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Clicks of dwarf sperm whales (*Kogia sima*)

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ABSTRACT

The two species of the genus *Kogia* are widely distributed throughout the world's temperate and tropical oceans, but because they are small and highly cryptic, they are difficult to monitor. The acoustic signals of *K. breviceps* have been described previously, but the signals of *K. sima* have remained unknown. Here we present three recordings of *K. sima*, two from free-ranging animals and one from a captive setting, representing both the Atlantic Ocean and Pacific Ocean. The acoustic signals of *K. sima* are very similar to the signals of *K. breviceps* and other species that have narrow-band, high-frequency (NBHF) clicks. Free-ranging *K. sima* produce "usual" clicks that have mean peak and centroid frequencies of 127–129 kHz, mean −3 dB bandwidth of 10 kHz, mean −10 dB bandwidth of 16–17 kHz, and mean interclick interval of 110–164 ms. Although *K. sima* clicks cannot yet be distinguished from those of *K. breviceps* or other NBHF clicking species, our detailed description of this species' signals reveals the similarities between the two *Kogia* species, and thus allows for passive acoustic monitoring of the genus *Kogia* in regions where other NBHF species are not present.

Key words: *Kogia sima*, dwarf sperm whale, narrow-band high-frequency, echolocation, biosonar, click, The Bahamas, Florida, Atlantic, Guam, Pacific.

The genus *Kogia* comprises two species, the dwarf (*Kogia sima)* and the pygmy sperm whale (*K. breviceps*). Both species are highly cryptic visually; they are small-bodied (2–2.7 m as adults) and travel in small groups (1–12 animals) (Willis and Baird 1998, McAlpine 2002, Dunphy-Daly *et al*. 2008). They make deep (>250 m), long-duration (~25 min) dives interspersed with short surfacings (Fitch and Brownell 1968, Breese and Tershy 1993, Plön 2004, West *et al*. 2009). At the surface, they produce no visible blow and are not known to raise their flukes or engage in other visible behavior patterns (Willis and Baird 1998). Much of their

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distribution is known from records of stranded individuals, which have been found on beaches throughout the world's temperate and tropical oceans (summaries in Willis and Baird 1998, Taylor *et al*. 2012).

All odontocetes produce sounds to communicate and forage, and their sounds are believed to be species specific. Having a clear description of the acoustic signals made by any species is essential for fully understanding its foraging and social behavior and to allow the use of passive acoustic monitoring (PAM) to record species occurrence. PAM is particularly useful for species that are cryptic and/or inhabit remote, hard-to-reach locations, such as the open ocean. By using PAM, we can monitor the presence of *Kogia* spp. at off-shore locations that would otherwise be unavailable for long-term monitoring of such cryptic species. PAM methods may also eventually generate the information required for density and abundance estimation, which could lead to more reliable estimates of population sizes than are currently possible, thereby facilitating management directives (*e.g.*, Van Parijs *et al*. 2009, Marques *et al*. 2013).

Little information is available on the sound production of either *Kogia* species. Early publications were limited because the instruments that were used did not record at high enough frequencies to accurately capture *Kogia* spp. echolocation signals (Caldwell *et al*. 1966, Caldwell and Caldwell 1987 in Marten 2000, Thomas *et al*. 1990). More recent efforts analyzed recordings of two stranded *K. breviceps* being held in captivity for rehabilitation (Marten 2000, Ridgway and Carder 2001, Madsen *et al*. 2005*a*). The characteristics of the clicks included a high peak frequency (125–130 kHz), moderate duration (100–000 μs), and interclick intervals (ICI) of 40–70 ms, as well as high directionality (Table 1). Such narrow-band, high-frequency (NBHF) clicks appear to be an adaptation to take advantage of low ambient noise levels at these frequencies and to avoid predation by killer whales (*Orcinus orca*) by generating signals above the predator's hearing range (Madsen *et al*. 2005*a*, Morisaka and Connor 2007).

This paper presents details about the echolocation clicks of *K. sima* from both free-ranging and captive settings. These are the first confirmed recordings of the clicks of this species.

METHODS

Free-ranging Recording 1: The Bahamas

An opportunistic encounter with a small group of *K. sima* during field research in The Bahamas in the western North Atlantic Ocean provided the setting for a recording of free-ranging animals. Visual observers searching for beaked whales aboard a 6.5 m vessel saw a group of three *K. sima*, including two adults (sex unknown) and one subadult (sex unknown), at 25.91°N, 77.18°W, southwest of Abaco Island, on 21 May 2005. The water depth was approximately 600 m. The animals were observed and recorded during 3.5 h of observation while they repeatedly dove and surfaced within 20–200 m of the boat. No other cetaceans were seen in the area during this period, despite ongoing visual observation, so it is unlikely that these clicks came from another species. A BK8103 hydrophone (Brüel and Kjær Sound & Vibration Measurement A/S, Nærum, Denmark; frequency range 0.1 Hz to 180 kHz $+3.5/-12.5$ dB, sensitivity -211 ± 2 dB re: 1V/μPa) with a BK2635 charge amplifier was suspended approximately 2 m below the surface. Recordings were made at 375 kHz sample rate on an Avisoft UltraSoundGate 416

Table 1. Click parameters for captive and free-ranging recordings of *K. sima* based on recordings from 2002 (captive), 2005 (The Bahamas) and 2016 (Guam) (± standard deviation). Also shown are parameters from recordings of captive *K. breviceps* for comparison (Madsen *et al.* 2005*a*). Peak frequency, centroid frequency, duration, −3 dB bandwidth, −10 dB bandwidth, rms bandwidth, Q_{-3dB}, Q_{rms}, and inter-click interval are shown as mean/median (± SD).

