Source levels of social sounds in migrating humpback whales (*Megaptera novaeangliae*)

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The source level of an animal sound is important in communication, since it affects the distance over which the sound is audible. Several measurements of source levels of whale sounds have been reported, but the accuracy of many is limited because the distance to the source and the acoustic transmission loss were estimated rather than measured. This paper presents measurements of source levels of social sounds (surface-generated and vocal sounds) of humpback whales from a sample of 998 sounds recorded from 49 migrating humpback whale groups. Sources were localized using a wide baseline five hydrophone array and transmission loss was measured for the site. Social vocalization source levels were found to range from 123 to 183 dB *re* 1 μPa @ 1 m with a median of 158 dB *re* 1 μPa @ 1 m. Source levels of surface-generated social sounds ("breaches" and "slaps") were narrower in range (133 to 171 dB *re* 1 μPa @ 1 m) but slightly higher in level (median of 162 dB *re* 1 μPa @ 1 m) compared to vocalizations. The data suggest that group composition has an effect on group vocalization source levels in that singletons and mother-calf-singing escort groups tend to vocalize at higher levels compared to other group compositions.

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I. INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) are one of the most vocal of the baleen whale species. They produce two distinct classes of sounds: Songs and social sounds. Songs are long, complex, highly structured vocal signals produced only by males primarily during migration and on the breeding grounds. All the males in a breeding population use the same song pattern at any time (Payne and McVay, 1971; Payne and Payne, 1985). Social sounds on the other hand, are isolated vocal sounds or brief sequences of largely unstructured vocal sounds. They include non-vocal sounds generated by energetic surface behaviors, such as breaches, pectoral slaps, and tail slaps (Payne, 1978; Tyack, 1983). These far less studied social sounds are unlike songs in that they are not confined to adult males, but may also be made by females (Dunlop *et al.*, 2008; Zoidis *et al.*, 2008) and calves (Zoidis *et al.*, 2008). All social sounds, including surface-generated sounds, probably have a communicative function in humpback whales which relate to the social and behavioral context of the sound (Dunlop *et al.*, 2008; Dunlop *et al.*, 2010). In humpback whales, sounds used in the song and sounds used as social sounds are not mutually exclusive. In other words, single sound units within the song may also be used as non-song social vocalizations (known as "song-unit social sounds"), the difference being that song is a long, continuous, patterned, complex signal, whereas these song-unit social sounds are un-patterned, in short bursts and not necessarily from the song structure of that year (Dunlop *et al.*, 2007). Previous work recorded social sounds on the feeding grounds (Thompson *et al.*, 1977, 1986; Jurasz and Jurasz, 1979; D'Vincent *et al.*, 1985; Mobley *et al.*, 1988; Sharpe *et al.*, 1998; Cerchio and Dahlheim, 2001; Stimpert *et al.*, 2011), on the breeding grounds (Silber, 1986) and on migration (Dunlop *et al.*, 2007).

Many acoustic studies have been carried out on humpback whale songs and these studies have mainly involved the analysis of the sequence of song units, phrases, themes, and song cycles (e.g., Payne and McVay, 1971; Winn *et al.*, 1971; Payne and Payne, 1985; Cato, 1991; Miller *et al.*, 2000). There have also been studies of the characteristics of the song units, quantifying frequency characteristics and duration of the sounds (e.g., Hafner *et al.*, 1979; Helweg *et al.*, 1998; MacKnight *et al.*, 2001). Frequency and temporal characteristics of migrating humpback whale social sounds have also been described previously by Dunlop *et al.* (2007), who found 34 discrete social sound types ranging in

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frequency from 40 Hz to 3 kHz, and in duration from 0.1 to 3.5 s. These sounds were recorded from humpback whales migrating along the east coast of Australia. A further study by Stimpert *et al.* (2011) on feeding humpback whales (in the North Atlantic) found a few sound types that were structurally similar to those found in the Dunlop *et al.* (2007) study, suggesting some inter-population similarities in the types of social sounds used. Quantifying the source level of the humpback whale sound signals is needed to determine the distances over which the sounds are audible and this will provide further information on the function of these sounds. Vocal source levels may also be an important measure of behavior. Source levels are therefore important in studies of acoustic behavior and the effects of masking by anthropogenic noise.

