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Acoustic interaction of humpback whales and whale-watching boats

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Abstract

The underwater acoustic noise of five representative whale-watching boats used in the waters of west Maui was measured in order to study the effects of boat noise on humpback whales. The first set of measurements were performed on 9 and 10 March, close to the peak of the whale season. The ambient noise was relatively high with the major contribution from many chorusing humpback whales. Measurements of boat sounds were contaminated by this high ambient background noise. A second set of measurements was performed on 28 and 29 April, towards the end of the humpback whale season. In both sets of measurements, two of the boats were inflatables with outboard engines, two were larger coastal boats with twin inboard diesel engines and the fifth was a small water plane area twin hull (SWATH) ship with inter-island cruise capabilities. The inflatable boats with outboard engines produced very complex sounds with many bands of tonal-like components. The boats with inboard engines produced less intense sounds with fewer tonal bands. One-third octave band measurements of ambient noise measured on 9 March indicated a maximum sound pressure level of about 123 dB re 1 μPa at 315 Hz. The maximum sound pressure level of 127 dB at 315 Hz was measured for the SWATH ship. One of the boats with outboard engines produced sounds between 2 and 4 kHz that were about 8–10 dB greater than the level of background humpback whale sounds at the peak of the whale season. We concluded that it is unlikely that the levels of sounds produced by the boats in our study would have any grave effects on the auditory system of humpback whales.

Keywords: Humpback whales; Whale watching; Boat interaction with whales; Disturbance; Behavior; Effects-whole organisms

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1. Introduction

Humpback whales (*Megaptera novaeangliae*) annually migrate from their summer feeding grounds off southeast Alaska to winter in waters off the Hawaiian Islands, Baja California Sur, Mexico and northern Japan (Baker et al., 1986; Darling & McSweeney, 1985). The number of humpback whales in the Hawaiian waters generally peaks from mid-February through mid-March (Baker & Herman, 1984). Calving and breeding is an important function of humpback whales while wintering at lower latitudes (Herman & Antinoja, 1977; Herman, Forestell & Antinoja, 1980). The presence of these whales has spawned a popular and rapidly growing whale-watching industry. Whale watches are undertaken with a wide assortment of vessels. Because of the ever-growing number of boats involved, concerns are often expressed by those in the whale-watching industry, environmental groups and governmental agencies about the effects of vessel disturbance on the whales (Green, 1998).

Humpback whales have been observed to react to approaching boats in a number of different ways ranging from approach to avoidance. On rare occasions, humpback whales have been observed charging towards approaching boats and screaming underwater (Payne, 1978). Bauer (1986) and Bauer and Herman (1986) found that respiration rates, diving, swimming speed, social exchange and aerial behaviors correlated with vessel numbers, proximity, speed and direction changes. They reported that humpback whales generally attempted to avoid vessels and sometimes directed threats towards them. Increased frequencies of surfacing without blows and dives initiated without raised flukes were some behaviors indicative of avoidance. Green and Green (1990) reported that humpback whales often reduced the proportion of time at the surface, took longer dives, altered direction as the boats approached (horizontal avoidance) and continued to spend more time underwater and decreased swim speed (vertical avoidance) after boats departed. These effects persisted over 20 min after the boats departed. Green (1990) also observed that humpback whales moved from a favored area on days when parasail boats operated. Bauer and Herman (1986) concluded that reactions to vessels probably are stressful to humpback whales but the significance of the stress is unknown.

Research performed by Baker and Herman (1989), Baker, Herman, Bays and Stifel (1982), Baker, Herman, Bays and Bauer (1983), and Bauer (1986) in Alaskan waters suggests that humpback whales usually use two main type of avoidance methods. The first involves a vertical avoidance in which the dive duration increases, with a corresponding decrease in the blow interval and in swim speed. The second method involves a horizontal avoidance in which there is a decrease in the dive duration, longer blow intervals and an increase in swim speed. Baker, Herman, Bays and Stifel (1982) and Baker, Herman, Bays and Bauer (1983) also found that approaching boats often triggered some aerial behaviors such as breaching, flipper and tail slapping.