Species	Recording Setting	Sample size (# clicks)	Peak frequency (kHz)	Centroid frequency (kHz)	Duration (μs)	−3 dB bandwidth (kHz)	−10 dB bandwidth (kHz)	rms bandwidth (kHz)	Q_{-3dB}	Q_{rms}	Interclick interval (ms)
K. sima (calf)	captive	49	112/110 (± 9)	108/105 (±9)	91/52 (±85)	21/16 (± 11)	43/43 (± 20)	18/17 (± 19)	6/6 (± 2)	7/7 (± 5)	83/79 (± 24)
K. sima (2 adults + 1 subadult)	free-ranging The Bahamas	328	129/129 (± 2)	129/129 (± 2)	199/179 (± 54)	10/10 (± 2)	16/17 (± 3)	9/9 (± 2)	15/15 (± 4)	14/13 (± 3)	164/135 (± 79)
K. sima (adult + calf)	free-ranging Guam	759	127/127 (± 2)	121/122 (± 5)	186/192 (± 62)	10/10 (± 3)	17/16 (± 7)	20/20 (± 7)	7/6 (± 3)	13/13 (± 3)	110/93 (± 73)
K. sima burst pulse clicks	free-ranging Guam	81	124/124 (± 2)	117/118 (± 6)	138/130 (± 46)	14/14 (± 4)	25/26 (±7)	23/22 (±7)	6/5 (± 2)	10/9 (± 4)	37/37 (± 10)
K. sima lower frequency clicks	free-ranging Guam	98	117/117 (± 3)	113/115 (± 6)	189/191 (± 75)	11/10 (± 7)	19/16 (± 12)	17/16 (± 7)	8/7 (± 4)	12/12 (± 3)	198/216 (± 120)
K. breviceps	captive	820	130/na (± 1)	129/na (± 1)	119/na (± 19)	8/na (± 2)	15/na (± 3)	na	16/na (± 1)	na	40–70/na

Note: Possible issues with the captive recording are detailed near the end of the article.

connected to a Toshiba laptop computer. A low pass filter was not used in this recording since the frequency response of the hydrophone fell off rapidly above the Nyquist frequency.

Free-ranging Recording 2: Guam

The second data set from free-ranging animals was also obtained during a small-boat survey and includes recordings of the same four individuals (two mother/calf pairs, confirmed by photo-identification) from two 1 h encounters (28 May 2016 and 4 June 2016). The animals were found off the west side of Guam in the western North Pacific Ocean at approximately 13.3°N, 144.6°E. No other cetaceans were seen in the area during this period, despite ongoing visual observation, so it is unlikely that these clicks came from another species. The water depth was approximately 650–800 m, and the animals were roughly 3.5 km from shore. Recordings were made using a compact acoustic recording buoy (CARB),[2] a free-floating instrument deployed in the vicinity of the animals, that includes an HTI-96-MIN hydrophone (High Tech, Inc., Long Beach, MS; sensitivity −180.7 dB re: 1V/μPa) suspended around 30 m depth. The manufacturer specified frequency range for this hydrophone is flat from 2 Hz to 30 kHz, but preliminary lab calibration has shown functionality out to at least 140 kHz (+3/−8 dB), with sensitivity of approximately −186 dB re: 1V/μPa at 130 kHz. Field testing has confirmed successful recording of NBHF porpoise clicks.[3] Please see below for further discussion of potential issues arising from using this type of hydrophone for high frequency recordings. Recordings were made at a sampling rate of 384 kHz on an SM2+ Song Meter (Wildlife Acoustics, Concord, MA), which included preamplifier gain of +36 dB and a 1 kHz high pass filter. There was no low-pass/anti-alias filter used at the time of data collection.

Captive Recording

A female *K. sima* calf, weighing 28.5 kg, stranded at Cape Canaveral, Florida in July 2002, and was taken to the Mote Marine Lab's Dolphin and Whale Hospital in Sarasota, Florida, for care. The animal remained in captivity for over 15 mo until October 2003, during which time recordings were made. The cause of stranding was unknown, however, later necropsy revealed an impacted colon and ink sac. The animal was recorded while free-swimming in a 9.1 m circular, fiberglass tank approximately 1.5 m deep. Unfortunately, due to loss of computer files only 4 s of data were saved for analysis. A Reson TC4013 hydrophone (frequency range 1 Hz to 170 kHz +2/−4 dB, sensitivity −211 ± 3 dB re: 1V/μPa; VP1000 preamplifier with 32 dB gain) was suspended at approximately 0.75 m depth, and about 0.5 m away from the wall of the tank. Recordings were digitized at 500 kHz using a Tucker-Davis Technologies AD2. There was no low-pass/antialias filter used at the time of data collection.