To estimate a source level of a sound requires measurement of received level and transmission loss (TL) between the source and receiver, which in turn requires a measurement of the distance between the source and the receiver. In many previous studies of humpback whale song source levels, distances were estimated rather than measured and TL was assumed to be by spherical spreading, leading to significant uncertainty in the results. There is also some confusion when comparing the result of these studies due to undocumented or varying analysis bandwidths. Winn *et al.* (1971) estimated broadband (20 Hz to 10 kHz) mean square pressure (rms) source levels of humpback whale song units to range from 175 to 188 dB *re* 1 μPa at 1 m (readings were converted to dB *re* 1 μPa at 1 m from those reported in dB *re* 1 μbar at various distances from the singing whale (23 to 92 m) assuming spherical spreading). Levenson (1972) reported lower source levels of sounds of humpback whales compared to Winn *et al.* (1971), varying from 144 to 174 dB with a mean of 155 dB *re* 1 μPa @ 1 m rms (bandwidth at least 71 Hz to 8.9 kHz) for 64 sounds measured at 2.5 km from the source. Frankel (1994) measured a mean source spectrum level of 152 dB *re* 1 μPa^2/Hz @ 1 m for humpback whale song units from which the estimated rms level in the average bandwidth of the units (175 Hz) was 174 dB *re* 1 μPa @ 1 m. This was within the range estimated by Winn *et al.* (1971). Spectrum levels in the Frankel (1994) study ranged from 136 to 174 dB *re* 1 μPa^2/Hz for the various units measured, which, if using a bandwidth of 175 Hz, would equate to 156 to 196 dB *re* 1 μPa @ 1 m. Cato *et al.* (2001) estimated broadband (20 Hz to 17 kHz) rms source levels of the most intense units of the song to range from 176 to 185 dB *re* 1 μPa @ 1 m for singers from East Australia. This was close to levels estimated by both Winn *et al.* (1971) and Frankel (1994). One of the latest and most comprehensive studies to date used a vertical hydrophone array deployed close to the whale (about 10 m) and therefore should have had minimal errors in TL estimations between the source and the receiver (Au *et al.*, 2006). This study found song unit source levels (broadband, 100 Hz to 15 kHz) to range from 144 to 173 dB *re* 1 μPa @ 1 m (rms) close to the range of levels found by Levenson (1972). The Au *et al.* (2006) study also found evidence of intraspecific variation (due to difference in source levels of different units) as well as interspecific variation and therefore reported levels for various different song units within each of the three recorded singers. To date, there is only one published study that reports source levels of social sounds in humpback whales. Thompson *et al.* (1986) estimated peak (maximum) source levels of a sample of 53 sounds of "grunts" (190 dB *re* 1 μPa @ 1 m), "trumpeting" (181 to 185 dB *re* 1 μPa @ 1 m), "tail slaps" (192 dB *re* 1 μPa @ 1 m), "flipper slaps" (183 to 192 dB *re* 1 μPa @ 1 m), low frequency pulse trains (162 to 171), blowhole "shrieks" (179 to 181 dB *re* 1 μPa @ 1 m), "moans" (175 dB *re* 1 μPa @ 1 m), and a "low-frequency broadband pulse" (median of 176 dB *re* 1 μPa @ 1 m). Spherical spreading was assumed for TL and levels were measured over the "effective bandwidth" of the sounds (system response was ±3 dB from 20 to 12 000 Hz).

Humpback whales, on migration, are found in social groups as well as on their own, and have social interactions characterized by frequent changes in group membership. During these social interactions social sounds are often heard from the group (Dunlop *et al.*, 2007). In our study site (a shallow water environment), songs can be heard more than 10 km, whereas social sounds are rarely heard past 5 km. These sounds are apparently used for communication in a closer group or individual interactions (Dunlop *et al.*, 2008), although this hypothesis has yet to be tested. Earlier work assumed these sounds were produced only in aggressive and/or competitive social encounters (Baker and Herman, 1984; Tyack, 1983; Tyack and Whitehead, 1983; Silber, 1986). Later studies have found that they are used in various other social and behavioral contexts such as between a female and her calf or by single animals that were not part of a group (Dunlop *et al.*, 2008) suggesting that social sounds may be used to broadcast to other groups in the area. Previous work has been carried out to determine the function of social sounds in humpback whales; however, much of this work has focused on the use of different types of sound with different behavioral and social contexts, rather than changes in the source level of sounds with different social contexts.

The goals of this study are to: (1) Estimate the source levels of social vocalizations and surface-generated sounds produced by migrating humpback whales using a site-specific empirical sound propagation model and (2) to assess differences in source levels between different sound types, between different sound categories (social vocalizations, song-unit social sounds, and surface-generated sounds), and between different group compositions.

II. METHODS

A. Acoustic data collection

Recordings of humpback whale vocalizations were carried out during September and October in 2003, 2004, and 2008 at Peregian Beach (26°S, 153°E), Queensland, on the east coast of Australia, during the whales' annual southward migration from their breeding grounds inside the Great Barrier Reef to their feeding grounds in the Southern Ocean. About half the migrating whales pass within 10 km of the shore at Peregian Beach.

Acoustic recordings were made from five hydrophone buoy systems anchored in 18 to 28 m of water. Each hydrophone buoy consisted of a surface buoy with attached solar panel, and contained batteries, a custom made (at the Defence, Science and Technology Organisation, Australia) amplifier (+20 dB) and VHF radio transmitter (from an AN/SSQ 41B sonobuoy). A High Tech HTI-96-MIN hydrophone with built-in +40 dB pre-amplifier was suspended above the buoy anchor by a subsurface buoy and the cable attached to the main buoy mooring line to the surface buoy. This allowed the buoy to swing on its moorings without causing significant movement of the hydrophone.

The hydrophone buoys formed a T shape array. Buoys 1 to 3 were in a line 1.5 km from the beach, parallel to the shoreline, and approximately 700 m apart. Buoys 4 and 5 extended seaward from buoy 2 in a line perpendicular to the shore and were approximately 600 m apart. The positions of the hydrophones were determined using two shore based theodolites at known positions taking cross bearings of a rod held above the hydrophone by a diver (Noad *et al.*, 2004).