There appears to be little doubt that boat traffic may affect the behavior of humpback whales. Examples of such disturbance by vessels on humpback whales in Hawaii can be found in Tinney (1988) and in the humpback whale recovery team report (HWRT, 1991). Consequently, the National Marine Fisheries Service (NMFS), the Federal agency primarily responsible for enforcing the Marine

Mammal Protection Act, has imposed a regulation prohibiting boats from approaching within 91 m (100 yards) of any humpback whale in Hawaii (NMFS, 1987).

One issue that has not received much attention is the specific effect of boat noise on the whales. All boats from the smallest motor boat to the largest super-tanker produce underwater noise. However, there is limited information on noise produced by small boats typically used in coastal waters (Richardson, Greene, Malme & Thomson, 1995). Considerably more attention has been focused on large ocean-going vessels. McCauley, Cato and Jeffery (1966) have measured the noise generated by whale-watching vessels in Hervey Bay, Australia. Many of these boats in Hervey Bay operated as ferrys and modify their routine slightly upon encountering a pod of whales. Present regulations in Hervey Bay for approaching whales state that boats must slow within 300 m of whales, which is very different than the 91 m standoff range in Hawaii with no speed limitations. It is also difficult to apply noise measurements from one location to another because underwater acoustic propagation can vary considerably depending on the depth and types of bottom.

In order to understand the effects of boat noises on humpback whales, we embarked on a project to measure the noise of representative types of whale-watching boats in the waters of west Maui, where there is the highest whale-watching activity in the State of Hawaii. The goal of this project was to measure boat noises in a simulated whale-watching scenario in which the participating boats would maintain a standoff distance of 91 m (100 yards) from the boat performing the sound measurements, and the measurements were made in the very waters where whale watching takes place.

2. Materials and methods

The measurement equipment consisted of either an H-52 hydrophone from the US Navy Underwater Sound Reference Division or an ITC-1032 hydrophone from International Transducer Corporation, a Princeton Applied Research model 113 low-noise amplifier and a Sony TC-7 DAT (digital audio tape) tape recorder. The H-52 hydrophone had a relatively flat (± 3 dB) frequency response to 200 kHz and the ITC-1032 hydrophone had a flat response to 40 kHz. The PAR 113 amplifier had an adjustable low-pass filter set at 10 kHz. The Sony DAT recorder has a flat frequency response to 22 kHz with a dynamic range in excess of 90 dB. Its gain was fixed to unity. Both the amplifier and DAT recorder were operated on batteries. The recording system had a flat frequency response from 20 Hz to 22 kHz. The sound measurement system was housed in a small 4.6 m inflatable boat.

The sites where measurement of ambient and boat noise was performed are shown in Fig. 1. The upper most X marks the spot off Lahaina Harbor, the center X is for the waters off Olowalu and the bottom X is the location of Maalaea Harbor. Most of the boat sounds were recorded off Olowalu except for the Navatek II which was recorded as it left Maalaea Harbor.

Five whale-watching boats participated in our project, four were for in-shore use and a fifth boat was the Navatek II, a small water plane area twin hull (SWATH)

