

1      **Clicks of Dwarf sperm whales (*Kogia sima*)**

2      K. Merkens<sup>1\*</sup>, D. Mann<sup>2</sup>, V. M. Janik<sup>3</sup>, D. Claridge<sup>4</sup>, M. Hill<sup>5</sup>, E. Oleson<sup>6</sup>  
3

4      Author Affiliations and Contact Information:

5            1. Karlina Merkens\* (corresponding author)

6                Contractor to NOAA NMFS Pacific Islands Fisheries Science Center

7                3710 SW Caldew St.

8                Portland, OR 97219

9                United States

10                (503) 803-9239

11                Karlina.Merkens@noaa.gov

13            2. David Mann

14                Loggerhead Instruments

15                6576 Palmer Park Circle

16                Sarasota, FL 34238

17                United States

18                (941) 923-8855

19                dmann@loggerhead.com

21            3. Vincent M. Janik

22                Sea Mammal Research Unit

23                Scottish Oceans Institute

24                School of Biology

25                University of St Andrews

26                Fife KY16 8LB

27           United Kingdom  
28           +44 (0)1334 467214  
29           vj@st-andrews.ac.uk  
30  
31        4. Diane Claridge  
32           Bahamas Marine Mammal Research Organisation  
33           P.O. Box AB-20714  
34           Marsh Harbour, Abaco  
35           Bahamas  
36           +1242 366 4155  
37           dclaridge@bahamaswhales.org  
38  
39        5. Marie Hill  
40           Joint Institute for Marine and Atmospheric Research  
41           Pacific Islands Fisheries Science Center  
42           NOAA IRC  
43           NMFS/PIFSC/PSD/Marie Hill  
44           1845 Wasp Blvd., Building 176  
45           Honolulu, HI 96818  
46           United States  
47           (808) 725-5710  
48           Marie.Hill@noaa.gov  
49  
50        6. Erin Oleson  
51           Pacific Islands Fisheries Science Center

52 NOAA IRC  
53 NMFS/PIFSC/PSD/Erin Oleson  
54 1845 Wasp Blvd., Building 176  
55 Honolulu, HI 96818  
56 United States  
57 (808) 725-5712  
58 [Erin.Oleson@noaa.gov](mailto:Erin.Oleson@noaa.gov)

59           **Abstract**

60           The two species of the genus *Kogia* are widely distributed throughout the  
61           world's temperate and tropical oceans, but because they are small and  
62           highly cryptic, they are difficult to monitor. The acoustic signals of *K.*  
63           *breviceps* have been previously described (Madsen *et al.* 2005a), but the  
64           signals of *K. sima* have remained unknown. Here we present three  
65           recordings of *K. sima*, two from free-ranging animals and one from a  
66           captive setting, representing both the Atlantic Ocean and Pacific Ocean.  
67           The acoustic signals of *K. sima* are very similar to the signals of *K.*  
68           *breviceps* and other species that have narrow-band, high-frequency  
69           (NBHF) clicks. Free-ranging *K. sima* produce “usual” clicks (*sensu*:  
70           Weilgart and Whitehead 1988) that have mean peak and centroid  
71           frequencies of 127-129 kHz, mean -3 dB bandwidth of 10 kHz, mean -10  
72           dB bandwidth of 16-17 kHz, and mean inter-click interval of 110-164 ms.  
73           Although *K. sima* clicks cannot yet be distinguished from those of *K.*  
74           *breviceps* or other NBHF clicking species, our detailed description of this  
75           species' signals reveals the similarities between the two *Kogia* species,  
76           and thus allows for passive acoustic monitoring of the genus *Kogia* in  
77           regions where other NBHF species are not present.

78           **Keywords:** *Kogia sima*, dwarf sperm whale, narrow-band high-frequency,  
79           echolocation, biosonar, click, The Bahamas, Florida, Atlantic, Guam,  
80           Pacific

82     **Introduction**

83           The genus *Kogia* comprises two species, the dwarf (*Kogia sima*) and the pygmy  
84   sperm whale (*K. breviceps*). Both species are highly cryptic visually; they are small-  
85   bodied (2-2.7 m as adults) and travel in small groups (1-12 animals) (Willis and Baird  
86   1998, McAlpine 2002, Dunphy-Daly *et al.* 2008). They make deep (>250 m), long-  
87   duration (~25 min) dives interspersed with short surfacings (Fitch and Brownell 1968,  
88   Breese and Tershy 1993, Plön 2004, West *et al.* 2008). At the surface, they produce no  
89   visible blow and are not known to raise their flukes or engage in other visible behavior  
90   patterns (Willis and Baird 1998). Much of their distribution is known from records of  
91   stranded individuals, which have been found on beaches throughout the world's  
92   temperate and tropical oceans (summaries in Willis and Baird 1998, Taylor *et al.* 2012).

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

104           Little information is available on the sound production of either *Kogia* species.  
105   Early publications were limited because the instruments that were used did not record at  
106   high enough frequencies to accurately capture *Kogia* spp. echolocation signals

107 (Caldwell *et al.* 1966, Caldwell and Caldwell 1987 in Marten 2000, Thomas *et al.*  
108 1990). More recent efforts analyzed recordings of a stranded *K. breviceps* being held in  
109 captivity for rehabilitation (Marten 2000, Ridgway and Carder 2001, Madsen *et al.*  
110 2005a). The characteristics of the clicks included a high peak frequency (125-130 kHz),  
111 moderate duration (100-600  $\mu$ s), and inter-click intervals (ICI) of 40-70 ms, as well as  
112 high directionality (Table 1). Such narrow-band, high-frequency (NBHF) clicks appear  
113 to be an adaptation to take advantage of low ambient noise levels at these frequencies  
114 and to avoid predation by killer whales (*Orcinus orca*) by generating signals above the  
115 predator's hearing range (Madsen *et al.* 2005a, Morisaka and Connor 2007).

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

## 119 **Methods**

### 120 ***Free-ranging Recording 1: The Bahamas***

121 An opportunistic encounter with a small group of *K. sima* during field research in The  
122 Bahamas in the western North Atlantic Ocean provided the setting for a recording of  
123 free-ranging animals. Visual observers searching for beaked whales aboard a 6.5 m  
124 vessel saw a group of three *K. sima*, including two adults (sex unknown) and one sub-  
125 adult (sex unknown), at 25.91 N, 77.18 W, southwest of Abaco Island, on 21 May 2005.  
126 The water depth was approximately 600 m. The animals were observed and recorded  
127 during 3.5 h of observation while they repeatedly dove and surfaced within 20-200 m of  
128 the boat. No other cetaceans were seen in the area during this period, despite ongoing  
129 visual observation, so it is unlikely that these clicks came from another species. A

130 BK8103 hydrophone (Brüel and Kjær Sound & Vibration Measurement A/S, Nærum,  
131 Denmark, frequency range 0.1 Hz to 180 kHz +3.5–12.5 dB, sensitivity -211±2 dB re:  
132 1V/µPa) with a BK2635 charge amplifier was suspended approximately 2 m below the  
133 surface. Recordings were made at 375 kHz sample rate on an Avisoft UltraSoundGate  
134 416 connected to a Toshiba laptop computer. A low pass filter was not used in this  
135 recording since the frequency response of the hydrophone fell off rapidly above the  
136 Nyquist frequency.