Radio transmissions from the buoys were received at a base station just behind the beach using a vertically-orientated Yagi antenna matched to the radio transmission frequencies, and linked to a four-channel, low-noise, VHF receiver (type 8101) and (in 2003) a Winradio receiver (a four-channel VHF receiver type B101). Signals were passed via custom made anti-aliasing filters (−30 dB at 20 kHz) to two computers equipped with National Instruments E-series data acquisition cards (N6034E) and with *Ishmael* software (Mellinger, 2001). One computer was used to record the acoustic signals while the other was used to determine the location of the sound sources using time-of-arrival differences. Recordings were made as wav files with a sampling rate of 22.05 kHz and a depth of 16 bits.

B. Visual localization

Land-based behavioral observations were collected on a daily basis (7 am to 5 pm, weather permitting) from an elevated survey point, Emu Mountain (73 m high), adjacent to the coast. A theodolite (Leica TM 1100 in 2003 and 2004; TC407 in 2008) was connected to a notebook computer running *Cyclopes* software (E. Kniest, University Newcastle, Australia) which calculated the positions of the whales from the bearing and the angle to the horizon (with a correction for refraction) and displayed the tracks on a map of the area. The whales' positions were annotated with observed behaviors and group compositions (e.g., adult and calf, two adults). We considered a distance of 10 km to be the effective limit of the study area.

C. Localization of whale sounds

Whale sounds were tracked by time of arrival differences between hydrophone pairs using *Ishmael*. The T shaped array allowed position ambiguities to be resolved. There were times when one or two buoys was not operating but generally the ambiguity could be resolved (e.g., when only the three buoys parallel to the shore were operating, the ambiguity solution was usually on shore). Acoustic tracking was performed either in the field in real-time, simultaneously with the theodolite tracking, or during post-field analysis. The accuracy of the acoustic tracking was determined by comparing acoustic positions with theodolite positions of singing whales. There is a characteristic part of any song that occurs when the singer approaches the surface and the received level drops as a result of the interference of the direct and surface reflected paths (used by Tyack, 1981, to help locate singers). This allowed visual identification and theodolite fixing of the positions of the singing whales when surfacing. On some occasions, the position of the singing was confirmed from a small boat. When the tracked singer was noted to be surfacing (from the live acoustic recordings), a radio message was sent to the small boat located at the acoustically tracked position of the singer. The surfacing singer was then sighted from the small boat as it surfaced. The accuracy of theodolite positions had been determined for the site by comparison of theodolite and GPS positions of a research boat and was estimated to be <100 m for distances up to 10 km (Noad and Cato, 2001). The accuracy of an individual acoustic position varied from 5% of the distance at 2 km and 10% at 10 km (Noad and Cato, 2001). Taking the center of the positions of several consecutive sounds provided a more accurate estimate of the position of the vocalizing whale. Since surface activity (e.g., breaching) was both visible and audible, the positions could be obtained directly with the theodolite and compared with the acoustic positions.

Acoustic tracks of vocalizing whales were overlaid on the visual tracking map in *Cyclopes* and the combined acoustic/visual data was shared between the base and hilltop stations using a wireless network. This provided almost real-time superposition of acoustic and visual tracks out to the 10 km limit of the study area. There were rarely more than six groups migrating through the 10 km-radius study area at any one time, and these were usually widely dispersed, unless a joining interaction between two groups was occurring. Given the accuracy of the system and the way in which groups could be simultaneously visually and acoustically tracked in real-time, there was no doubt as to which groups were vocalizing at any time. Within groups, however, it was not possible to determine which animal was vocalizing.

D. Calculation of received levels

The hydrophone with a built-in preamplifier was calibrated at the Defence Science and Technology Organisation calibration facility in Woronora Dam. The rest of the recording chain was calibrated by inserting tones and white noise of known levels into the amplifier in the buoy in place of the hydrophone. Acoustic recordings were measured in the standard 1/3 octave bands using SpectraPLUS (Sound Technology, Inc.). The results were imported into Microsoft Excel. The full system sensitivity varied by 1.5 dB in the 1/3 octave bands over the frequency range 40 to 10 000 Hz.

Received levels of social sounds ($n = 998$) were measured in the standard 1/3 octave filter bands over the range 40 Hz to 10 kHz from 49 migrating humpback whale groups. Most of the energy of the social sounds was in the 40 Hz to 3.15 kHz band. Broadband levels were calculated by summing the mean square voltages in the 1/3 octave bands and then converting to decibels (by calculating 10 log of the sum). The results were then converted into pressure levels using the systems calibration.

Three measures of the received level were made: Mean square pressure level $\mathrm{RL}_{\mathrm{rms}}$ (often referred to as rms level), the peak-to-peak level of pressure of the wave form RL_{pp}, and the sound exposure level $\mathrm{RL}_{\mathrm{SE}}$. RL_{pp} was obtained by taking 20 log of the greatest change from positive to negative pressures in any cycle in the wave form. Sound exposure level is defined as

$$\mathrm{RL}_{\mathrm{SE}} = 10\log\left(\int_{t_1}^{t_2} p^2(t)dt\right) \quad (1)$$

hence

$$= \mathrm{RL}_{\mathrm{rms}} + 10\log(t_2 - t_1), \quad (2)$$

where p is pressure, and t_1 and t_2 are the start and end times, respectively, of the transient social sound. Sound exposure level is proportional to the level of the acoustic energy per unit area (sometimes referred to as energy flux level in underwater acoustics) under the same conditions as mean square pressure level is proportional to intensity level.