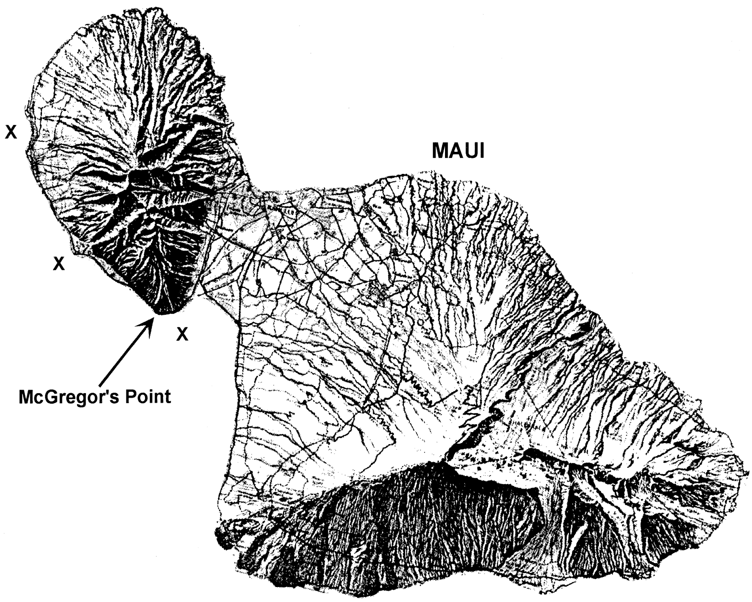

Fig. 1. A map of Maui showing the locations of the ambient noise and boat noise measurements. The upper most X designates the entrance of Lahaina Harbor, the middle X is for the waters off Olowalu and the lower most X designates the entrance of Maalaea Harbor. The location of McGregor's point is shown by the arrow.

used for inter-island travel (Table 1 and Fig. 2). The skippers of the in-shore boats were instructed to approach the instrumentation boat and drive in a circle around the measuring boat maintaining a standoff distance of 91 m at a speed of 10 knots. The skippers were willing participants in the acoustic measurement and no efforts were taken to measure the 91-m standoff distance or boat speed. We wanted to simulate as accurately as possible the manner in which a boat would approach a whale and therefore we relied on the skill of the skippers. The uncertainty in distance is not a great problem since a 25% error in distance estimation represents an error of only 2 dB in the sound pressure level measurements, assuming a spherical transmission loss model. Sounds of the Navatek II were measured as the boat left Maalaea Harbor with the skipper instructed to pass within 91 m of our measurement boat. All acoustic measurements were performed approximately 2 miles from shore in

Table 1
Boats participating in the noise measurements

Spyhop	15-ft inflatable with a 25 hp outboard engine
Manta Raiv	25 ft inflatable on a rigid aluminium hull with twin 250 hp outboard engines
Wailea Kai	40-ft catamaran with twin inboard 200 hp diesel engines
Kiwi II	Bertram class cabin cruiser with twin 165 hp diesel engines
Navatek II	82-ft SWATH ship with twin 950 hp inboard diesel engines