137 ***Free-ranging Recording 2: Guam***

138 The second data set from free-ranging animals was also obtained during a small-boat  
139 survey and includes recordings of the same four individuals (two mother/calf pairs,  
140 confirmed by photo-identification) from two one-hour encounters (28 May 2016 and 4  
141 June 2016). The animals were found off the west side of Guam in the western North  
142 Pacific Ocean at approximately 13.3 N, 144.6 E. No other cetaceans were seen in the  
143 area during this period, despite ongoing visual observation, so it is unlikely that these  
144 clicks came from another species. The water depth was approximately 650-800 m, and  
145 the animals were roughly 3.5 km from shore. Recordings were made using a Compact  
146 Acoustic Recording Buoy (CARB, Y. Barkley, pers. comm.<sup>1</sup>), a free-floating  
147 instrument deployed in the vicinity of the animals, that includes an HTI-96-MIN  
148 hydrophone (High Tech, Inc., Long Beach, MS, sensitivity -180.7 dB re: 1V/µPa)  
149 suspended around 30 m depth. The manufacturer specified frequency range for this  
150 hydrophone is flat from 2 Hz to 30 kHz, but preliminary lab calibration has shown

---

<sup>1</sup> Yvonne Barkley, NOAA IRC, NMFS/PIFSC/PSD/Yvonne Barkley, 1845 Wasp Blvd.,  
Building 176, Honolulu, HI 96818, October 2016

151 functionality out to at least 140 kHz (+3/-8 dB), with sensitivity of approximately -186  
152 dB re: 1V/ $\mu$ Pa at 130 kHz. Field testing has confirmed successful recording of NBHF  
153 porpoise clicks (J. Barlow, pers, comm.<sup>2</sup>). Please see below for further discussion of  
154 potential issues arising from using this type of hydrophone for high frequency  
155 recordings. Recordings were made at a sampling rate of 384 kHz on an SM2+ Song  
156 Meter (Wildlife Acoustics, Concord, MA), which included pre-amplifier gain of +36 dB  
157 and a 1 kHz high pass filter. There was no low-pass/anti-alias filter used at the time of  
158 data collection.

159 ***Captive Recording***

160 A female *K. sima* calf, weighing 28.5 kg, stranded at Cape Canaveral, Florida in July  
161 2002, and was taken to the Mote Marine Lab's Dolphin and Whale Hospital in Sarasota,  
162 Florida for care. She remained in captivity for over 15 months until October 2003,  
163 during which time recordings were made. The cause of stranding was unknown,  
164 however, later necropsy revealed an impacted colon and ink sac. The animal was  
165 recorded while free-swimming in a 9.1 m circular, fiberglass tank approximately 1.5 m  
166 deep. Unfortunately, due to loss of computer files only 4 s of data were saved for  
167 analysis. A Reson TC4013 hydrophone (frequency range 1 Hz to 170 kHz +2/-4dB,  
168 sensitivity -211±3 dB re: 1V/ $\mu$ Pa; VP1000 preamplifier with 32 dB gain) was  
169 suspended at approximately 0.75 m depth, and about 0.5 m away from the wall of the  
170 tank. Recordings were digitized at 500 kHz using a Tucker-Davis Technologies AD2.  
171 There was no low-pass/anti-alias filter used at the time of data collection.

---

<sup>2</sup> Jay Barlow, NOAA-SWFSC-MMTD, 8901 La Jolla Shores Dr., La Jolla CA, March 2017

172     ***Click Analysis***

173     Analysis of the *K. sima* recordings was performed using a trained analyst (KM) and  
174     custom MATLAB subroutines (MathWorks, Natick, MA, USA). Although multiple  
175     animals were present during the Bahamas and Guam recordings, it is not possible to  
176     identify which clicks came from which individual; therefore, all clicks from within a  
177     given region were combined for analysis. In each data set, a human analyst identified  
178     periods of time with clicks present, and any unusual features were noted. In the Guam  
179     recording, there were several burst-pulse click sequences with shorter inter-click  
180     intervals, and a subset of clicks with visibly lower peak frequencies. Both subsets of  
181     clicks were analyzed separately from the remainder of the signals. All sets of clicks  
182     were analyzed using a two-stage automated detector based on Soldevilla *et al.* (2008),  
183     Roch *et al.* (2011), and Baumann-Pickering *et al.* (2013). Archived code is available at:  
184     <http://doi.org/10.5281/zenodo.164881>. Individual clicks were filtered using a 4-pole  
185     Butterworth bandpass filter with a high pass threshold at 10 kHz and a low pass  
186     threshold at 170 kHz. The captive recording was also filtered using Butterworth notch  
187     filters at 81 and 160 kHz to remove tonal noise. After filtering, the clicks were retained  
188     if they passed a peak-to-peak amplitude threshold for each click. This threshold was  
189     adjusted independently for each data set based on ambient noise conditions to retain the  
190     maximum number of clicks while excluding nonclick noise.

191                 The retained clicks were used to calculate multiple parameters. The spectral  
192     characteristics were computed using a 1200  $\mu$ s Fast Fourier Transform (FFT) on Hann-  
193     windowed data centered on each click. The number of sample points and the frequency  
194     bin size is slightly different for each recording because of the different sampling rates,  
195     ranging from 460 points and approximately 418 Hz/bin in the Guam recording to 450  
196     points and 416 Hz/bin in the recording from The Bahamas and 600 points and 416

197 Hz/bin for the recording of the captive animal. The mean frequency spectrum was  
198 computed across all detected clicks within each recording. A mean noise spectrum was  
199 also computed for each recording session based on periods of data preceding each click,  
200 lasting an equal duration to each click, but separated from the click by approximately 5  
201 ms. The mean and median of the following parameters were calculated for each click:  
202 peak frequency, centroid frequency, -3 dB bandwidth, -10 dB bandwidth, rms  
203 bandwidth, click duration, and ICI. The duration was calculated as the time spanned by  
204 95% of the energy of the signal envelope (the absolute value of the analytical  
205 waveform), following methods by Madsen *et al.* (2004). ICIs longer than 500 ms were  
206 excluded as outliers based on examination of histograms of all ICIs. ICIs shorter than 2  
207 ms were excluded because they were all caused by reflections. In the captive recording,  
208 there were substantial echoes due to the nature of the tank; therefore, a lock-out period  
209 of 50 ms after the initial click was used to remove all echoes from consideration.

210 **Results**

211 Recordings from both free-ranging and captive *K. sima* contained only NBHF  
212 clicks, more similar to those of porpoise (e.g., Villadsgaard *et al.* 2007, Kyhn *et al.*  
213 2013) than those of other deep diving cetaceans such as beaked whales (family  
214 Ziphidae) and sperm whales (*Physeter macrocephalus*) (e.g., Weilgart and Whitehead  
215 1988, Goold and Jones 1995, Johnson *et al.* 2004). No whistle-like sounds were  
216 recorded. Click parameters are summarized in Table 1. The majority of the clicks could  
217 be described as “usual” clicks with a consistent ICI and received level throughout each  
218 encounter (*sensu*: Weilgart and Whitehead 1988).