Since the social sounds are transients, determining $\mathrm{RL}_{\mathrm{rms}}$ and $\mathrm{RL}_{\mathrm{SE}}$ required determination of the start and end times t_1 and t_2, respectively, of the transient. An iterative process was used for this purpose using SpectraPLUS, and the recorded voltages converted to pressures using the recording system calibrations. First, a spectrum was calculated by selecting the period where the transient signal was clearly above noise in the wave form display. A second spectrum was calculated for the noise by selecting a section of the wave form well before or after the transient. A spectrum was then calculated by selecting a short section of the wave form ending at the time where the transient appeared to start (from visual inspection of the spectrogram). If this spectrum showed evidence that it contained some transient energy by having levels above noise in the frequency band containing most of the transient energy, another section of the wave form was selected at a slightly earlier time. This process was repeated to estimate the time of the start of the transient t_1. A similar process was used to find the end of the transient t_2. A 1/3 octave spectrum was then obtained for the transient over the period t_1 to t_2. Since this included a contribution from the background noise, this was removed by subtracting the mean square voltage of the background noise (measured well before or after the transient) from the mean square voltage over the period t_1 to t_2 for each 1/3 octave band. The resulting 1/3 octave band mean square voltages of the signal were summed and converted to decibels to give the broadband signal level. $\mathrm{RL}_{\mathrm{rms}}$ and $\mathrm{RL}_{\mathrm{SE}}$ were then determined from these results using the system calibration.

E. Sound propagation measurements and estimates of source levels

TL was measured using two sources: The noise generated by a noisy boat and a J11 acoustic projector broadcasting white noise filtered in octave bands over the frequency range of interest. The boat conducted runs along lines radiating from the array, from distances of 100 m out to about 10 km from the array. The boat speed was kept constant to minimize variations in radiated level. Wind speed for that day ranged from 10 to 15 knots, swell was less than 1 m, and there are no significant currents in the area. Regression lines were fitted to the received levels as a function of the logarithm of the distance from the source. The results over the distances of measurement were of the form

$$\mathrm{TL} = a + b\log(x), \quad (3)$$

where b is the slope of the regression line, x is the distance, and a is a constant (which may be frequency dependent). The value of a may vary with the direction of the boat (approaching or going away from the receivers) as the noise radiated forward differs from the noise radiated aft. For most frequencies, b varied with distance but could be well approximated by two values; one applying to distances less than, and the other greater than, a cross over value. Absolute values of TL (*re* 1 m) were determined by measuring received levels with the J11 source suspended from a boat at three distances between 200 and 1000 m from the array. The source level of the signal was measured with a hydrophone suspended from the same boat at a distance of 3 m from the J11, and corrected to the equivalent value at 1 m assuming spherical spreading. TL was then calculated as the difference between the received levels and the source level. The trend in loss, b log(x), from the boat runs was fitted to the absolute values of loss from the J11 measurements to determine the value of a for each octave band, by minimizing the sum of the squares of the differences between $a + b$ log(x) and the data points from the J11 measurements. Both a and b were found to be a function of frequency, so TL was estimated for the frequency band of the particular sound. The estimated values of a and b are given in Table I, with the cross over distances.

The mean square pressure source level of a social sound could then be calculated as

$$\mathrm{SL}_{\mathrm{rms}} = \mathrm{RL}_{\mathrm{msp}} + \mathrm{TL}, \quad (4)$$

with similar equations for the peak-to-peak source level SL_{pp} and sound exposure source level $\mathrm{SL}_{\mathrm{SE}}$. Since this TL is

TABLE I. Values of a and b in Eq. (3) used to estimate TL, for the octave bands and the distances shown.

Octave center frequency (Hz)	Distance (m)	a	b
63	All distances	−5.0	20.4
125	≤580	+3.2	16.7
	≥580	−16.14	23.7
250	≤890	−4.3	18. 3
	≥890	−24.3	25.1
500	≤890	+3.7	14.6
	≥890	−32.4	26.8
1000	<1100	+2.0	15.0
	>1100	−44.6	30.3
2000	≤1700	−7.6	19.7
	≥1700	−61.2	36.2

TABLE II. Descriptions of terms used to define humpback whale group compositions on migration with the number of groups with each composition.

Group composition	Definition	Number
Singleton	lone whale	10
Pair	2 adult/sub-adult whales	6
Mother-calf group	1 adult female with calf	9
Mother-calf-escort	2 (usually) adult whales and 1 calf	7
Mother-calf-multiple escorts	more than two adults (may include sub-adult whales) and one calf	10
Mother-calf-singing escort	2 (usually) adult whales, 1 of which is singing and 1 calf	7

the transmission loss from 1 m to the distance of the receiver from the source, Eq. (4) gives source level as the equivalent level at a distance of 1 m from a point source radiating the same level in the far field as the actual source.

F. Group composition

Humpback whale groups display coordinated surfacing activity and individuals within the group are no more than 50 m from each other. Humpback whale groups generating social sounds ($n = 49$) were divided into six different social group compositions (Table II). It is important to note that whale groups may have comprised adults and/or sub-adults (it was not possible to visually separate adults from sub-adults). It was assumed that one of the adults in a group with a young calf was the mother, a mature female. Adults accompanying a known female or a mother and calf pair are generally referred to as "escorts." Groups with two or more adults and a calf generally consist of a female calf and one or more male escorts (Baker and Herman, 1984; Tyack and Whitehead, 1983).