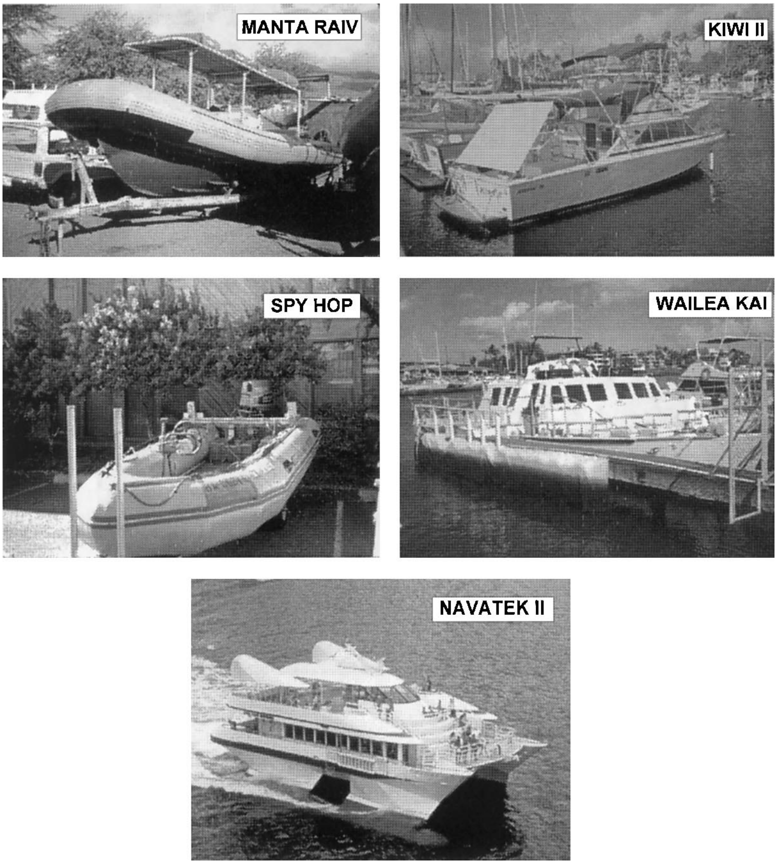

Fig. 2. Photographs of boats who's sounds were measured in this study.

waters that varied in depth from about 15 to 30 m and with the hydrophones submerged to a depth of 7.6 m.

Recorded sounds were digitized with a sound card on a personal computer at a sample rate of 44.1 kHz with a 16-bit accuracy. The digitized data were stored in files on the computer's hard disk for later analyses. Spectrograms showing time versus amplitude information along with relative intensity were calculated with Orincon's Rippen™ software using fast Fourier Transform (FFT) algorithms. A Hanning window was applied to the data and a 50% overlap was used in computing the spectrograms. Frequency spectra were also calculated in Quick Basic 45 using a FFT algorithm, partitioning the information into 1/3 octave bands. A raised cosine square window was applied to each block of 4096 points, representing 93 ms worth of data, before the spectrum was calculated with the FFT program. Before calculating 1/3 octave band spectra, the root mean square (rms) values of the boat noise data were calculated in blocks of 4096 points, and the 10 contiguous blocks having the highest rms values were used for the spectra calculations. The mean and standard deviation of the 1/3 octave band analysis for each 93 ms worth of data was then computed. No frequency weighting was applied to the data.

One of the authors (Green) has been observing the interaction of humpback whales with whale-watching boats since 1989 from shore-based sites in West Maui. These observations were made from an 80-m hill in Olowalu and from McGregor's Point (Fig. 1). The location, movement and behavior of whales and boats were recorded using a Sokia digital theodolite with 30 power magnification. Position of an object relative to the sighting platform was obtained by measuring the angles of depression or vertical deviation and angles of horizontal deviation to the object. This method, developed by R.S. Payne, allows one to follow the movements of whales and boats in detail (Tyack, 1981). Behaviors of focal pods were recorded before, during and after they were approached by vessels to approximately 91 m.

Five observers were normally stationed at a shore-based site. One person operated the theodolite, one person recorded the data and two people spotted whales and boats with binoculars. The fifth person communicated with and directed the waiting experimental impact vessel to approach the pod being observed. The following periods were defined: (1) the before-boat period: when there were no boats within 0.5–1.5 mi of the pod for a period of 15–20 min; (2) the boat period: while the boat was within 0.5 mi of the pod; and (3) the after-boat period: as the boat left the area around the pod and was 0.5 mi or more away.

Whale behaviors were initially recorded during the before-boat period. After 15–20 min, the shore team radioed the experimental vessel and directed it as it approached the focal pod. They recorded the movement of this vessel, and continued to record the movement and behaviors of the focal pod. The vessel approached the pod at 10 knots, passed by the pod at 91 m and then left the area. Observers continued to record whale behavior and movement for a minimum of 15 min or up to 30 min after the boat was 0.5 mi away from the pod.

The shore-based observations focused on five dependent variables consisting of the maximum downtime (the single longest time whales spent under water), average speed of travel, percentage of time spent under water, average number of surface behaviors per minute and direction of travel. Detail results of the shore-based observations along with a multiple analysis of variance statistical examination of the data will be published at a later date.