219 The parameters of the clicks from the two free-ranging recordings are assessed  
220 here, while the results for the captive recording are reported below. Examples of the

221 mean spectra, waveform, and time series for all three recordings are shown in Figure 1.  
222 The Bahamas recordings spanned 37 min and contained 328 “usual” clicks. The  
223 recordings from Guam spanned 2 h and contained 938 clicks (including 759 “usual”  
224 clicks and 179 clicks of two different types, described below). The characteristics of the  
225 clicks in these two sets of recordings were similar, except for centroid frequency, rms  
226 bandwidth and ICI. There was no notable frequency sweep, in contrast to the clicks of  
227 most beaked whale species (e.g., Baumann-Pickering *et al.* 2013).

228 The differences in the centroid frequencies were examined further, along with  
229 the rms bandwidth, which is calculated using the centroid frequency. In the Bahamas  
230 recording the centroid frequency was similar to the peak frequency and the rms  
231 bandwidth was similar to the -3 dB bandwidth, which was expected based on previous  
232 descriptions of the clicks of other NBHF species (e.g. Madsen *et al.* 2005a, Kyhn *et al.*  
233 2009, Götz *et al.* 2010, Kyhn *et al.* 2010, Kyhn *et al.* 2013). In contrast, the centroid  
234 frequency of the “usual” clicks from the Guam recording was lower than the peak  
235 frequency by about 6 kHz and the rms bandwidth was wider than the -3 dB bandwidth  
236 by about 10 kHz. These differences may have been caused by a large proportion of  
237 clicks in the Guam recording with a low signal-to-noise ratio (SNR), so a subset of  
238 clicks with SNR greater than 20 dB was examined separately. This subset of highest  
239 SNR clicks had a peak frequency of  $127 \pm 0.8$  kHz, centroid frequency of  $127 \pm 0.9$   
240 kHz, -3 dB bandwidth of  $8.6 \pm 1.0$  kHz, -10 dB bandwidth of  $13 \pm 2.0$  kHz, and an rms  
241 bandwidth of  $7 \pm 1.3$  kHz. These results are closer to what was expected for centroid  
242 frequency and rms bandwidth given the values for peak frequency and -3 dB bandwidth,  
243 and they are similar to the results for the Bahamas recording as well as those of NBHF  
244 clicks from other species (e.g. Madsen *et al.* 2005a, Kyhn *et al.* 2009, Kyhn *et al.* 2010,

245 Kyhn *et al.* 2013), which reinforces the possibility that low SNR clicks were impacting  
246 the summary results for the whole recording.

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

263 The second subset of signals that was separated included clicks with a lower  
264 peak frequency (below 120 kHz) than the majority of “usual” clicks (Fig. 2 C, D).  
265 These were present in short sequences of five to ten clicks that alternated with longer  
266 sequences of higher peak frequency clicks. The lower peak frequency clicks were  
267 removed from the larger data set and analyzed separately, and are not included in the  
268 description of “usual” clicks above. Compared to the “usual” clicks, the mean peak  
269 frequency for these 98 clicks was lower by about 10 kHz while the centroid frequency

270 was lower by about 8 kHz (Fig. 3). Additionally, the ICI was longer compared to the  
271 rest of the “usual” clicks by about 90 ms. As with the burst-pulse clicks, statistical  
272 analysis is not appropriate given the possibility that all of the clicks are from a single  
273 individual, and are therefore not independent samples.

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

288 **Discussion**

289 Here we present the first confirmed records of acoustic signals generated by the  
290 dwarf sperm whale (*K. sima*). The more than 1,000 clicks in this data set are sufficient  
291 to provide initial characterization for the species (*e.g.*, Madsen *et al.* 2005a, Baumann-  
292 Pickering *et al.* 2013). The production of NBHF clicks places *K. sima* in a group with a  
293 handful of other species, including its congener, *K. breviceps* (Marten 2000, Ridgway

294 and Carder 2001, Madsen *et al.* 2005a, Villadsgaard *et al.* 2007, Kyhn *et al.* 2009, Kyhn  
295 *et al.* 2010, Kyhn *et al.* 2013, Reyes *et al.* 2016). With known click characteristics of *K.*  
296 *sima*, it is now possible to conduct PAM for the genus *Kogia*. This may be particularly  
297 important for this genus given the difficulty of visual monitoring due to typically cryptic  
298 surface behavior and small group sizes. The main difference between our field sites was  
299 found in the ICI. This most likely reflects differences in the distances to the targets that  
300 the animals were investigating or behavior at the time of recording (*e.g.*, Miller *et al.*  
301 1995, Johnson *et al.* 2004, Madsen *et al.* 2005b). Thus, it seems that clicks of *K. sima*  
302 are similar in different ocean basins.

303 The characteristics of the clicks presented here are generally similar to the clicks  
304 produced by the single captive *K. breviceps* (Marten 2000, Ridgway and Carder 2001,  
305 Madsen *et al.* 2005a), as well as a few species of delphinids (*e.g.*, hourglass dolphins  
306 (*Lagenorhynchus cruciger*) and Hector's dolphins (*Cephalorhynchus hectori*) (Kyhn *et*  
307 *al.* 2009), the Chilean dolphin (*Cephalorhynchus eutropia*) (Götz *et al.* 2010), the  
308 Commerson's dolphin (*Cephalorhynchus commersonii*) (Kyhn *et al.* 2010, Reyes *et al.*  
309 2016)) and porpoises (*e.g.*, harbor porpoise (*Phocoena phocoena*) and Dall's porpoise  
310 (*Phocoenoides dalli*) (Villadsgaard *et al.* 2007, Kyhn *et al.* 2013)). Given the data  
311 presented here and what is available in the literature, it is still not possible to distinguish  
312 the two *Kogia* species from each other (Table 1). This is particularly true given the  
313 potential and unknown effects of recording an animal in captivity, which was the case  
314 for the only confirmed recording of *K. breviceps* (Madsen *et al.* 2005a). With the  
315 addition of field recordings for *K. breviceps*, differences in their click characteristics  
316 may yet emerge to allow their separation in PAM data. The clicks of *K. sima* are easily  
317 distinguished from non-NBHF odontocetes based simply on peak frequency, which is  
318 higher than that of many other species, and also on Q-value, which, generally being >10

319 in NBHF species, is higher than many other odontocetes. Distinguishing between  
320 *Kogia* spp. and the other species that produce NBHF clicks may be possible,  
321 particularly based on subtle differences between peak frequencies, signal duration, ICI,  
322 and bandwidth. For example, the range and habitat of *Kogia* spp. overlap with Dall's  
323 porpoise in the northeast Pacific Ocean. The peak frequencies of the porpoise are above  
324 130 kHz (Kyhn *et al.* 2013) compared to the *Kogia* spp. clicks, which are mostly below  
325 130 kHz.