Click Analysis

Analysis of the *K. sima* recordings was performed by a trained analyst (KM) using custom MATLAB subroutines (MathWorks, Natick, MA). Even though multiple

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[2] Personal communication from Yvonne Barkley, NOAA IRC, NMFS/PIFSC/PSD/Yvonne Barkley, 1845 Wasp Boulevard, Building 176, Honolulu, HI 96818, October 2016.

[3] Personal communication from Jay Barlow, NOAA-SWFSC-MMTD, 8901 La Jolla Shores Drive, La Jolla CA, March 2017.

animals were present during the Bahamas and Guam recordings, it was not possible to identify which clicks came from which individual; therefore, all clicks from within a given region were combined for analysis. In each data set, a human analyst identified periods of time with clicks present, and any unusual features were noted. In the Guam recording, there were several burst-pulse click sequences with shorter interclick intervals, and a subset of clicks with visibly lower peak frequencies. Both subsets of clicks were analyzed separately from the remainder of the signals. All sets of clicks were analyzed using a two-stage automated detector based on Soldevilla *et al.* (2008), Roch *et al.* (2011), and Baumann-Pickering *et al.* (2013). Archived code is available at http://doi.org/10.5281/zenodo.164881. Individual clicks were filtered using a 4-pole Butterworth bandpass filter with a high pass threshold at 10 kHz and a low pass threshold at 170 kHz. The captive recording was also filtered using Butterworth notch filters at 81 kHz and 160 kHz to remove tonal noise. After filtering, the clicks were retained if they passed a peak-to-peak amplitude threshold for each click. This threshold was adjusted independently for each data set based on ambient noise conditions to retain the maximum number of clicks while excluding nonclick noise.

The retained clicks were used to calculate multiple parameters. The spectral characteristics were computed using a 1,200 μs fast Fourier transform (FFT) on Hann-windowed data centered on each click. The number of sample points and the frequency bin size was slightly different for each recording because of the different sampling rates, ranging from 460 points and approximately 418 Hz/bin in the Guam recording to 450 points and 416 Hz/bin in the recording from The Bahamas and 600 points and 416 Hz/bin for the recording of the captive animal. The mean frequency spectrum was computed across all detected clicks within each recording. A mean noise spectrum was also computed for each recording session based on periods of data preceding each click, lasting an equal duration to each click, but separated from the click by approximately 5 ms. The mean and median of the following parameters were calculated for each click: peak frequency, centroid frequency, −3 dB bandwidth, −10 dB bandwidth, rms bandwidth, click duration, and ICI. The duration was calculated as the time spanned by 95% of the energy of the signal envelope (the absolute value of the analytical waveform), following methods by Madsen *et al.* (2004). ICIs longer than 500 ms were excluded as outliers based on examination of histograms of all ICIs. ICIs shorter than 2 ms were excluded because they were all caused by reflections. In the captive recording, there were substantial echoes due to the nature of the tank; therefore, a lock-out period of 50 ms after the initial click was used to remove all echoes from consideration.

RESULTS

Recordings from both free-ranging and captive *K. sima* contained only NBHF clicks, more similar to those of porpoise (*e.g.*, Villadsgaard *et al.* 2007, Kyhn *et al.* 2013) than those of other deep diving cetaceans such as beaked whales (family Ziphiidae) and sperm whales (*Physeter macrocephalus*) (*e.g.*, Weilgart and Whitehead 1988, Goold and Jones 1995, Johnson *et al.* 2004). No whistle-like sounds were recorded. Click parameters are summarized in Table 1. The majority of the clicks could be described as usual clicks with consistent ICI and received level throughout each encounter (*sensu* Weilgart and Whitehead 1988).

The parameters of the clicks from the two free-ranging recordings are assessed here, while the results for the captive recording are reported below. Examples of the mean spectra, waveform, and time series for all three recordings are shown in Figure