3. Results

In the initial set of measurements made on 9 and 10 March 1996, the background chorusing from many humpback whales was high enough to contaminate the recording of boat sounds. Included in the humpback whale chorusing was the noise produced by snapping shrimp. The high-level chorusing was essentially the same along the coast from Maalaea Bay to Lahaina Harbor, a distance of approximately 15 miles. Nevertheless, we continued to measure boat sounds with the intention of using the data as a back up in the event we would not be able to repeat the measurements at a future date. An example of effects of humpback chorusing on the ambient noise environment in the waters off west Maui during our initial measurement period is shown in Fig. 3a, for a 43 s sample. The 1/3 octave spectra had a peak in its mean value of about 123 dB re 1 μPa at 315 Hz. This peak in the mean value can be attributed to humpback whale chorusing. The loudest 93-ms block of data had a rms sound pressure level of 136 dB in the 1/3 octave band centered around 300 Hz. No whales were seen in the vicinity of the measurement boat. Some measurements were made at Olowalu within sight of an observation team located on a hill several hundred meters from shore. The observation team, with high powered binoculars, did not see any whales within several hundred meters from the measurement boat. Measurements of background humpback whale chorusing done at Maalaea Harbor, Olowalu and Lahaina Harbor had essentially the same levels.

A second set of measurements was made on 27 and 28 April 1996. During this period, only few whales remained and their chorusing was very faint. An example of the ambient noise environment during this time period is shown in Fig. 3b. The ambient noise had a relatively broad peak of about 110 dB re 1 μPa between 315 and

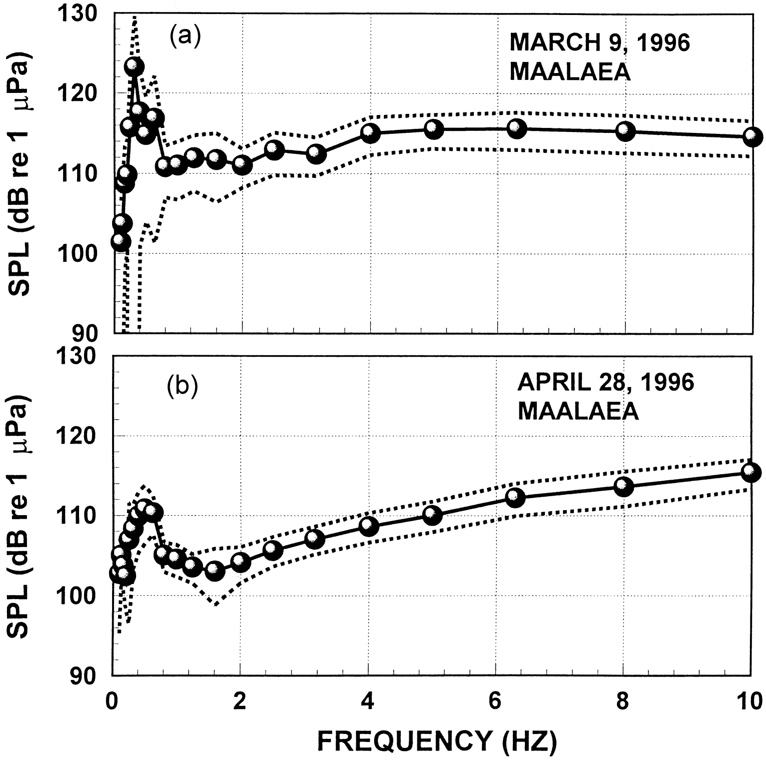

Fig. 3. Mean and standard deviation of the ambient noise measurements performed on 9 March and 28 April at the entrance of Maalaea Harbor. The closed circles are the mean sound pressure level (SPL) in each 1/3 octave band and the dashed lines are the standard deviations. Humpback whale chorusing contributed to the higher noise levels on the 9 March measurement. Humpback whale chorusing could only be faintly heard on 28 April.