III. RESULTS

Acoustic recordings of 49 vocal groups were made and from these 850 social vocalizations were extracted for analysis. The median, maximum, and minimum rms source levels (SL_{rms}), peak-to-peak source levels (SL_{pp}), and sound exposure source levels (SL_{SE}) of social vocalizations are shown in Table III.

Surface-generated sounds were measured from eight humpback whale groups ($n = 148$). Breaches were distinguished from slaps either by correlation with the visual observations, or, in the rare cases of single breaches not observed from Emu Mt, by the singularity of the event. Slaps were a surface-active series, which usually occurred in a bout. In some cases (where groups were close to the hydrophone) both the downward (fin slapping the surface of the water) and upward stroke (fin exiting the water) of the slap was audible. Here, the downward stroke of the slap was measured. Median and ranges of source levels of surface-generated sounds are shown in Table III.

The SL_{rms} of all recorded social vocalizations and surface-generated sounds were plotted as a function of distance from the array (Fig. 1). Rarely were social vocalizations audible beyond 5 km from the array (although the density of migrating whales past the array was similar out this distance) and surface-generated sounds were rarely audible beyond 3 km from the array. There was no obvious distance bias with the calculated source levels of surface-generated sounds, in that there was no significant trend in calculated source levels with the distance of the source from the receiver. However, there was an obvious distance bias in calculated source levels of social vocalizations. The highest calculated vocalization source levels (the ceiling) was constant, at about 180 dB *re* 1 μPa @ 1 m, regardless of the distance of the source from the receiver. However, the lowest calculated vocalization source levels (the floor) increased with increasing distance of the source from the receiver. In other words, the further the source was from the array, the more likely it was that lower level social vocalizations were being masked by the background or ambient noise and missed in the recordings. Figure 1 also shows the thresholds of measurement for two (broadband) background noise levels: 95 dB *re* 1 μPa (modal noise condition for this study site) and 110 dB *re* 1 μPa (typical "high noise" condition for this study site). These were determined by taking the lowest received level that could be measured for the particular background noise and adding the TL for the particular distance to obtain an equivalent source level. This shows that low source level sounds may not be measureable unless the source was close to the receiver. To avoid bias, we therefore had to take into account the distance of the source from the array in subsequent data exploration.

Social sounds (vocalizations and surface-generated sounds) were divided into 36 different sound types (34 different vocalizations and 2 surface-generated sounds) based on acoustic properties (Dunlop *et al.*, 2007). Table IV gives details of the source levels (SL_{rms}, SL_{pp}, and SL_{SE}) of the 23 most common social vocalizations heard including the range of distances at which they were recorded. Means and standard deviations of source levels will be biased by distance, in

TABLE III. Descriptive statistics for mean square pressure source level (SL_{rms}) in dB *re* 1 μPa @ 1 m, peak-to-peak source level (SL_{pp}) in dB *re* 1 μPa @ 1 m, and sound exposure source level (SL_{SE}) in dB *re* 1 $\mu Pa^2 \cdot s$ @ 1 m of all measured social vocalizations (34 sound types, $n = 850$) and surface generated sounds (2 sound types, $n = 148$).

		N	Median	Min	Max
Vocalizations	SL_{rms}	850	158.4	123.5	183.7
	SE	850	157.5	117.1	191.1
	SL_{pp}	850	179.9	136.3	203.6
Surface-generated sounds	SL_{rms}	148	162.4	133.2	171.0
	SE	148	154.1	135.4	172.6
	SL_{pp}	148	183.0	159.5	197.4

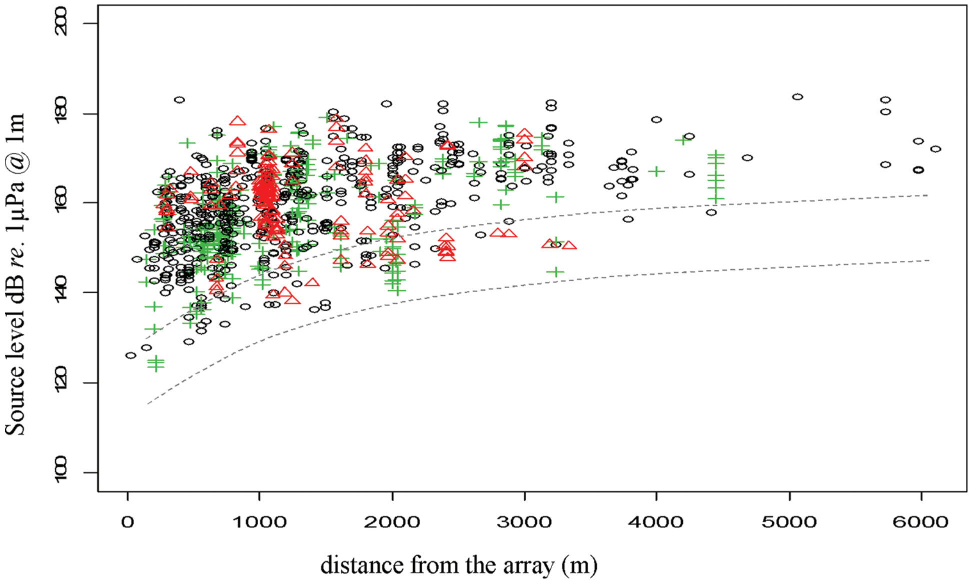

FIG. 1. A plot of mean square pressure source levels SL_{rms} of all social sounds as a function of the distance of the whale group from the array during measurement. Non-song vocalizations are represented by black circles, song-unit social sounds by green crosses, and surface-generated sounds by red triangles. The dashed lines show the thresholds of measurement of source levels for two background noise levels (broadband): 95 dB *re* 1 μPa (lower curve) and 110 dB *re* 1 μPa (upper curve) typical of the range during measurements. These represent the lowest source levels that could be measured for the particular distance and the background noise.