326 All clicks analyzed here are conservatively presumed to be off-axis, even though  
327 in the Bahamas clicks were only recorded when the animals were facing the  
328 hydrophone. Although we do not know the beam width of *K. sima* signals, other species  
329 that generate NBHF signals are known to have a narrow beam width (Kyhn *et al.* 2013),  
330 so capturing on-axis clicks during free-ranging recordings is difficult. Additionally, the  
331 exact orientation of the animals to the hydrophone is not known in any of the current  
332 recordings, and they cannot be localized with a single hydrophone. Madsen *et al.*  
333 (2005a) found that the temporal and spectral characteristics of *K. breviceps* clicks did  
334 not change notably in an off-axis recording, and similar results have been found for  
335 harbor porpoise (Hansen *et al.* 2008, Koblitz *et al.* 2012). This is in contrast to the  
336 broadband clicks of delphinids and sperm whales, which show strong off-axis effects  
337 (e.g. Zimmer *et al.* 2005, Lammers and Castellote 2009, Schulz *et al.* 2009, Au *et al.*  
338 2012). Our data support a similar conclusion for *K. sima*, with the peak and centroid  
339 frequencies being comparable across data sets despite animals being recorded in a  
340 variety of orientations.

341 One parameter that was different in both free-ranging data sets from previously  
342 recorded NBHF species was the click duration. For most other NBHF species the mean  
343 click duration is in the range of 50-120  $\mu$ s (Madsen *et al.* 2005a , Villadsgaard *et al.*

344 2007, Kyhn *et al.* 2009, Götz *et al.* 2010, Kyhn *et al.* 2010, Kyhn *et al.* 2013, Reyes *et*  
345 *al.* 2016), while the mean duration of the “usual” clicks from free-ranging animals  
346 recorded in The Bahamas and Guam is 199 ( $\pm 54$ ) and 186 ( $\pm 62$ ), respectively. While it  
347 is possible that the clicks of *K. sima* are indeed longer than other NBHF clicks, it is also  
348 possible that the arrangement of the recording instruments, with a shallow hydrophone  
349 and deeper animals, allows the production of surface reflections that artificially elongate  
350 each click. Examination of histograms of the click durations of “usual” clicks from the  
351 data sets revealed a strongly bimodal pattern in the Bahamas clicks (Fig. 4). It is likely  
352 that the first mode represents single clicks with little or no effect from surface  
353 reflections, while the second mode represents clicks plus reflections. To examine the  
354 characteristics of the clicks that comprise the first mode, we set a threshold of 235  $\mu$ s,  
355 which is the approximate location of the minimum between the two modes. The  
356 duration of the clicks from the first mode alone (*i.e.* those with duration less than 235  
357  $\mu$ s) was found to be  $161 \pm 22$   $\mu$ s (mean  $\pm$  standard deviation) (median 157  $\mu$ s) while the  
358 duration of the clicks in the second mode was  $264 \pm 21$   $\mu$ s and the mean of the entire  
359 data set (both modes combined) was  $199 \pm 54$   $\mu$ s. This serves as a good reminder that  
360 simple summary statistics, like mean and median, may not provide the details to reveal  
361 a complete description of the situation. Additionally, despite this closer analysis of the  
362 different modes of click durations in the Bahamas data, the click durations from this  
363 subset are still longer than the published values for most other NBHF clicking species.

364 The majority of clicks in the recordings presented here can be considered  
365 “usual” clicks, having a consistent ICI throughout each recording. In the data set from  
366 Guam, however, we recorded at least four sequences of burst-pulse clicks, which had a  
367 much shorter ICI for a short period of time (each sequence lasting  $<2$  s). These burst-  
368 pulse clicks were spread out in the recordings, with one in the first day and three in the

369 second. Across species, burst-pulses have been shown to have slightly different  
370 temporal and spectral characteristics than “usual” clicks, commonly being shorter in  
371 duration and wider in bandwidth (e.g., Johnson *et al.* 2006, Jaquet *et al.* 2001, Götz *et*  
372 *al.* 2010, Fais *et al.* 2016). In some species, the peak or centroid frequency is higher  
373 than in the “usual” clicks (e.g., sperm whale (Fais *et al.* 2016) and Blainville’s beaked  
374 whale, *Mesoplodon densirostris*, (Johnson *et al.* 2006)), while in other species the peak  
375 or centroid frequency is lower than in the “usual” clicks (e.g., Chilean dolphin, (Götz *et*  
376 *al.* 2010) and harbor porpoise, (Wisniewska *et al.* 2015)). Like the Chilean dolphin and  
377 the harbor porpoise, which both produce NBHF clicks, the burst-pulse clicks of *K. sima*  
378 have a shorter duration, wider bandwidth, and lower peak and centroid frequencies  
379 compared to the “usual” clicks. The abrupt change observed in ICI between regular and  
380 burst-pulse clicks in three out of four observations was similar to what was described  
381 for echolocation behavior for some nondelphinid species (e.g., Miller *et al.* 1995,  
382 Madsen *et al.* 2005b).

383 Burst-pulse sequences are seen in the acoustic repertoire of most odontocete  
384 species, and are assumed to be primarily a method of close-range echolocation with the  
385 goal of prey capture (e.g., Miller *et al.* 1995, Johnson *et al.* 2004, Madsen *et al.* 2005b,  
386 deRuiter *et al.* 2009, Wisniewska *et al.* 2014). Buzz sequences, with ICIs below 8-13  
387 ms, are generally assumed to indicate an attempt at prey capture in other cetaceans. If  
388 future studies can confirm an association of burst-pulse clicks with prey-capture  
389 attempts, our confirmation of the production of buzz-like clicks by *K. sima* could  
390 facilitate the monitoring of feeding behavior, which has heretofore been prevented by  
391 their deep-diving, deep-feeding behavior. However, in the current study the ICIs were  
392 higher ( $37 \pm 10$  ms) and visual observations provided no indication of feeding activity,  
393 which suggests these burst-pulses were intended for some other purpose than feeding.

394 Furthermore, most odontocete species use burst-pulses for communication, (e.g.  
395 bottlenose dolphins (*Tursiops truncatus*) (Caldwell & Caldwell 1967), Risso's dolphins  
396 (*Grampus griseus*) (Arranz *et al.* 2016) and short-finned pilot whales (*Globicephala*  
397 *macrorhynchus*) (Perez *et al.* 2017)). They also occur in animals that do not produce  
398 whistles, as is the case for *Kogia* spp. This variability in behavior serves as a reminder  
399 to carefully consider the species and the habitat being monitored with PAM devices as  
400 well as exploring a range of possible explanations for signals detected without  
401 corroborating visual observation, particularly for deep-diving species.