600 Hz. The ambient noise below a frequency of 3 kHz was between 13 and 16 dB lower on 27 and 28 April than on 9–10 March, allowing us to make relatively uncontaminated measurements of boat noises.

The dominant contribution to the ambient noise, shown in Fig. 3b came from snapping shrimps whereas humpback whale chorusing sounds were the dominant contributor to the ambient noise in Fig. 3a. The humpback whale chorusing sounds in Fig. 3a decreased below the snapping shrimp noise for frequencies greater than about 7 kHz. Therefore, both spectra have approximately the same levels for frequencies greater than about 7 kHz.

Spectrograms of the boat sounds are shown in Fig. 4. Four of the recordings were done during the 27 and 28 April time period and the fifth (Navatek II) was measured the following year, on 1 April 1997, as it departed out of Maalaea Harbor. There are several features of these spectrograms that are worth pointing out. First, the boat sounds consist of bands of tonal components and second, the boats with outboard engines had considerably more complex spectra with more bands than the boats with inboard diesel engines. The spectral lines of Spy Hop and Manta Raiv indicated the presence of many higher harmonics. Both of these boats propelled by outboard engines had over 15 broad spectral lines that extended to about 5 kHz. The boats with in-board diesel engines had considerably fewer line components; three for Kiwi II and Navatek II and seven for Wailea Kai. Some of the lines were much more distinct, being sharper or narrower in frequency than for the boats with outboard engines.

The mean and standard deviation of the 1/3 octave band spectra over a 0.93 time period is shown in Fig. 5. Ten 93-ms spectra were averaged to produce the results of Fig. 5. The results for the Navatek II were scaled downward by 5 dB since we estimated that it was moving at a speed close to 15 knots when its sounds were recorded. Ross (1976) showed curves indicating that a boat produces about 5–10 dB more noise at 15 knots than at 10 knots. Therefore, the 5-dB adjustment to the Navatek II

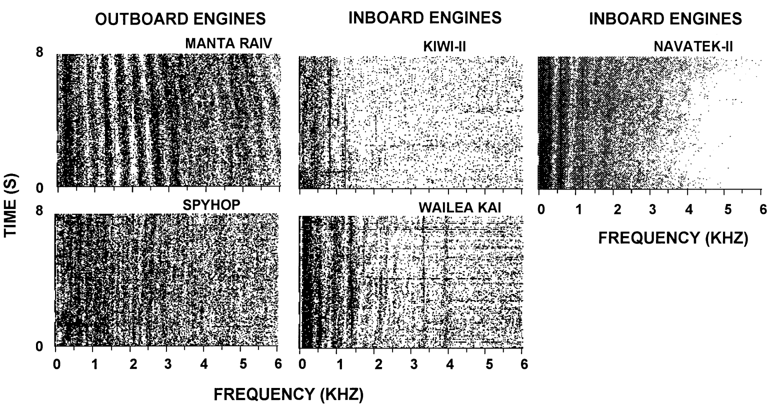

Fig. 4. Spectrograms of noises from the five boats that were recorded. The Manta Raiv and Spy Hop were inflatable boats with outboard engines. The Kiwi II, Wailea Kai and the Navatek II had twin inboard diesel engines.