that only sounds of higher source level will be recorded further away from the array leading to artificial inflation of these measures. Therefore minimum and maximum source levels are reported as well as the median, which is less affected by outliers and skewed data. Most of these vocalizations were similar in source level, apart from "violins," which were relatively low level sounds. These sounds were only recorded between 200 and 1200 m from the array. However, it is likely we may have missed lower level sounds in this sample.

Social sounds were then divided into the three categories: Non-song vocal sounds, song-unit social sounds, and surface-generated sounds, and the source levels compared within three distance bins, 0 to 2000 m, 2000 to 4000 m, and 4000 to 6000 m using a boxplot for visualization of the data. A boxplot graphing the data as medians and range in levels for each sound category is shown in Fig. 2. As the distance bias had to be accounted for, the data was also separated into three distance bins for display purposes. In the 0 to 2000 m distance bin (where the data is likely to be least affected by the distance bias), the range of source levels of surface-generated sounds was less compared to both categories of vocal sounds (rms source levels of surface-generated sounds ranged from 133 to 171 dB *re* 1 μPa @ 1 m compared to 123

TABLE IV. Range of mean square pressure source level SL_{rms} in dB *re* 1 μPa @ 1 m, peak-to-peak source levels SL_{pp} in dB *re* 1 μPa @ 1 m and sound exposure source level SL_{SE} in dB *re* 1 $\mu Pa^2 \cdot s$ @ 1 m of 23 of the most common measured social vocalizations (out of the total 34 observed), and the range of distances they were recorded in.

Sound type	No. groups	No. sounds	SL_{rms} range	SL_{rms} median	SL_{pp} range	SL_{pp} median	SE range	SE median	Distance range
Wop	33	115	126–184	165.0	153–204	186.0	123–182	164.0	30–3800
Grumble	28	107	128–183	161.0	164–196	184.0	131–191	165.0	80–6000
Grunt	10	97	133–173	158.0	161–192	178.0	129–171	153.0	290–1600
Snort	34	85	136–176	158.0	161–198	179.0	134–174	155.0	530–4500
Thwop	19	73	137–177	163.0	158–199	184.0	136–177	162.0	430–3400
Bark	12	63	142–177	165.0	165–197	189.0	130–171	157.0	150–4500
Squeak	7	18	131–167	149.0	159–189	174.0	121–160	145.0	200–2000
Short moan	7	13	145–167	155.0	171–192	180.0	147–162	154.0	300–2900
Mod moan	6	24	137–179	165.0	170–196	185.0	138–179	165.0	200–2000
Growl	6	12	133–174	157.0	164–191	178.0	136–178	163.0	280–4200
Trumpet	5	27	140–177	159.0	155–194	177.0	140–174	160.0	500–3000
Purr	5	20	131–169	155.0	158–187	175.0	134–169	158.0	250–2200
Croak	4	22	136–170	152.0	166–190	172.0	134–166	151.0	550–1100
Uw blow	4	18	133–166	150.0	167–185	176.0	144–162	149.0	300–1300
Yap	4	27	141–155	149.0	167–178	173.0	131–147	140.0	600–2000
Groan	4	12	143–178	155.0	168–195	176.0	139–182	156.0	300–2600
Scream	4	13	133–153	144.0	160–176	165.0	135–154	143.0	300–1300
Horn	4	11	129–162	147.0	163–181	167.0	120–160	141.0	200–2500
Violin	4	5	123–150	125.0	136–166	137.0	117–145	119.0	200–1200
Bellow	4	5	134–162	153.0	154–184	176.0	136–159	154.0	50–1500
Ascend moan	3	5	146–162	154.0	165–177	172.0	147–161	155.0	750–2000
Cry	2	10	142–169	152.0	162–187	174.0	145–170	154.0	1200–2600
Chirp	2	5	137–169	151.0	164–186	176.0	129–163	143.0	750–1700

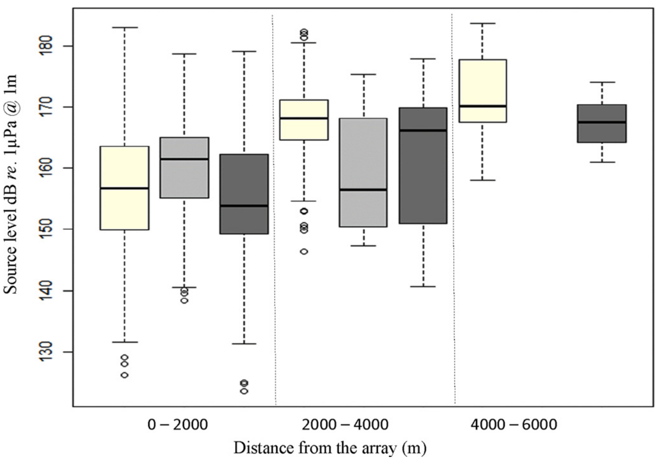

FIG. 2. (Color online) Boxplot displaying the median (the line), the 25th and 75th percentiles (defining the box), the maximum and minimum of the data or 1.5 times the interquartile range of the data (whichever is the smallest) as the whiskers and highlighting points more than 1.5 times the interquartile range above and below the quartiles as outliers (dots). The graph shows the distribution of source levels (SL_{rms} dB *re* 1 μPa @ 1 m) for the three different categories of sound (left to right: Non-song in white, surface-generated sounds in mid-gray, and song-unit sounds in dark gray) categorized into three different distance bins.

