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Source levels of foraging humpback whale calls

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Abstract: Humpback whales produce a wide range of low- to mid-frequency vocalizations throughout their migratory range. Non-song "calls" dominate this species' vocal repertoire while on high-latitude foraging grounds. The source levels of 426 humpback whale calls in four vocal classes were estimated using a four-element planar array deployed in Glacier Bay National Park and Preserve, Southeast Alaska. There was no significant difference in source levels between humpback whale vocal classes. The mean call source level was 137 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m in the bandwidth of the call (range 113–157 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m), where bandwidth is defined as the frequency range from the lowest to the highest frequency component of the call. These values represent a robust estimate of humpback whale source levels on foraging grounds and should append earlier estimates.

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1. Introduction

Many animal species rely on acoustic communication for vital life functions (Bradbury and Vehrencamp, 2011). This is particularly prevalent in the marine environment where sound, unlike light, propagates well (Urick, 1983). As a result, sound is the primary sensory modality used by many marine animals and most, if not all, marine mammal species (Dudzinski *et al.*, 2009). For an acoustic signal to reach an intended recipient, it must be sufficiently noticeable, despite ambient noise conditions. If the risks associated with acoustic detection are high, however (e.g., by a predator or a competitor), there may be a biologically "optimal" loudness at which an acoustic signal exceeds ambient noise levels that maximizes reaching intended listener(s) while minimizing eavesdropping (Bradbury and Vehrencamp, 2011). Measurements of source level are essential for understanding communication range, call function, intended listeners, and the potential for acoustic masking.

Humpback whales (*Megaptera novaeangliae*) are a highly vocal baleen whale species that produce a wide range of low- to mid-frequency vocalizations associated with breeding (Au *et al.*, 2006; Payne and McVay, 1971), foraging (Cerchio and Dahlheim, 2001; D'Vincent *et al.*, 1985), and social interactions (Dunlop *et al.*, 2008; Silber, 1986; Zoidis *et al.*, 2008). Among humpback whale vocalizations, song—a long, repetitive male

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vocal display—is the best described (see Herman, 2017 for a review). Source level estimates have been made for song, with maximum estimates ranging from 152 to 195 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m (Au *et al.*, 2006; Frankel, 1994). Source level estimates have also been calculated for calling whales along migratory corridors, where humpbacks produce both song and non-song vocalizations or "calls" (Dunlop *et al.*, 2013). Measured source levels of calls in migrating humpback whales are similar to song, ranging from 128 to 184 dB $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m, with an average of 158 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m.

On foraging grounds, humpback whales produce both late-season song (Gabriele and Frankel, 2002) and calls in association with feeding and social interactions (Cerchio and Dahlheim, 2001; Sharpe, 2001; Wild and Gabriele, 2014). Calls on foraging grounds were first described by Thompson (1986), who calculated peak source levels for percussive sounds, blowhole-generated sounds, and underwater calls. This was the first and only study to date to estimate source level values for humpback whale calls on foraging grounds. Using a sample set of 32 calls, Thompson (1986) found that source levels for underwater vocalizations ranged from 162 to 190 $\mathrm{dB_{Zero\text{-}Peak}}$ re 1 μPa @ 1 m. Improvements in technology, most notably the ability to acoustically localize calling animals, and a deeper understanding of transmission loss in the recording region, however, revealed a need to revisit calls in Southeast Alaska in order to expand upon previous investigations into the acoustic properties of humpback calls on foraging grounds.

A study in Southeast Alaska in 2012 quantitatively classified humpback whale calls in the foraging region and expanded the repertoire to include 16 call types nested within four vocal classes, low frequency harmonic (LFH), noisy/complex (NC), pulsed (P), and tonal (T) (Fournet *et al.*, 2015). These calls, which in some cases are stable across multiple generations on foraging grounds (Fournet *et al.*, 2018), serve diverse foraging and communicative purposes that appear to vary by call type or class (Cerchio and Dahlheim, 2001; Fournet, 2014; Wild and Gabriele, 2014). Differences in amplitude may be an indication of intended listeners and be therefore useful for forming hypotheses pertaining to call function, or for assessing the potential risk of acoustic masking.