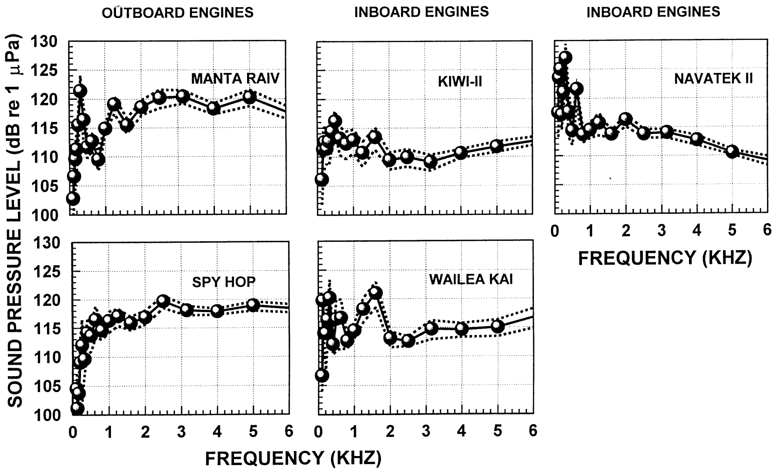

Fig. 5. The mean (closed triangle) and standard deviation (dashed lines) of 1/3 octave band spectra of the boat noises. The ten consecutive blocks of 93 ms having the highest rms sound pressure levels were used to obtain the spectra.

sound pressure levels is a relatively conservative one. All of the boats except for Spy Hop had a spectral peak between 200 and 1.6 kHz. The maximum level of 120 dB at 2.5 kHz for Spy Hop at a distance of 91 m is about 7 dB higher than the 152 dB at 1 m reported in Richardson et al. (1995) for a Zodiac having a 25 hp outboard motor, assuming a spherical spreading transmission loss of 39 dB. The 121-dB maximum level at 315 Hz of the Manta Raiv is about 4 dB higher than the boat with 80 hp twin outboard motors reported by Richardson et al. (1995) after correcting for transmission loss. Unfortunately, the speed of the outboard motor boats were not reported in Richardson et al. (1996) so our comparison can only be made in a very general sense. The Navatek II produced the highest mean peak amplitude (127 dB at 315 Hz) followed by the Manta Raiv. However, the Manta Raiv had the broadest range of frequencies above and close to the 120 dB level. The Wailea Kai had a peak amplitude of 121 dB at 1.6 kHz with a secondary peak of 120 dB at 315 Hz. Spy Hop also had a relatively large frequency range at which the sounds produced were within several dB from the 120 dB.

The theodolite and binocular observations indicated that whales exhibited the strongest reaction to the Navatek II. They often made abrupt changes in their course and also remained submerged for longer periods of time when approached by the Navatek II compared to the other boats. The Navatek II was not a participant in the shore-based observational experiment but there were many occasions in which it came into our observational area and therefore the responses of whales to it could be monitored. The Manta Raiv and Wailea Kai also produced strong reactions by whales. Whales swam approximately three times faster when Manta Raiv approached them and twice as fast when Wailea Kai approached them compared to Spyhop and Kiwi II. Both the Manta Raiv and the Wailea Kai had spectral peaks that were above 120 dB. The Manta Raiv had the most complex spectrum and was the noisiest boat over a fairly wide frequency span. Detail results of humpback whale reactions to these vessels will be published at a later date.

4. Discussion and conclusions

The smaller boats with outboard engines produced sounds that were as equal in level or higher than the larger boats with inboard diesel engine. Most of the underwater sounds of boats are caused by propeller cavitation (Ross, 1976). The smaller boats with outboard engines have much smaller propellers than the larger boats with inboard engines. The revolutions per minute (RPM) required for an outboard engine to obtain a certain level of thrust must be much higher than the RPM necessary for a boat driven by inboard engines with larger propellers. Therefore the amount of cavitation caused by an outboard engine can be higher than for larger boats with inboard engines and larger propellers.

The waters on the west shore of Maui during the humpback whale season are extremely noisy with much of the ambient noise coming from humpback whale choruses. We found that the peak level of the background humpback whale chorus was about 12–15 dB lower on 28 April than on 9 March. Only the Navatek II produced sounds that had a peak higher than the peak of 123 dB for the humpback whale chorusing during the March 9–10 time period. The peak in the mean value of the Navatek II sound was about 127 dB. However, the Manta Raiv produced broader sounds than the Navatek II and had a wider frequency range at which its sounds were greater than that of the background humpback whale chorusing in the March time frame. The highest spectral peak for Manta Raiv was 121 dB at 3.1 kHz. The sounds of the Manta Raiv and Navatek II are plotted along with the 9 March recording of the humpback whale sounds in Fig. 6. From the figure we can see that the Manta Raiv sounds were greater than the humpback