to 184 dB *re* 1 μPa @ 1 m for all vocal sounds). It is unlikely that surface-generated sounds of lower source level were missed in this distance bin as the detection limits for these sounds in noise was similar to vocalizations. The median level of surface-generated sounds was 162 dB *re* 1 μPa @ 1 m compared to 158 dB *re* 1 μPa @ 1 m for vocalizations (in this distance bin). Although the median and ranges of source levels for both non-song and song-unit social sounds look higher compared to surface-generated sounds in the 2000 to 4000 m distance bin (Fig. 2), it is probably an effect of losing vocal sounds with lower source levels at this range. Interestingly, no surface-generated sounds were recorded in the 4000 to 6000 m distance bin but this is probably due to chance rather than a specific effect; as given by the detection limits of the system, if they were available for detection (in low noise), they would have been detected.

Source level data (using non-song and song-unit social sounds only) were re-categorized into the six different group compositions defined above and separated into the three different distance bins for display purposes. Data is again displayed as a boxplot as a way of representing the median and range of the source level data for visual comparison (Fig. 3) while accounting for the effect of distance. In the 0 to 2000 m distance bin, source levels of vocalizations produced by singletons seemed to be greater compared to other group compositions. Almost all of the vocalizations of singletons were between 150 and 183 dB *re* 1 μPa @ 1 m and the median as well as the 25% to 75% percentiles of the data were also higher compared to all other group compositions. In this distance bin, mother-calf-singing escort groups did not vocalize below 145 dB *re* 1 μPa @ 1 m suggesting this group composition may not utilize low source level sounds. Only singletons and mother-calf-singing escort groups were captured in the 4000 to 6000 m distance bin suggesting that these groups are more likely to vocalize at higher source levels compared to other group compositions.

IV. DISCUSSION

Humpback whales have a widely varied vocal repertoire in terms of acoustic characteristics such as frequency and modulation characteristics (Dunlop *et al.*, 2007) and, as shown in this study, source levels. This study found source levels (rms) of humpback whale social vocalizations to range from 124 to 184 dB *re* 1 μPa @ 1 m, and peak-to-peak levels to range from 136 to 204 dB *re* 1 μPa @ 1 m. The range of source levels of social sounds in this study was found to be much wider compared those found by Thompson *et al.* (1986) of 162 to 192 dB *re* 1 μPa @ 1 m. The latter study measured only 7 different sound types ($n = 53$ sounds) and reported maximum levels only. This study measured 34 different vocalization types and 2 types of surface generated sound ($n = 998$ sounds) recorded from 49 different humpback whale groups which included 6 different group compositions. The difference in the range of source levels between the two studies may be largely due to the difference in the sample size. When comparing the results found in this study to studies on other large whale species, a similar range of source level was observed for bowhead whale (*Balaena*

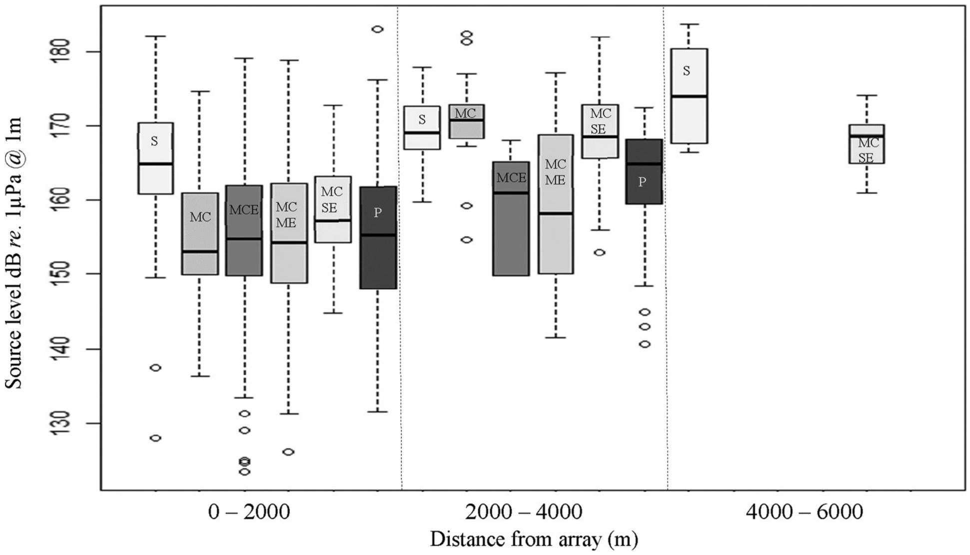

FIG. 3. Boxplot displaying the median (the line), the 25th and 75th percentiles (defining the box), the maximum and minimum of the data or 1.5 times the interquartile range of the data (whichever is the smallest) as the whiskers and highlighting points more than 1.5 times the interquartile range above and below the quartiles as outliers (dots). The graph shows the distribution of source levels of vocal sounds (SL_{rms} dB *re* 1 μPa @ 1 m) for the six different categories of group composition (left to right: Singleton = S, mother-calf = MC, mother-calf-escort = MCE, mother-calf-multiple escorts = MCME, mother-calf-singing escort = MCSE, and adult pair = P) categorized into three different distance bins.