A critical first step toward understanding the effects of anthropogenic noise in today's increasingly industrialized oceans is accurately measuring the source levels of humpback whale vocalizations in this high-latitude foraging ground. Acoustic masking can be defined as the point at which sounds from other sources are loud enough to reduce the probability of an acoustic signal being detected by a listener (Yost *et al.*, 2008). Put simply, loud background noise has the potential to "drown out" an intentional acoustic signal (Clark *et al.*, 2009). Humpback whale calls on foraging grounds overlap in frequency with vessel noise, indicating that this species is at a risk for acoustic masking (McKenna *et al.*, 2012; Ross, 1976). Managers in Glacier Bay National Park and Preserve (GBNPP) in Southeast Alaska have been tasked with assessing the impact of vessel noise on marine mammal species, including humpback whales. Reporting the source levels of humpback whale calls on this foraging ground is a critical step toward accomplishing this mandate.

In this study we used a four-element hydrophone array deployed over two summer foraging seasons in Southeast Alaska (1) to calculate source levels for humpback whale calls on a high-latitude foraging grounds and (2) to assess differences in source levels between vocal classes.

2. Methods

2.1 Acoustic data

We deployed four calibrated autonomous underwater hydrophone (AUH) packages (hydrophone model ITC-1032) in GBNPP from May to October 2015 and April to October 2016 (Fig. 1). GBNPP is a well-monitored marine wilderness park with an historic humpback whale population that returns annually to forage (Gabriele *et al.*, 2016). Hydrophones were bottom mounted in the Beardslee Island Complex at depths between 62 and 81 m, arranged in a diamond-shaped planar array and separated by approximately 1 km. Each AUH recorded continuously in the 15–4000 Hz range with a 10 kHz sampling rate, 16-bit resolution, and 4 kHz low pass filter, which adequately encompasses the energy content of the humpback whale vocal range in this region (Fournet *et al.*, 2015). All AUHs included a highly accurate internal clock (Q-Tech model number QT-2001, error of approximately 1 s per year), that was calibrated to satellite time at both deployment and recovery, which allowed for clock drift over the deployment to be quantified. Drift rates were retroactively corrected using a custom written algorithm in MATLAB. Prior to deployment and directly following recovery hydrophones were group together and a percussive sound was simultaneously recorded

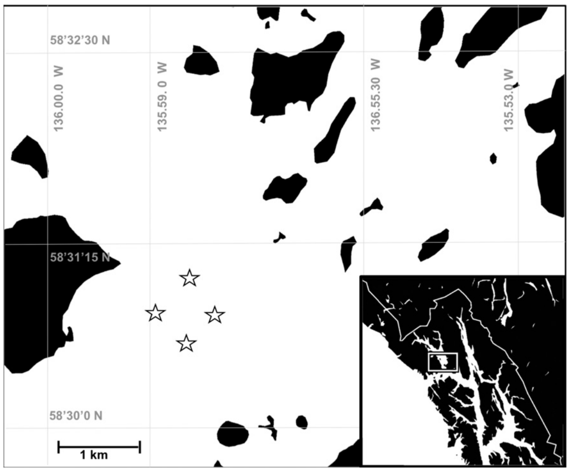

Fig. 1. Field site in Glacier Bay National Park and Preserve, Southeast Alaska. Hydrophone array location in 2015 marked with stars, the 2016 locations were moved approximately 1 km northeast.

on all four phones. Hydrophones were time-aligned by matching the times of the percussive sounds on all four hydrophones. Acoustic data were recorded as custom-format.dat files, which upon recovery were converted to WAVE (.wav) files using a custom MATLAB script. Recordings were then filtered according to their lab-calibrated gain curve in the 15–4000 Hz range (ADOBE AUDITION) to correct for nonlinearities in the frequency sensitivity of the recording system. In 2015 the easternmost hydrophone could not be time-aligned due to a clock error and was therefore excluded from analysis in that year.

2.2 Visual data collection

Photographs of humpback whale flukes and dorsal fins were systematically collected from shore and by kayak between June and September in both 2015 and 2016 in order to identify individual whales (Katona and Whitehead, 1981). Photographs were matched to an existing database of known humpback whales in Southeast Alaska (Straley and Gabriele, 1997) to generate a minimum number of individuals present throughout the study period.