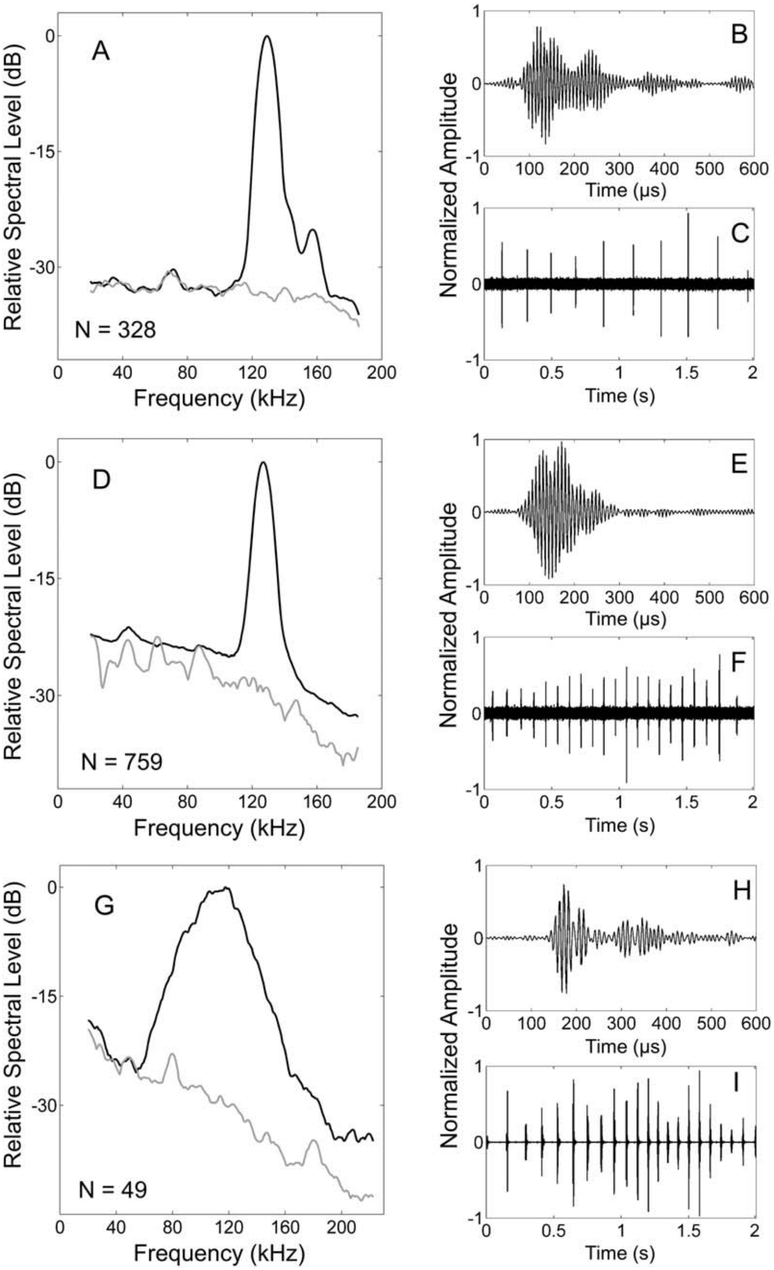

Figure 1. Example clicks from The Bahamas (A, B, C), Guam (D, E, F) and captive (G, H, I), recordings, including (A, D,G) the mean spectrum of extracted usual clicks (black line) and mean noise before each click (light gray line), (B, E, H) an example waveform of a single click, and (C, F, I) an example time series of 2 s of data.

1. The Bahamas recordings spanned 37 min and contained 328 usual clicks. The recordings from Guam spanned 2 h and contained 938 clicks (including 759 usual clicks and 179 clicks of two different types, described below). The characteristics of the clicks in these two sets of recordings were similar, except for centroid frequency, rms bandwidth and ICI. There was no notable frequency sweep, in contrast to the clicks of most beaked whale species (*e.g.*, Baumann-Pickering *et al.* 2013).

The differences in the centroid frequencies were examined further, along with the rms bandwidth, which is calculated using the centroid frequency. In the Bahamas recording the centroid frequency was similar to the peak frequency and the rms bandwidth was similar to the −3 dB bandwidth, which was expected based on previous descriptions of the clicks of other NBHF species (*e.g.*, Madsen *et al.* 2005*a*; Kyhn *et al.* 2009, 2010, 2013; Götz *et al.* 2010). In contrast, the centroid frequency of the usual clicks from the Guam recording was lower than the peak frequency by about 6 kHz, and the rms bandwidth was wider than the −3 dB bandwidth by about 10 kHz. These differences may have been caused by a large proportion of clicks in the Guam recording with a low signal-to-noise ratio (SNR), so a subset of clicks with SNR > 20 dB was examined separately. This subset of highest SNR clicks had a peak frequency of 127 ± 0.8 kHz, centroid frequency of 127 ± 0.9 kHz, −3 dB bandwidth of 8.6 ± 1.0 kHz, −10 dB bandwidth of 13 ± 2.0 kHz, and an rms bandwidth of 7 ± 1.3 kHz. These results are closer to what was expected for centroid frequency and rms bandwidth given the values for peak frequency and −3 dB bandwidth, and they are similar to the results for the Bahamas recording as well as those of NBHF clicks from other species (*e.g.*, Madsen *et al.* 2005*a*; Kyhn *et al.* 2009, 2010, 2013), which reinforces the possibility that low SNR clicks were impacting the summary results for the whole recording.

Two unique subsets of clicks in the recording from Guam were examined separately (Fig. 2). Visual analysis of the spectrograms revealed the presence of four burst-pulse click sequences, with notably shorter ICIs than the majority of usual clicks (Fig. 2A, B). There was a total of 81 clicks in these four burst-pulse sequences, which were removed from the larger data set for exploration and are not included in the description of usual clicks above. Three of the four sequences appeared to be terminal to a chain of usual clicks that had a longer, stable ICI. The mean ICI of 37 ms for the clicks in these sequences is longer than the standard definition of a “buzz” for porpoises and delphinid species, which decreases from onset of approximately 8–15 ms to <2 ms (*e.g.*, DeRuiter *et al.* 2009, Wisniewska *et al.* 2014), however, there was a clear visual difference between the sets of burst-pulse clicks and the remainder of the usual clicks in this recording. In addition to having a shorter ICI, the burst-pulse clicks had a lower mean peak frequency, lower centroid frequency, shorter click duration, wider bandwidths, and larger Q-values compared to the usual clicks in the same recording. Statistical analysis is not appropriate given the possibility that all of the clicks are from a single individual, and are therefore not independent samples.