402 Another variant click type in the recording of free-ranging *K. sima* from Guam  
403 was characterized by lower peak frequencies compared to the majority of the “usual”  
404 clicks (mean  $\pm$  standard deviation  $117 \pm 3$  kHz vs.  $127 \pm 2$  kHz). These lower peak  
405 frequency clicks were present during a period of 6 min at the end of the recording, and  
406 were present in short sequences of 5-10 clicks that were interspersed with longer  
407 sequences of “usual” clicks with the more typical, higher peak frequency. The lower  
408 peak frequency clicks appear to belong to a separate click type, visibly different in 5 or  
409 10 s spectrograms (e.g. Fig. 2), and also apparent as a secondary peak in the histogram  
410 of peak frequencies for the entire Guam data set (Fig. 3A), as well as the histograms of  
411 the peak frequencies and centroid frequencies of a subset of clicks with SNR  $>20$  dB  
412 from the same data set (Fig. 3B&C). It is possible that surface reverberation may have  
413 caused interference in the spectral characteristics of some clicks, causing them to have  
414 lower peak frequencies; however, the correspondingly lower centroid frequencies  
415 suggest that these are in fact a variant click type. The bandwidths and click duration  
416 were similar between the lower peak frequency clicks and more abundant “usual”  
417 clicks; however, peak frequency and centroid frequency were both lower and ICI was  
418 longer. The source of these lower peak frequency clicks cannot be confirmed; however,

419 we can speculate that they were generated by the adult animals for a different purpose  
420 than the majority of the “usual” clicks, or perhaps they were made by one of the calves,  
421 also observed during this period. It is known from other odontocete species that the  
422 signals generated by calves can be different from the more common clicks of adults  
423 (e.g., Madsen *et al.* 2003, Li *et al.* 2007, Harder *et al.* 2016). However, very little is  
424 known about juvenile or calf sound production in the majority of species of cetaceans,  
425 including the members of the genus *Kogia*.

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

443 we only had 4 s of data to analyze from the captive animal, due to loss of computer  
444 files, and these could have come from a context not represented in the wild recordings.

445 Issues may also have arisen from the recording equipment used in The Bahamas  
446 and Guam. Specifically, the lack of an anti-alias filter in either recording may be  
447 problematic because the Nyquist frequency is relatively close to the peak energy of the  
448 signal, which may have resulted in aliased energy present in our recordings.

449 Additionally, the use of the HTI-MIN-96 hydrophone in the Guam recording should be  
450 treated with great caution because this hydrophone has not been formally calibrated  
451 above 50 kHz. The effect of decreasing sensitivity based on preliminary calibration was  
452 tested, producing no notable effect on the mean peak frequency of the clicks in the  
453 Guam data set, however the results presented here should not be considered to be  
454 officially calibrated. Simultaneously, this type of hydrophone will be highly directional  
455 at high frequencies like the peak frequencies of *Kogia* spp., which may produce  
456 variability in sensitivity that depends on recording angle, and is otherwise  
457 unpredictable. Results from such instrumentation, while highly informative for  
458 preliminary exploration of sounds, should be treated with care and not assumed to be as  
459 reliable as those from hydrophones specifically designed for high frequency data  
460 collection.

461 The recordings presented here were made from a small number of individuals,  
462 and the amount of individual variability in this species is unknown. However, based on  
463 the similarities among the free-ranging recordings, we can conclude that some of the  
464 signals produced by this species are fairly stereotyped. However, the identification of  
465 unique click types within the Guam recordings does suggest that *K. sima* signals may  
466 vary based on behavioral state, group size, or group composition, as has been shown for  
467 other NBHF clicking species (Dawson and Thorpe 1990, Reyes *et al.* 2016). However,

468 advances in characterizing the signals of *K. sima* may also facilitate distinguishing the  
469 signals of Kogiids from other NBHF clicking species, which will help to enhance  
470 management and protection of this “data deficient”, cryptic species (Taylor *et al.* 2012).

471   **Acknowledgements**

472   We wish to acknowledge the outstanding field efforts of the many people who assisted  
473   in collecting these recordings: Yvonne Barkley, Andrea Bendlin, Julian Dale, Charlotte  
474   Dunn, Megan Dunphy-Daly, Erik Norris, Allan Ligon, Nicola Quick, Adam Ü. We also  
475   acknowledge the staff involved with rescue and rehabilitation of the captive animal,  
476   particularly Charlie Manire, Lynne Byrd, and Petra Cunningham-Smith. We thank John  
477   Hildebrand, Tess Gridley, Peter T. Madsen and three anonymous reviewers for their  
478   insightful comments that improved this manuscript. Captive acoustic recordings were  
479   approved by the Institutional Animal Care and Use Committee of the University of  
480   South Florida. Research in The Bahamas was conducted under the Department of  
481   Fisheries research permit 12A and was supported by a Royal Society University  
482   Research Fellowship to VMJ. Recordings in Guam were made under NMFS permit  
483   15240 and were supported with funding provided by the NOAA/NMFS Pacific Islands  
484   Fisheries Science Center, and the U.S. Navy Pacific Fleet.

485

486

487    **Literature Cited**

- 488    Arranz, P., S.L. DeRuiter, A. K. Stimpert, *et al.* 2016. Discrimination of fast click-series  
489                  produced by tagged Risso's dolphins (*Grampus griseus*) for echolocation or  
490                  communication. *Journal of Experimental Biology* 219:2898-2907.
- 491    Au, W. W. L. 1993. *The Sonar of Dolphins*. Springer-Verlag, New York, NY.
- 492    Au, W. W. L., B. Branstetter, P. W. Moore and J. J. Finneran. 2012. The biosonar field  
493                  around an Atlantic bottlenose dolphin (*Tursiops truncatus*). *The Journal of the*  
494                  *Acoustical Society of America* 131:569-576.
- 495    Baumann-Pickering, S., M. A. McDonald, A. E. Simonis, *et al.* 2013. Species-specific  
496                  beaked whale echolocation signals. *The Journal of the Acoustical Society of*  
497                  *America*. 134:2293-2301.
- 498    Breese, D. and B. R. Tershy. 1993. Relative abundance of Cetacea in the Canal de  
499                  Ballenas, Gulf of California. *Marine Mammal Science* 9:319–324.
- 500    Caldwell, M. C., and D. K. Caldwell. 1967. Intraspecific transfer of information via the  
501                  pulsed sound in captive odontocete cetaceans. In: *Animal sonar systems -*  
502                  *biology and bionics*. R. G. Bullock (ed.). Jouy-en-Josas, Laboratoire Physiologie  
503                  Acoustique. II: 879-936.
- 504    Caldwell, D. K., and M. C. Caldwell. 1987. Underwater echolocation-type clicks  
505                  created by captive stranded pygmy sperm whales, *Kogia breviceps*. *Abstracts,*  
506                  *Seventh Biennial Conference of the Biology of Marine Mammals*, Miami,  
507                  Florida, Dec. 5-9, 1987, p.8.
- 508    Caldwell, D. K., J. H. Prescott and M. C. Caldwell. 1966. Production of pulsed sounds  
509                  by the pigmy sperm whale, *Kogia breviceps*. *Bulletin of the Southern California*  
510                  *Academy of Sciences* 65:245–248.