2.3 Acoustic analysis

We randomly sub-sampled 50 one-hour acoustic files collected in 2015 and 25 one-hour acoustic files from 2016. The additional 25 one-hour acoustic files were selected from 2015 to ensure approximately the same number of calls were represented from both years. All sub-sampled recordings were made during daylight hours between July and September. Spectrograms for each hour of recording were manually reviewed in RAVEN PRO 2.0 (Bioacoustics Research Program) [Hann window, discrete Fourier transform (DFT) size 1024, analysis resolution 9.7 Hz and 0.05 s, 50% overlap] by a single experienced observer (MF). All humpback whale calls were annotated and assigned to vocal class based on a known catalog for the region (Fournet *et al.*, 2015). Some humpback whale calls are highly variable, and appear to persist along a continuum, which may confound classification at fine scales (Fournet *et al.*, 2015; Rekdahl *et al.*, 2013; Stimpert *et al.*, 2011; Murray *et al.*, 1998). Calls in Southeast Alaska, however, follow a hierarchical classification structure which allows for call placement into broader-scale groupings that encompass the variability associated with a repertoire of static-dynamic call types (Fournet *et al.*, 2015). For these reasons, acoustic samples in this study were only classified to the vocal class level. Calls that did not merit classification within one of the four known vocal classes were classified as "unknown." No other baleen whale species with similar call types are consistently sympatric with this population of humpback whales in GBNPP, and no other baleen whale species were visually or acoustically identified during the 75 subset hours, which allowed for accurate identification of humpback whale calls during this period.

Humpback whale calls were localized in RAVEN PRO 2.0 using the near-field beamforming method and each call was assigned a latitude and longitude position. This method searches for the set of time of arrival delays that give maximum power from the beamformer output (Hawthorne and Salisbury, 2016). We used a simulated annealing algorithm to find the point in space that generated maximum power for each call. We used a sound speed of 1481 m/s based on CTD casts done in the study area by the National Park Service in summer months in 1981, 1993, 2001, 2012, 2015, and 2016. Although sound speed profiles varied slightly over time, the choice of a sound speed (range 1472–1481 m/s) had a negligible impact on source level estimates (<1 dB), thus the sound speed that corresponded to the oceanographic conditions in 2015 and 2016, was selected. Bartlett's formula was used to estimate the variance of the energy output from the beamformer, which resulted in error values for the northern and eastern bearings for each call. To select for the highest quality calls, only calls that were localized to within 6 km of the array center, with an error less than 100 m and a signal-to-noise ratio (SNR) of 6 dB or higher, were included in analysis.

2.4 Source level calculations

Source levels (SL) were calculated using Eq. (1) based on (1) an estimated transmission loss (TL) value and (2) the calibrated in-band received level (RL) for each call:

$$\boldsymbol{SL} = \boldsymbol{RL} + \boldsymbol{TL}. \tag{1}$$

Transmission loss for this region has been empirically measured (Malme *et al.* 1982) as well as semi-empirically modeled (Frankel and Gabriele, 2017), and is known to have an approximate $15\log_{10}r$ dependency, where r is range. For each call, the distance between the localized call and the hydrophone was measured using the EARTH.DIST function from the "fossil" package in R (Vavrek, 2011) and a transmission loss value was calculated. For each call, a root-mean-squared (RMS) received level was extracted in the measured bandwidth of the call using the "inband power" feature in RAVEN PRO. Bandwidth in this context is defined as the frequency range from the lowest to the highest frequency component measured for a given call. Inband RMS ambient noise levels were also calculated for the 2 s directly preceding each call in order to calculate SNR values and to measure source level excess above ambient noise.

Using Eq. (1) three source level measurements in 2015, and four source level measurements in 2016 (corresponding to the number of hydrophones used for localization) were made for each call. These source level estimates, which were in $\mathrm{dB_{RMS}}$, were converted to voltages, averaged, and converted back to $\mathrm{dB_{RMS}}$ to produce a single source level estimate for each call. All source level estimates are reported as $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m in the bandwidth of the call (Table 1).

2.5 Call class comparison

A Levene's test for homogeneity of variance indicated that the assumption of equal variance was not met ($f_{d.f=4} = 4.16$, $p = 0.002$); therefore, a non-parametric Kruskal-Wallis test was used to assess differences in median source levels in dB between call classes.