The second subset of signals that was separated included clicks with a lower peak frequency (below 120 kHz) than the majority of usual clicks (Fig. 2C, D). These were present in short sequences of 5–10 clicks that alternated with longer sequences of higher peak frequency clicks. The lower peak frequency clicks were removed from the larger data set and analyzed separately, and are not included in the description of usual clicks above. Compared to the usual clicks, the mean peak frequency for these 98 clicks was lower by about 10 kHz while the centroid frequency was lower by about 8 kHz (Fig. 3). Additionally, the ICI was longer compared to the rest of

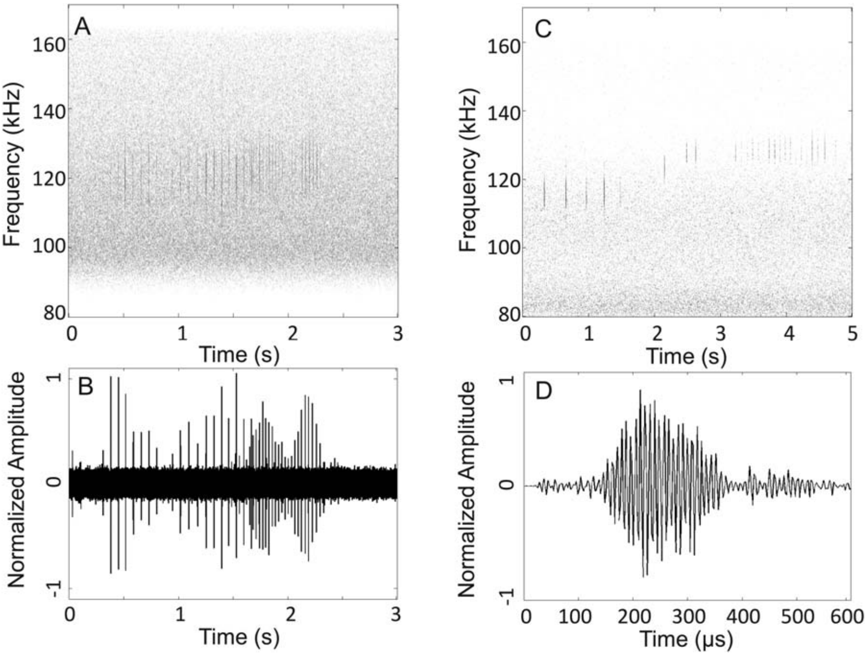

Figure 2. Examples of the burst-pulse clicks (A, B) and the lower frequency clicks (C, D) from Guam, including an example spectrogram (A) and time series (B) of the burst-pulse clicks, and an example spectrogram (C) and waveform (D) of the lower frequency clicks. The burst-pulse is visible in A and B between 1.6 s and 2.4 s. Lower frequency clicks are visible in C between 0 s and 1.5 s, followed by usual clicks from 2.5 s to 5 s.

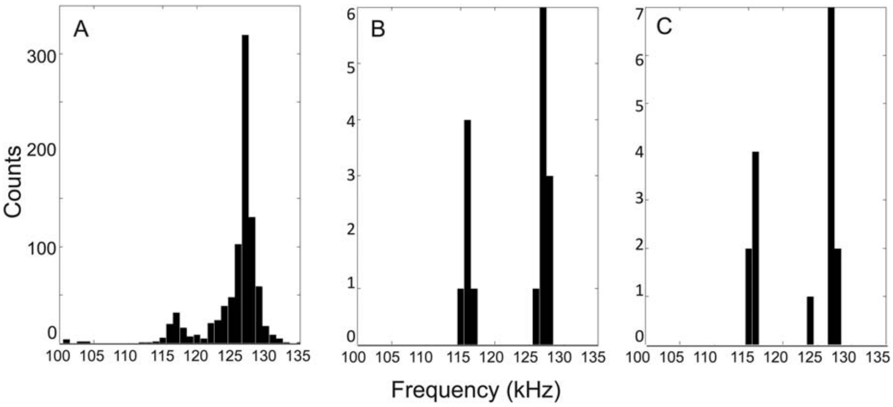

Figure 3. Histograms of peak and centroid frequencies for clicks in the Guam data set, highlighting the usual and lower peak frequency click types. (A) Peak frequencies of all clicks, with a primary peak at 127 kHz and a secondary peak at 117 kHz. (B) Peak frequencies and (C) centroid frequencies of the clicks with SNR $\geq$ 20 dB, with a primary peak at 127–128 kHz and a secondary peak at 116–117 kHz.

the usual clicks by about 90 ms. As with the burst-pulse clicks, statistical analysis is not appropriate given the possibility that all of the clicks are from a single individual, and are therefore not independent samples.