- 511 Dawson, S. M., and C. W. Thorpe. 1990. A quantitative analysis of the sounds of  
512 Hector's dolphin. *Ethology* 86:131-145.
- 513 DeRuiter, S. L., A. Bahr, M. Blanchet, S.F. Hansen, J. H. Kristensen, P. T. Madsen, P.  
514 L. Tyack and M. Wahlberg. 2009. *The Journal of Experimental Biology*  
515 212:3100-3107.
- 516 Dunphy-Daly, M. M., M. R. Heithaus and D. E. Claridge. 2008. Temporal variation in  
517 dwarf sperm whale (*Kogia sima*) habitat use and group size off Great Abaco  
518 Island, Bahamas. *Marine Mammal Science* 24:171-182.
- 519 Fais, A., M. P. Johnson, M. Wilson, N. Aguilar Soto and P. T. Madsen. 2016. Sperm  
520 whale predator-prey interactions involve chasing and buzzing, but no acoustic  
521 stunning. *Scientific Reports* 6: 28562 doi:10.1038/srep28562
- 522 Fitch, J.E., and R. L. Brownell, Jr. 1968. Fish otoliths in cetacean stomachs and their  
523 importance in interpreting feeding habits. *Journal of the Fisheries Research  
524 Board of Canada* 25: 2561-2574.
- 525 Goold, J. C. and S. E. Jones. 1995. Time and frequency domain characteristics of sperm  
526 whale clicks. *Journal of the Acoustical Society of America* 98:1279-1291.
- 527 Götz, T., R. Antunes and S. Heinrich. 2010. Echolocation clicks of free-ranging Chilean  
528 dolphins (*Cephalorhynchus eutropis*). *The Journal of the Acoustical Society of  
529 America* 128:563-566.
- 530 Hansen, M., M. Wahlberg and P. T. Madsen. 2008. Low-frequency components in  
531 harbor porpoise (*Phocoena phocoena*) clicks: communication signal, by-  
532 products, or artifacts? *The Journal of the Acoustical Society of America*  
533 124:4059-4068.
- 534 Harder, J. H., H. M. Hill, K. M. Dudzinski, K. T. Sanabria, S. Guarion, S. A. Kuczaj, II.  
535 2016. The development of echolocation in bottlenose dolphins. *International*

- 536 Journal of Comparative Psychology 29. uclapsych\_ijcp\_32240. Retrieved from:  
537 <http://escholarship.org/uc/item/0q22949q>
- 538 Jaquet, N., S. Dawson and L. A. Douglas. 2001. Vocal behavior of male sperm whales:  
539 Why do they click? The Journal of the Acoustical Society of America  
540 109:2254–2259.
- 541 Johnson, M. P., P. T. Madsen, W. M. X. Zimmer, N. Aguilar de Soto, and P. L. Tyack.  
542 2006. Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce  
543 distinct click types matched to different phases of echolocation. Journal of  
544 Experimental Biology 209:5038–5050.
- 545 Johnson, M. P., P. T. Madsen, W. M. X. Zimmer, N. Aguilar de Soto, and P. L. Tyack.  
546 2004. Beaked whales echolocate on prey. Proceedings of the Royal Society  
547 London B (Supplement) 271:S383-386.
- 548 Koblitz, J. C., M. Wahlberg, P. Stilz, P. T. Madsen, K. Beedholm and H. Schnitzler.  
549 2012. Asymmetry and dynamics of a narrow sonar beam in an echolocating  
550 harbor porpoise. The Journal of the Acoustical Society of America  
551 131:2315:2324.
- 552 Kyhn, L.A., J. Tougaard, F.H. Jensen, M. Wahlberg, G. Stone, A. Yoshinaga, K.  
553 Beedholm, and P.T. Madsen. 2009. Feeding at a high pitch: Source parameters  
554 of narrow band, high-frequency clicks from echolocating off-shore  
555 hourglassdolphins and coastal Hector's dolphins. The Journal of the Acoustical  
556 Society of America 125: 1783-1791.
- 557 Kyhn, L. A., F. H. Jensen, K. Beedholm, J. Tougaard, M. Hansen and P. T. Madsen.  
558 2010. Echolocation in sympatric Peale's dolphins (*Lagenorhynchus australis*)  
559 and Commerson's dolphins (*Cephalorhynchus commersonii*) producing narrow-  
560 band high-frequency clicks. Journal of Experimental Biology 213:1940–1949.

- 561 Kyhn, L. A., J. Tougaard, K. Beedholm, F. H. Jensen, E. Ashe, R. Williams, P. T.
- 562 Madsen. 2013. Clicking in a Killer Whale Habitat: Narrow-Band, High-
- 563 Frequency Biosonar Clicks of Harbour Porpoise (*Phocoena phocoena*) and
- 564 Dall's Porpoise (*Phocoenoides dalli*). PLoS ONE 8, e63763.
- 565 Lammers, M. O., and M. Castellote. 2009. The beluga whale produces two pulses to
- 566 form its sonar signal. Biology Letters 5:297-301.
- 567 Li, S., D. Wang, K. Wang, J. Xiao, T. Akamatsu. 2007. The ontogeny of echolocation in
- 568 a Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) (L).
- 569 The Journal of the Acoustical Society of America. 122:715-718.
- 570 Madsen, P. T., D. A. Carder, W. W. L. Au, P. E. Nachtigall, B. Møhl, S. H. Ridgway.
- 571 2003. Sound production in neonate sperm whales (L). The Journal of the
- 572 Acoustical Society of America 113:2988-2991.
- 573 Madsen, P. T., I. Kerr and R. Payne. 2004. Echolocation clicks of two free-ranging,
- 574 oceanic delphinids with different food preferences: False killer whales
- 575 *Pseudorca crassidens* and Risso's dolphins *Grampus griseus*. Journal of
- 576 Experimental Biology 207:1811–1823.
- 577 Madsen, P. T., D. A. Carder, K. Bedholm and S. H. Ridgway. 2005a. Porpoise clicks
- 578 from a sperm whale nose - convergent evolution of 130 kHz pulses in toothed
- 579 whale sonars? Bioacoustics 15:195–206.
- 580 Madsen, P. T., M. Johnson, N. Aguilar de Soto, W. M. X. Zimmer and P. Tyack. 2005b.
- 581 Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*).
- 582 Journal of Experimental Biology 208:181-194.
- 583 Marques, T., L. Thomas., S. W. Martin, D. K. Mellinger, J. A. Ward, D. J. Moretti, D.
- 584 Harris, P. L. Tyack. 2013. Estimating animal population density using passive
- 585 acoustics. Biological Reviews 88:287-309.

- 586 Marten, K. 2000. Ultrasonic analysis of pygmy sperm whale (*Kogia breviceps*) and  
587 Hubbs' beaked whale (*Mesoplodon carlhubbssi*) clicks. *Aquatic Mammals*  
588 26:45–48.
- 589 McAlpine, D. F. 2002. Pygmy and Dwarf Sperm Whales. Pages 1007–1009 in W. F.  
590 Perrin, B. Würsig. and J. Thewissen, eds. *Encyclopedia of marine mammals*.  
591 Academic Press, San Diego, CA.
- 592 Miller, L.A., J. Pristed, B. Møhl, A. Surlykke. 1995. The click sounds of narwhals  
593 (*Monodon monoceros*) in Inglefield Bay, Northwest Greenland. *Marine*  
594 *Mammal Science* 11:491-502.
- 595 Morisaka, T. and R. C. Connor. 2007. Predation by killer whales (*Orcinus orca*) and the  
596 evolution of whistle loss and narrow-band high frequency clicks in  
597 odontocetes. *Journal of Evolutionary Biology* 20:1439-1458.
- 598 Perez, J. M., F. H. Jensen, L. Rojano-Donate and N. Aguilar de Soto. 2017. Different  
599 modes of acoustic communication in deep-diving short-finned pilot whales  
600 (*Globicephala macrorhynchus*). *Marine Mammal Science* 33:59-79.
- 601 Reyes, M. V., V. P. Tossenberger, M. A. Iniguez, J. A. Hildebrand and M. L. Melcon.  
602 2016. Communication sounds of Commerson's dolphins (*Cephalorhynchus*  
603 *commersonii*) and contextual use of vocalizations," *Marine Mammal Science* 32:  
604 1219–1233.
- 605 Plön, S. 2004. The status and natural history of pygmy (*Kogia breviceps*) and dwarf (K.  
606 sima) sperm whales off Southern Africa. Doctoral dissertation, Rhodes  
607 University, Grahamstown, South Africa. 551 pp.
- 608 Ridgway, S. H. and D. A. Carder. 2001. Assessing hearing and sound production in  
609 cetaceans not available for behavioral audiograms: Experiences with sperm,  
610 pygmy sperm, and gray whales. *Aquatic Mammals* 27:267–276.