mysticetusis) vocalizations (129 to 189 dB *re* 1 μPa @ 1 m rms: Cummings and Holliday, 1985) and a slightly lower range was observed for the North Atlantic right whale (*Eubalaena glacialis*) vocalizations (137 to 192 dB *re* 1 μPa @ 1 m rms: Parks and Tyack, 2005). The bowhead whale study measured 182 sounds (mostly low-frequency moans, trumpeting roars, and repetitive sequences which they called songs) and the North Atlantic right whale study measured 3435 sounds comprised of 6 different sound types. In comparison, a study estimating the source level of the blue whale (*Balaenoptera musculus*) and the fin whale (*Balaenoptera physalus*) vocalizations found a source level range of only 181 to 196 and 180 to 196 dB *re* 1 μPa @ 1 m rms, respectively, for each species, but only measured one sound type per species (Širović *et al.*, 2007). The lower ranges found in studies of other species may also be partly due to the noise limiting the detection and measurement of sounds of lower source levels. It is likely that not all social vocalizations were detected in this study and we have shown that as the distance between the whale and the receiver increases, the more likely low level sounds are being missed. However, care must be taken when comparing results from different studies. Differences in methodology, study site characteristics, measured band widths, and sample size can all lead to variable results.

Source levels were measured in three ways: The SL_{rms} (proportional to the intensity of the sound), the sound exposure level, SL_{SE} (proportional to the energy density of the sound), and the instantaneous peak-to-peak level of the sound (SL_{pp}). For both social vocalizations and surface-generated social sounds, the peak level was generally about 20 dB above the rms sound intensity. The measured source levels of surface-generated sounds in this study were lower in range compared to vocalizations (vocalizations ranged from 123 to 184 dB *re* 1 μPa @ 1 m rms, whereas surface generated sounds ranged from 133 to 171 dB *re* 1 μPa @ 1 m rms). Although there may be differences in the ranges of source levels and/or medians of non-song vocalizations compared with surface-active sounds and song-unit sounds, this should be tested to determine if this is statistically significant in an analysis that accounts for the effect of distance (or limits the data to less than 1 km from the array to minimize the bias introduced by distance). This would require a larger sample size than achieved in this study.

To statistically test for differences in source levels between group compositions would also require a larger sample size of groups close to the array. In the boxplot illustrating the effect of group composition on social vocalization levels (Fig. 3), the data suggests that humpback whale singletons, not involved in social interactions, vocalized at higher levels compared to other group compositions. This is clear in the 0 to 2000 m distance bin where we assume the effect of the distance bias is minimal. The source level of a vocal signal is a crucial parameter determining the active space for communication; higher level signals travel further and can be better detected by the receiver against the background of interfering sounds (reviewed in Klump, 1996). Killer whales have been found to switch from "long-distance" more intense vocal signals to "short-distance" less intense signals depending on the behavioral context (Miller, 2006). Similarly, lone humpback whales (singletons) may be using long-distance more intense vocalizations to signal (or broadcast) to other groups or whales in the area (inter-group signaling), while whales within a group could be using more short-distance less intense signals directed at other members within the group (intra-group signaling) or nearby groups. Interestingly, the minimum source level of vocalizations recorded from groups consisting of a mother-calf escorted by a singing whale was 145 dB *re* 1 μPa @ 1 m rms. All other group compositions vocalized at source levels down to 130 dB *re* 1 μPa @ 1 m rms. Perhaps this is an effect of having a loudly singing whale within close proximity to the vocalizing mother-calf. However, it is possible that some of the lowest level vocalizations were not detected in this group composition as sounds of low source level may have been masked by the song. It is likely there are particular sound types that are used for very short-distance (between-group-member) communication such as between a mother and her calf (as found in Zoidis *et al.*, 2008) that were not recorded in this study due to the problem with distance. Further studies using suction-cup digital recording tags may help with these analyses as well as find a sub-set of sounds that were not recorded on the array.

This study forms the basis for further studies of song-unit and non-song social vocalizations and surface-generated social sounds in humpback whales with regard to the different acoustic properties of each sound type and the changes in source level with social contexts. It is the most comprehensive study of social sound source levels in humpback whales to date and one of the few studies to use measurements of TL. It also highlights potential problems with using a static array to record sounds in that a distance sampling bias can occur and this sampling bias is also dependent on noise. A topical area in marine mammal studies is the concern of increasing anthropogenic noise in the ocean. Baleen whales use lower frequency sounds which lie within the band of noise produced by many anthropogenic activities including shipping and oil and gas seismic exploratory activities (Richardson *et al.*, 1995). To understand the effects and biological significance of increasing ocean noise, we must first further our understanding of acoustic communication in baleen whales and then determine the ability of this communication system to cope with the effects of anthropogenic noise. This study provides a basis for further studies into estimating the potential audible range of each social sound type and determining the social and environmental effects on humpback whale acoustic communication sounds, not only with regard to the changes in frequency and duration of sounds, but on changes in sound source level.

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