The characteristics of the clicks in the captive recording were different from those in the free-ranging recordings. Although recordings of the captive animal were made on multiple occasions, loss of computer files resulted in only 4 s of data being available for analysis. From this small sample there were 49 clicks. These clicks had a mean peak frequency that was about 15 kHz lower than the free-ranging recordings, while the centroid frequency was 15–20 kHz lower. The bandwidths were more than twice as wide as in the other recordings, while both the duration and the ICI were shorter in comparison by approximately 100 μs and 25–80 ms, respectively. The ICI was closest to the ICI values from the clicks of the captive *K. breviceps* described by Madsen *et al.* (2005*a*), which may indicate that a shorter ICI is an effect of being in a pool where walls present a close target for echolocation. The Q-values of the clicks in the captive recording were lower than for those in the Bahamas recording, but compared to the usual clicks from the Guam recording the Q_{-3dB} was similar while the Q_{rms} was lower in the captive data.

DISCUSSION

Here we present the first confirmed records of acoustic signals generated by the dwarf sperm whale (*K. sima*). The more than 1,000 clicks in this data set are sufficient to provide initial characterization for the species (*e.g.*, Madsen *et al.* 2005*a*, Baumann-Pickering *et al.* 2013). The production of NBHF clicks places *K. sima* in a group with a handful of other species, including its congener, *K. breviceps* (Marten 2000; Ridgway and Carder 2001; Madsen *et al.* 2005*a*; Villadsgaard *et al.* 2007; Kyhn *et al.* 2009, 2010, 2013; Reyes *et al.* 2016). With known click characteristics of *K. sima*, it is now possible to conduct PAM for the genus *Kogia*. This may be particularly important for this genus given the difficulty of visual monitoring due to typically cryptic surface behavior and small group sizes. The main difference between our field sites was found in the ICI. This most likely reflects differences in the distances to the targets that the animals were investigating or behavior at the time of recording (*e.g.*, Miller *et al.* 1995, Johnson *et al.* 2004, Madsen *et al.* 2005*b*). Thus, it seems that clicks of *K. sima* are similar in different ocean basins.

The characteristics of the clicks presented here are generally similar to the clicks produced by captive *K. breviceps* (Marten 2000, Ridgway and Carder 2001, Madsen *et al.* 2005*a*), as well as a few species of delphinids, *e.g.*, hourglass dolphin (*Lagenorhynchus cruciger*) and Hector's dolphin (*Cephalorhynchus hectori*) (Kyhn *et al.* 2009), Chilean dolphin (*Cephalorhynchus eutropia*) (Götz *et al.* 2010), Commerson's dolphin (*Cephalorhynchus commersonii*) (Kyhn *et al.* 2010, Reyes *et al.* 2016), and porpoises, *e.g.*, harbor porpoise (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*) (Villadsgaard *et al.*2007, Kyhn *et al.* 2013). Given the data presented here and what is available in the literature, it is still not possible to distinguish the two *Kogia* species from each other (Table 1). This is particularly true given the potential and unknown effects of recording an animal in captivity, which was the case for the only confirmed recordings of *K. breviceps* (Marten 2000, Madsen *et al.* 2005*a*). With the addition of field recordings for *K. breviceps*, differences in their click characteristics may yet emerge to allow their separation in PAM data. The clicks of *K. sima* are easily distinguished from nonNBHF odontocetes based simply on peak frequency, which is higher than that of many other species, and also on Q-value, which, generally being >10 in NBHF species, is higher than many other odontocetes. Distinguishing between *Kogia* spp. and the other species that produce NBHF clicks may be possible, particularly based on subtle differences between peak frequencies, signal duration, ICI, and bandwidth. For example, the range and habitat of *Kogia* spp. overlap with Dall's porpoise in the northeast Pacific Ocean. The peak frequencies of the porpoise are above 130 kHz (Kyhn *et al.* 2013) compared to the *Kogia* spp. clicks, which are mostly below 130 kHz.

All clicks analyzed here are conservatively presumed to be off-axis, even though in the Bahamas data clicks were only recorded when the animals were facing the hydrophone. Although we do not know the beam width of *K. sima* signals, other species that generate NBHF signals are known to have a narrow beam width (Kyhn *et al.* 2013), so capturing on-axis clicks during free-ranging recordings is difficult. Additionally, the exact orientation of the animals to the hydrophone is not known in any of the current recordings, and the sound source cannot be localized with a single hydrophone. Madsen *et al.* (2005*a*) found that the temporal and spectral characteristics of *K. breviceps* clicks did not change notably in an off-axis recording, and similar results have been found for harbor porpoise (Hansen *et al.* 2008, Koblitz *et al.* 2012). This is in contrast to the broadband clicks of delphinids and sperm whales, which show strong off-axis effects (*e.g.*, Zimmer *et al.* 2005, Lammers and Castellote 2009, Schulz *et al.* 2009, Au *et al.* 2012). Our data support a similar conclusion for *K. sima*, with the peak and centroid frequencies being comparable across data sets despite animals likely being recorded in a variety of orientations.