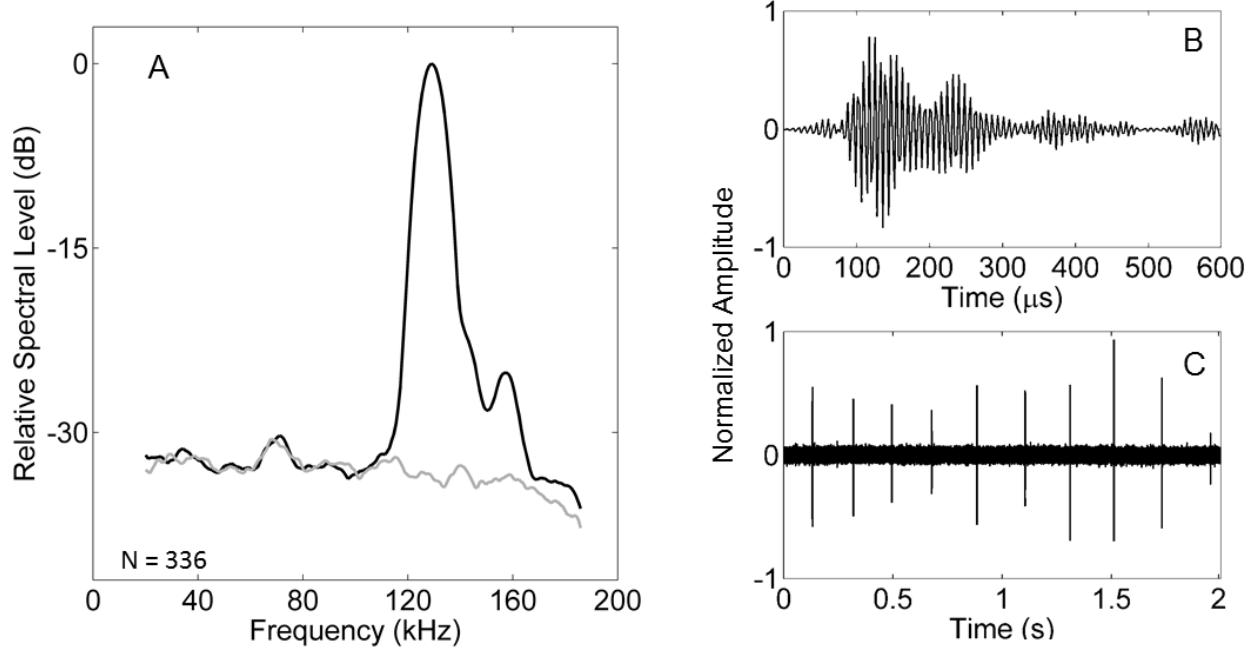
- 611      Roch, M. A., H. Klinck, S. Baumann-Pickering, D. K. Mellinger, S. Qui, M. S.
- 612           Soldevilla and J.A. Hildebrand. 2011. Classification of echolocation clicks from  
613           odontocetes in the Southern California Bight. *The Journal of the Acoustical  
614           Society of America*. 129:467-475.
- 615      Schulz, T. M., H. Whitehead and L. Rendell. 2009. Off-axis effects on the multi-pulse  
616           structure of sperm whale coda clicks. *The Journal of the Acoustical Society of  
617           America* 125:1768-1773
- 618      Soldevilla, M. S., E. E. Henderson, G. S. Campbell, S. M. Wiggins, J. A. Hildebrand,  
619           and M. A. Roch. 2008. Classification of Risso's and Pacific white-sided  
620           dolphins using spectral properties of echolocation clicks. *The Journal of the  
621           Acoustical Society of America* 124:609-624.
- 622      Taylor, B.L., R. Baird, J. Barlow, *et al.* 2012. *Kogia sima*. The IUCN Red List of  
623           Threatened Species 2012: e.T11048A17695273.  
624           <http://dx.doi.org/10.2305/IUCN.UK.2012.RLTS.T11048A17695273.en>.  
625           Downloaded on 04 November 2016.
- 626      Thomas, J. A., P. Moore, P. E. Nachtigall and W. G. Gilman. 1990. A new sound  
627           from a stranded pygmy sperm whale. *Aquatic Mammals* 16:28–30.
- 628      Van Parijs, S. M., C. W. Clark, R. S. Sousa-Lima, S. E. Parks, S. Rankin, D. Risch, I.  
629           V. Van Opzeeland. 2009. Management and research applications of real-time  
630           and archival passive acoustic sensors over varying temporal and spatial scales.  
631           *Marine Ecology Progress Series* 395:21-36.
- 632      Villadsgaard, A., M. Wahlberg and J. Tougaard. 2007. Echolocation signals of wild  
633           harbour porpoises, *Phocoena phocoena*. *The Journal of Experimental Biology*  
634           210:56-64.

- 635 Weilgart, L. and H. Whitehead. 1988. Distinctive vocalizations from mature male sperm  
636 whales (*Physeter macrocephalus*). Canadian Journal of Zoology 66: 1931–1937.
- 637 West, K. L., W. A. Walker, R. W. Baird, W. White, G. Levine, E. Brown, D. Schofield.  
638 2009. Diet of pygmy sperm whales (*Kogia breviceps*) in the Hawaiian  
639 Archipelago. Marine Mammal Science 25:931-943.
- 640 Willis, P. M. and R. W. Baird. 1998. Status of the dwarf sperm whale, *Kogia simus*,  
641 with special reference to Canada. Canadian Field-Naturalist 112:114–125.
- 642 Wisniewska, D. M., M. Johnson, P. E. Nachtigall and P. T. Madsen. 2014. Buzzing  
643 during biosonar-based interception of prey in the delphinids *Tursiops truncatus*  
644 and *Psuedorca crassidens*. The Journal of Experimental Biology 217:4279-  
645 4282.
- 646 Wisniewska, D. M., J. M. Ratcliffe and K. Beedholm. 2015 Range-dependent flexibility  
647 in the acoustic field of view of echolocating porpoises (*Phocoena phocoena*).  
648 Elife. doi:10.7554/eLife.05651.001.
- 649 Zimmer, W. X., P. T. Madsen, V. Teloni, M. P. Johnson and P. L. Tyack. 2005. Off-  
650 axis effects on the multipulse structure of sperm whale usual clicks with  
651 implications for sound production. The Journal of the Acoustical Society of  
652 America 118:3337-3345.