3. Results and discussion

Within this study, 426 calls spread across 33 days, over seven months, in April to October 2015–2016 fit the inclusion criteria (2015: $n = 200$; 2016: $n = 226$). Of those, 230 were LFH calls, 26 were NC calls, 135 were P calls, 4 were T calls, and 20 were unknown. The mean source level for all call classes was 137 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m in the bandwidth of the call (SD ± 8, mean bandwidths reported in Table 1). Source levels ranged from 113 to 157 $\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m. There was no significant difference in source levels between call classes ($\chi^2_{\mathrm{d.f.}=425} = 425$, $p = 0.5$, Fig. 2, Table 1). On average, source levels were 52 dB higher than ambient noise levels in the bandwidth of each respective call (95% C.I. 51–53 dB). On average callers were 1425 m from the hydrophone array (95% C.I. 1333–1518).

Table 1. Mean low (RavenPro 5% frequency feature) and high frequency (RavenPro 95% frequency feature) measurements with standard deviations in parentheses of calls by class (LFH = low-frequency harmonic, NC = noisy complex, P = pulsed, T = tonal, U = unknown). Mean, minimum, and maximum source levels ($\mathrm{dB_{RMS}}$ re 1 μPa @ 1 m in the bandwidth of the call) by call class.

Call class	n	Low frequency (Hz)		High frequency (Hz)		Source level (dB)		Min source level (dB)	Max source level (dB)
LFH	230	34.7	(49.6)	656.1	(331.7)	138.6	(8.6)	113.0	156.0
NC	26	358.8	(133.2)	2781.3	(506.7)	138.9	(10.7)	112.9	156.7
P	135	107.8	(155.4)	1202.8	(950.1)	135.5	(6.9)	114.8	147.5
T	4	115.3	(25.7)	973.5	(34.5)	132.0	(7.4)	120.1	136.7
U	31	263.4	(19.8)	1142.4	(26.9)	132.2	(6.3)	116.8	141.8
All	426	95.0	(144.2)	997.4	(915.2)	137.0	(8.2)	112.9	156.7

Thirty-six known individuals were photographically identified in the listening area of the array over the two summer seasons. Twenty-five individuals were identified in 2015, 21 individuals were identified in 2016, and 10 individuals were sighted in both years. Because photo ID effort was not comprehensive this likely underrepresents the number of individuals present during the recording period.

The source level values reported in concert with these visual observations represent a quantitative estimate for humpback whales on a Southeast Alaskan foraging ground supported by over 400 calls, produced over two years and in the presence of a robust number of individuals. While it is possible that for a selection of calls some acoustic energy was shadowed by islands in the survey area, 85% of calls ($n = 362$) originated from within a 2.5 km radius of the hydrophone array that contained no islands. It is therefore highly likely that the estimates reported in this study are indicative of the range of source levels for this population in this region, assuming a similar range of ambient noise conditions.

The source level estimates derived in this study are approximately 25 to 65 dB lower than those reported by Thompson *et al.* (1986). There are several critical differences in how these values were calculated that are relevant to these differences. First, the report made by Thompson (1986) had a limited sample size of 32 underwater calls (i.e., not surface impacts or blowhole-associated sounds). The distances to the callers were visually estimated, and when whales were travelling in groups—as they often were throughout the 1975 study—the caller was assumed to be the whale nearest to the vessel. In the absence of directional recordings, however, it is problematic to ascribe the recorded vocalizations to the whales directly within visual range, and even more so to the whale closest to the vessel. These potentially erroneous distance values would have impacted source level estimates in an already limited dataset, particularly if the calling animals were beyond visual range and errors in distance estimates were high. More importantly, Thompson (1986) assumed that spherical spreading loss (i.e., $20\log_{10}r$) was appropriate to estimate transmission loss. Empirical transmission loss measurements made in Frederick Sound, Southeast Alaska, where the Thompson study was conducted, demonstrate that the assumption of spherical spreading was likely incorrect. Instead, transmission loss for that region was measured as approximately a $15\log_{10}r$ dependency (Malme *et al.*, 1982); this error may have had a significant upward impact on the estimated values of Thompson *et al.* Demonstrating this point, when applying a $20\log_{10}r$ spreading loss coefficient to our data, the mean source level shifted upward by 25 dB to 152 dB$_{\mathrm{RMS}}$ re 1 μPa@ 1 m with values ranging from 127 to 173 dB$_{\mathrm{RMS}}$ re 1 μPa@ 1 m. Although these example values are still slightly lower than those reported by Thompson, they are within the range of the 1975 study.