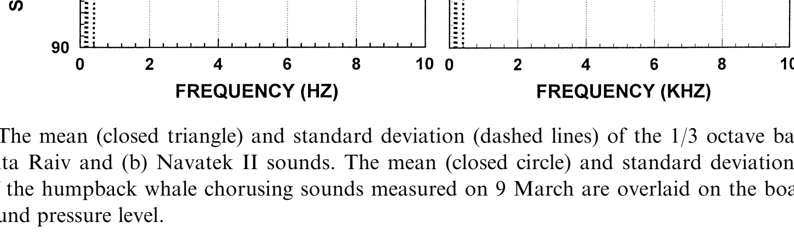

Fig. 6. The mean (closed triangle) and standard deviation (dashed lines) of the 1/3 octave band of the (a) Manta Raiv and (b) Navatek II sounds. The mean (closed circle) and standard deviations (dashed lines) of the humpback whale chorusing sounds measured on 9 March are overlaid on the boat sounds. SPL, sound pressure level.

whale chorusing at frequencies between 400 Hz and 6.2 kHz, the maximum difference being about 8 dB at about 3 kHz. On the other hand, the Navatek II sounds were higher in level than the background humpback whale sounds only up to a frequency of 3 kHz.

There is little doubt that humpback whales can hear the sounds of an approaching boat even at the peak of the whale season when the background chorusing is the loudest. There are broad ranges of frequency in which the spectra of boat sounds are higher than the background chorusing. The complex sounds from boats with outboard engines such as the Manta Raiv will probably cause more disturbances than the quieter boats with inboard engines such as the Kiwi II. However, the levels of even the noisiest boats measured in our study, the Manta Raiv and the Navatek II, would probably not cause any harm to the auditory system of the whales. Female whales have been observed joining singers (Tyack, 1981) and singers have been observed escorting females (Baker & Herman, 1984) and singers have been observed joining a pod while continuing to sing (Frankel, 1994).

The source level of a singing humpback whale has been estimated by Frankel (1994) to be between 170 and 175 dB re 1 μPa at 1 m, which is much higher than the sounds of the boats measured in this study. The sound pressure level at a distance of 91 m from a singer, will be close to 130–135 dB which is still higher than the sounds of boats we measured at 91 m. If these non-singing whales freely swim up to a singing whale without any apparent adverse effects, it is not improbable to conclude that the boats in this study also would not cause any harm to the auditory system of the whales. Whale-watching boats typically approach whales at about 10 knots, but eventually will slow down and the engines are either put in idle or turned off, considerably reducing or eliminating the noise source. Therefore, whales are exposed to the loudest sounds of the boat engines only for a short period of time, in the vicinity of several minutes. Furthermore, during the peak of the humpback whale season, the chorusing noises are often higher in levels than the sounds of whale-watching boats traveling less than 10 knots and maintaining a 91-m standoff distance from the whales. The chorusing sounds are essentially continuous through out the season compared to the short-term nature of boat sound, once again suggesting that these boat sounds would have little or no adverse effects on the whales auditory system.

The shore-based observations of Green (1998) seem generally consistent with the acoustic effects of Manta Raiv on humpback whales. That is, the whales appeared to swim fastest in response to the loudest boat. However, it is difficult to know exactly what a pod of humpback whales reacts to. The mere presence of a boat moving into their vicinity could cause serious reactions. Besides the levels of the underwater sounds and the complexity of the sound, the size and shape of a boat may also be important factors.

Although our conclusion that the noise from whale-watching boats abiding by NMFS standoff distance or 91 m should not cause any harm to the auditory system, the ramifications of behavioral changes induced by the presence of boats are open to assessment.

Acknowledgments

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