One parameter that was different in both free-ranging data sets from previously recorded NBHF species was the click duration. For most other NBHF species the mean click duration is in the range of 50–120 μs (Madsen *et al.* 2005*a*; Villadsgaard *et al.* 2007; Kyhn *et al.* 2009, 2010, 2013; Götz *et al.* 2010; Reyes *et al.* 2016), while the mean duration of the usual clicks from free-ranging animals recorded in The Bahamas and Guam is 199 (± 54) and 186 (± 62), respectively. While it is possible that the clicks of *K. sima* are indeed longer than other NBHF clicks, it is also possible that the arrangement of the recording instruments, with a shallow hydrophone and deeper animals, allows the production of surface reflections that artificially elongate each click. Examination of histograms of the click durations of usual clicks from the data sets revealed a strongly bimodal pattern in the Bahamas clicks (Fig. 4). It is likely that the first mode represents single clicks with little or no effect from surface reflections, while the second mode represents clicks plus reflections. To examine the characteristics of the clicks that comprise the first mode, we set a threshold of 235 μs, which is the approximate location of the minimum between the two modes. The duration of the clicks from the first mode alone (*i.e.*, those with duration less than 235 μs) was found to be 161 ± 22 μs (mean ± standard deviation) (median 157 μs) while the duration of the clicks in the second mode was 264 ± 21 μs and the mean of the entire data set (both modes combined) was 199 ± 54 μs. This serves as a good reminder that simple summary statistics, like mean and median, may not provide the details to reveal a complete description of the data. Additionally, despite this closer analysis of the different modes of click durations in the Bahamas data, the click durations from this subset are still longer than the published values for most other NBHF clicking species.

The majority of clicks in the recordings presented here can be considered usual clicks, having a consistent ICI throughout each recording. In the data set from Guam, however, we recorded at least four sequences of burst-pulse clicks, which had a much shorter ICI for a short period of time (each sequence lasting <2 s). These

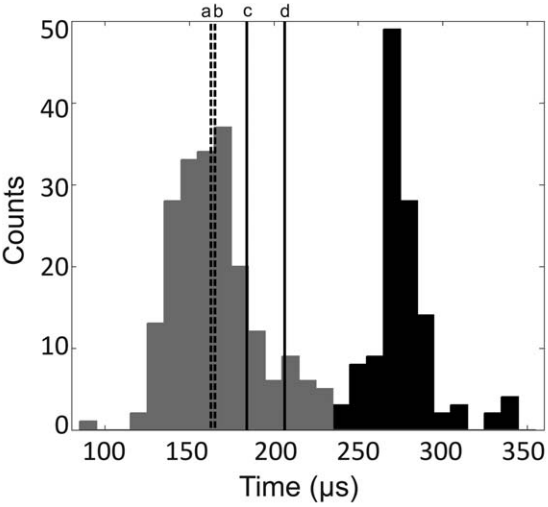

Figure 4. Histogram of click duration in the recording of free-ranging *K. sima* from the Bahamas. Gray bars indicate first mode (duration <235 μs), likely comprised of single clicks. Black bars indicate second mode (duration >235 μs), likely comprised of clicks-plus-reverberations. Dashed black lines indicate (a) median (157 μs) and (b) mean (161 μs) of the first mode (gray bars only). Solid black lines indicate (c) median (179 μs) and (d) mean (199 μs) of the complete data set (gray bars and black bars), which is reflected in the summary data, Table 1.

burst-pulse clicks were spread out in the recordings, with one in the first day and three in the second. Across odonotocete species, burst-pulses have been shown to have slightly different temporal and spectral characteristics than usual clicks, commonly being shorter in duration and wider in bandwidth (*e.g.*, Jaquet *et al.* 2001, Johnson *et al.* 2006, Götz *et al.* 2010, Fais *et al.* 2016). In some species, the peak or centroid frequency is higher than in the usual clicks, *e.g.*, sperm whale (Fais *et al.* 2016) and Blainville's beaked whale (*Mesoplodon densirostris*) (Johnson *et al.* 2006), while in other species the peak or centroid frequency is lower than in the usual clicks, *e.g.*, Chilean dolphin (Götz *et al.* 2010) and harbor porpoise (Wisniewska *et al.* 2015). Like the Chilean dolphin and the harbor porpoise, which both produce NBHF clicks, the burst-pulse clicks of *K. sima* have a shorter duration, wider bandwidth, and lower peak and centroid frequencies compared to the usual clicks. The abrupt change observed in ICI between regular and burst-pulse clicks in three out of four observations was also similar to what was described for echolocation behavior for some nondelphinid species (*e.g.*, Miller *et al.* 1995, Madsen *et al.* 2005*b*).

Burst-pulse sequences are seen in the acoustic repertoire of most odontocete species, and are assumed to be primarily a method of close-range echolocation with the goal of prey capture (*e.g.*, Miller *et al.* 1995, Johnson *et al.* 2004, Madsen *et al.* 2005*b*, DeRuiter *et al.* 2009, Wisniewska *et al.* 2014). Buzz sequences, with ICIs below 8–13 ms, are generally assumed to indicate an attempt at prey capture in other cetaceans. If future studies can confirm an association of burst-pulse clicks with prey-capture attempts, our confirmation of the production of buzz-like clicks by *K. sima* could facilitate the monitoring of feeding behavior, which has heretofore been prevented by their deep-diving, deep-feeding behavior. However, in the current study the ICIs were larger than the typical definition for buzz clicks (37 ± 10 ms) and visual observations provided no indication of feeding activity, which suggests these burst-pulses were intended for some other purpose than feeding. Furthermore, most odontocete species use burst-pulses for communication, *e.g.*, bottlenose dolphins (*Tursiops truncatus*) (Caldwell and Caldwell 1967), Risso's dolphins (*Grampus griseus*) (Arranz *et al*. 2016) and short-finned pilot whales (*Globicephala macrorhynchus*) (Perez *et al*. 2017). They also occur in animals that do not produce whistles, as is the case for both *Kogia* species. This variability in behavior serves as a reminder to carefully consider the species and the habitat being monitored with PAM devices as well as exploring a range of possible explanations for signals detected without corroborating visual observation, particularly for deep-diving species.