The differences in source levels between 1975 and 2015 to 2016 are further explained by the choice of source level measurement. Thompson *et al.* reported zero-peak source level (the difference in pressure between zero and the greatest pressure of the signal) in the effective bandwidth of the call, while we report RMS source level (the square root of the average of the square of the pressure of the sound signal over a given duration), which in most cases would be 3 dB less than zero-peak (Urick, 1983). The discrepancy in measurements explains some portion of the difference seen in this

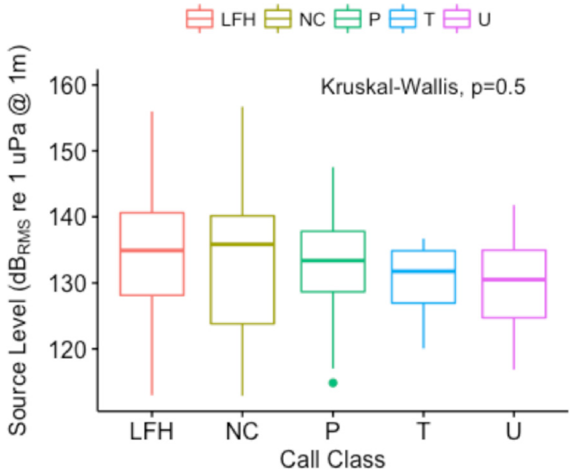

Fig. 2. (Color online) Boxplot of source levels by vocal class. Whiskers represent the range of the data, the dot represents a potential outlier. LFH = low-frequency harmonic ($n = 230$), NC = noisy complex ($n = 26$), P = pulsed ($n = 135$), T = tonal ($n = 4$), U = unknown ($n = 20$).

study and the historical one. Overall, the assumptions used by Thompson (1986) coupled with the limited sample size lead us to believe that the values reported here represent more accurate source level estimates of calls by foraging humpback whales in Southeast Alaska.

Average source level estimates for humpback whale calls made with a calibrated hydrophone array along the Eastern Australian migratory corridor were 29 dB higher than mean source level values found in this study (Dunlop *et al.*, 2013). It is likely that given the robustness of the methodologies used in that study, and the equivalence of measurement units between the two studies, that these differences represent true ecological variation. There are two probable explanations that would account for decreased source levels in GBNPP. First, GBNPP is a marine wilderness area with restricted vessel traffic. The hydrophone array used in this study bordered non-motorized waters that were infrequently used by vessels. As a result, ambient noise conditions in this particular location may be lower than ambient noise conditions along the unmanaged coastal Australia migratory corridor. Dunlop *et al.* (2013) reported modal noise conditions of 95 dB; by comparison, modal ambient noise levels for this study were only 81 dB RMS. Since humpback whales have exhibited a Lombard effect—louder vocalizations in response in elevated environmental noise conditions (Dunlop *et al.*, 2014)—it is reasonable to assume that ambient noise contexts may impact call source levels. Our maximal source level estimates, in the range of 156 dB RMS, were comparable to those of the migrating Australia humpbacks.

Second, humpback whale social affiliations on foraging grounds can best be described as "inconspicuous." High latitude social behavior varies from solitary individuals to stable short-term associations, with animals in GBNPP typically travelling alone or forming small ephemeral groups (Baker *et al.*, 1985; Clapham, 1996; Ramp *et al.*, 2010; Weinrich *et al.*, 2006). In comparison, humpback whales on migratory corridors show high levels of social interaction, ranging from group travel to male-male competition and vocal breeding displays (Corkeron and Brown, 1995; Dunlop *et al.*, 2008). The lower source levels observed on foraging grounds may be a result of the intended audience. Indeed, humpbacks along the East Australian migratory corridor maintained source levels that were 60 dB higher on average than background noise, while in this study calls exceeded background noise levels by 52 dB on average. This may indicate that humpback whales vocalize to closer listeners, perhaps intentionally, on foraging grounds. Future investigations relating social context with acoustic behavior, including source levels, of humpback whales on foraging grounds will facilitate understanding the function of high-latitude calls, which are of particular importance given changing ocean soundscapes and ecology.

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