases considerably and the focus shifts from killer whales to other species. Killer whales spend less time in Haro Strait, passing through only once every 1-2 wk, being followed by up to two boats on average. How much they are targeted by private whale-watchers in other areas is unknown. The relationship between noise dose and hearing loss is still not fully understood. In other words, in what way do increased noise levels due to many boats during the summer months make up for lower noise levels due to few boats during the winter months, and do animals thus receive enough noise energy throughout the year to cause PTS after many years?

It is important to stress that there are few data on TTS in marine mammals and no data on PTS in marine mammals. 5 dB-TTS results were based on Au's *et al.* (1999) study with bottlenose dolphins scaled down to the noise levels of whale-watching boats based on sound pressure level SPL-TTS relationships found in humans (Kryter 1985). PTS prediction was based on human data (Kryter 1985). It is not known how hearing loss and the relationship between TTS, PTS, exposure duration and level changes from species to species. Noise levels were scaled with respect to the corresponding audiogram (bottlenose dolphins, humans, killer whales). This was the only species-specific adjustment made. The predicted impact ranges are therefore speculative. Once more data on TTS and perhaps PTS become available for marine mammal species, the model can be ground-truthed.

Marine mammals rely on acoustics for communication and orientation. Masking or hearing damage can affect the animals' ability to communicate, echolocate for finding prey and for orientation, navigate by environmental sounds, and detect predators. If communication is important for successful mating, then masking or hearing damage could have long-term effects on reproductive success. Masking or –more likely- hearing damage could play a role in animal strandings, if animals experience problems echolocating (in the case of odontocetes) or hearing the sound of surf. In another study, the masking of non-communication sounds (echolocation and environmental sounds) could be modeled.

Whale-watching guidelines

Some commercial whale-watching companies in this area abide by their own conservative code of ethics and stay a minimum of 100 m away. A major problem is posed by private whale-watchers, who can vastly outnumber commercial operators. Private people are unaware of the whale-watching code of ethics and often do not know how to watch whales properly. The results of this study should aid in producing whale-watching guidelines for southern British Columbia and northern Washington State. For example, a minimum allowable distance of approach by slowly cruising boats of not less than 50 m could avoid hearing loss and changes in behavior. Boats should go slowly near the whales to decrease noise emission; a cruising speed of about 10 km/h is suggested within a few hundred meters of killer whales. There should be a maximum allowable number of boats following a group of whales; according to my model, 5 boats within 400 m is a safe number to avoid long-term hearing loss. I also suggest switching motors off rather than idling to observe whales quietly, and switching motors on again once the whales have left. Some tour operators do this already, particularly those who carry underwater microphones and provide headphones to their customers to listen to the killer whales' own vocalizations.

These are suggested guidelines based entirely on the results of this particular acoustic model. There are other studies going on (acoustic and non-acoustic), which will produce their own results, from which differing conclusions might be drawn. Finally, management will have to consider a wide range of factors.

Future research

Whale-watching is still increasing in British Columbia and Washington State. Careful monitoring of ambient noise levels due to whale-watching boats is therefore crucial over the coming years in order not to exceed critical levels. In other regions, whale-watching is often licensed in order to limit the number of boats. However, as this type of regulation does not affect the number of private boats, which sometimes exceeds the number of commercial boats in this area, licensing commercial vessels may not effectively limit underwater noise emission. It would further be beneficial to do a more controlled study of single-boat noise at various speeds and operational modes. This would require boater co-operation, which was lacking in my study. I was unable to clearly identify quiet boat designs and engines, due to uncertainties in speed measurements and due to the refusal of most companies to name their type of motor. It seems that fewer large boats carrying many people have a lower total noise output than many small boats carrying only few people. Engine and propulsor design could be altered to exhibit lower noise levels. Though his boat would be too small and slow for commercial whale-watching, Schevill's (1968) fun article is full of ideas and describes a motor-and-propeller-driven whale-watching boat, that was not discernible at 3 m distance at full speed in calm sea state.

Conclusion

Sustenance of the whale watching industry is desirable both from an economical point of view for the Canadian and US districts involved, and also from a conservational point of view, since whale watching has aided in our scientific understanding of whales and has raised public awareness of these animals. Yet there is a conflict if wildlife viewing poses threats itself.

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