Another variant click type in the recording of free-ranging *K. sima* from Guam was characterized by lower peak frequencies compared to the majority of the usual clicks (mean ± standard deviation 117 ± 3 kHz *vs*. 127 ± 2 kHz). These lower peak frequency clicks were present during a period of 6 min at the end of the recording and were present in short sequences of 5–10 clicks that were interspersed with longer sequences of usual clicks with the more typical, higher peak frequency. The lower peak frequency clicks appear to belong to a separate click type, visibly different in 5 s or 10 s spectrograms (*e.g.*, Fig. 2), and they also appear as a secondary peak in the histogram of peak frequencies for the entire Guam data set (Fig. 3A), as well as the histograms of the peak frequencies and centroid frequencies of a subset of clicks with SNR > 20 dB from the same data set (Fig. 3B, C). It is possible that surface reverberation may have caused interference in the spectral characteristics of some clicks, causing them to have lower peak frequencies; however, the correspondingly lower centroid frequencies suggest that these are in fact a variant click type. In addition to having lower peak and centroid frequencies, these clicks differed from the remainder of the usual clicks by having a longer ICI, however, the bandwidths and click duration were similar between the two sets. The source of these lower peak frequency clicks cannot be confirmed; however, we can speculate that they were generated by the adult animals for a different purpose than the majority of the usual clicks, or perhaps they were made by one of the calves, also observed during this period. It is known from other odontocete species that the signals generated by calves can be different from the more common clicks of adults (*e.g.*, Madsen *et al*. 2003, Li *et al*. 2007, Harder *et al*. 2016). However, very little is known about juvenile or calf sound production in the majority of species of cetaceans, including the members of the genus *Kogia*.

There are some potential problems in the data analyzed here. For example, there are notable differences between the characteristics of the usual clicks in the captive and free-ranging recordings. In particular, the signals from the captive setting have lower peak and centroid frequencies, shorter duration, wider bandwidths, smaller Q-values, and a shorter ICI. These differences could be a result of the acoustic environment in the tank and/or unknown effects of captivity on a previously free-ranging animal (Au 1993). Additionally, the captive animal was a calf, and was ill. We do not know if or how the animal may have altered its acoustic signals because of being in captivity or experiencing compromised health. Also, although we only selected one click from each set of echoes in the captive recording, it is likely that some of the clicks analyzed were actually echoes or were distorted due to reverberation, which may have increased variability in the mean signal characteristics. Madsen *et al*. (2004) showed notable differences between clicks of captive and free-ranging animals for two species of delphinids (false killer whales, *Pseudorca crassidens*, and Risso's dolphins), particularly a lower peak frequency and source level in the captive setting. Therefore, using only the captive signals to develop tools for PAM may lead to incorrect species identification and/or missing signals from healthy, free-ranging animals. Additionally, we only had 4 s of data to analyze from the captive animal, due to loss of computer files, and these could have come from a context not represented in the wild recordings.

Issues may also have arisen from the recording equipment used in The Bahamas and Guam. Specifically, the lack of an anti-alias filter in either recording may be problematic because the Nyquist frequency is relatively close to the peak energy of the signal, which may have resulted in aliased energy present in our recordings. Additionally, the use of the HTI-96-MIN hydrophone in the Guam recording should be treated with great caution because this hydrophone has not been formally calibrated above 50 kHz. The effect of decreasing sensitivity based on preliminary calibration was tested, producing no notable effect on the mean peak frequency of the clicks in the Guam data set, however, the results presented here should not be considered to be officially calibrated. Simultaneously, this type of hydrophone will be highly directional at high frequencies like the peak frequencies of *Kogia* spp., which may produce variability in sensitivity that depends on recording angle, and is otherwise unpredictable. Results from such instrumentation, while highly informative for preliminary exploration of sounds, should be treated with care and not assumed to be as reliable as those from hydrophones specifically designed for high frequency data collection.

The recordings presented here were made from a small number of individuals, and the amount of individual variability in this species is unknown. Based on the similarities among the free-ranging recordings, we can conclude that some of the signals produced by this species are fairly stereotyped. However, the identification of unique click types within the Guam recordings does suggest that *K. sima* signals may vary based on behavioral state, group size, or group composition, as has been shown for other NBHF clicking species (Dawson and Thorpe 1990, Reyes *et al.* 2016). Future advances in characterizing the signals of *K. sima* may also facilitate distinguishing the signals of kogiids from other NBHF clicking species, which will help to enhance management and protection of these "data deficient," cryptic species (Taylor *et al.* 2012).

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