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) ( $\pm$  standard deviation). Also shown are parameters from recordings of captive *K. breviceps* for comparison (Madsen *et al.* 2005a). Peak frequency, centroid frequency, duration, -3 dB bandwidth, -10 dB bandwidth, rms bandwidth, Q<sub>3dB</sub>, Q<sub>rms</sub>, and inter-click interval are show as Mean/Median ( $\pm$ Standard Deviation). Note: possible issues with the captive recording are detailed near the end of the article. na = “not available”

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 <sub>3dB</sub>	Q <sub>rms</sub>	Inter-click Interval (ms)
<i>K. sima</i> (calf)	captive	49	112/110 ( $\pm$ 9)	108/105 ( $\pm$ 9)	91/52 ( $\pm$ 85)	21/16 ( $\pm$ 11)	43/43 ( $\pm$ 20)	18/17 ( $\pm$ 19)	6/6 ( $\pm$ 2)	7/7 ( $\pm$ 5)	83/79 ( $\pm$ 24)
<i>K. sima</i> (2 adults + 1 sub-adult)	free-ranging The Bahamas	328	129/129 ( $\pm$ 2)	129/129 ( $\pm$ 2)	199/179 ( $\pm$ 54)	10/10 ( $\pm$ 2)	16/17 ( $\pm$ 3)	9/9 ( $\pm$ 2)	15/15 ( $\pm$ 4)	14/13 ( $\pm$ 3)	164/135 ( $\pm$ 79)
<i>K. sima</i> (adult + calf)	free-ranging Guam	759	127/127 ( $\pm$ 2)	121/122 ( $\pm$ 5)	186/192 ( $\pm$ 62)	10/10 ( $\pm$ 3)	17/16 ( $\pm$ 7)	20/20 ( $\pm$ 7)	7/6 ( $\pm$ 3)	13/13 ( $\pm$ 3)	110/93 ( $\pm$ 73)
<i>K. sima</i> – burst pulse clicks	free-ranging Guam	81	124/124 ( $\pm$ 2)	117/118 ( $\pm$ 6)	138/130 ( $\pm$ 46)	14/14 ( $\pm$ 4)	25/26 ( $\pm$ 7)	23/22 ( $\pm$ 7)	6/5 ( $\pm$ 2)	10/9 ( $\pm$ 4)	37/37 ( $\pm$ 10)
<i>K. sima</i> – Lower frequency clicks	free-ranging Guam	98	117/117 ( $\pm$ 3)	113/115 ( $\pm$ 6)	189/191 ( $\pm$ 75)	11/10 ( $\pm$ 7)	19/16 ( $\pm$ 12)	17/16 ( $\pm$ 7)	8/7 ( $\pm$ 4)	12/12 ( $\pm$ 3)	198/216 ( $\pm$ 120)
<i>K. breviceps</i>	captive	820	130/na ( $\pm$ 1)	129/na ( $\pm$ 1)	119/na ( $\pm$ 19)	8/na ( $\pm$ 2)	15/na ( $\pm$ 3)	na	16/na ( $\pm$ 1)	na	40-70/na

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 grey line), (B,E,H) an example waveform of a single click and (C,F,I) an example time series of 2 seconds of data.



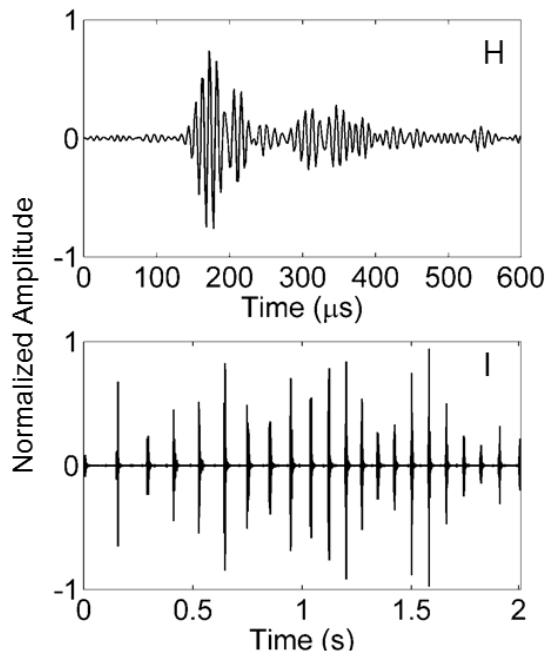
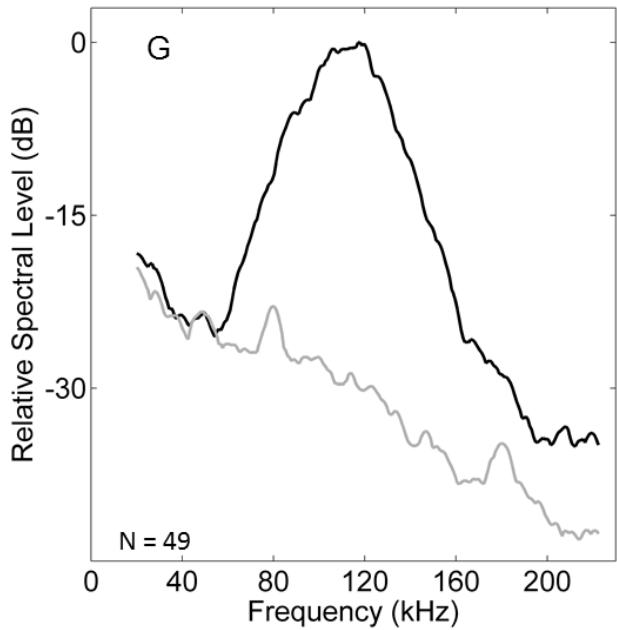
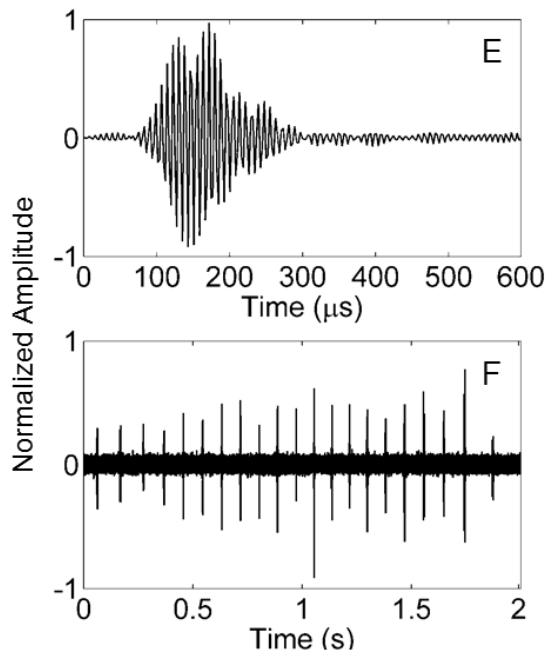
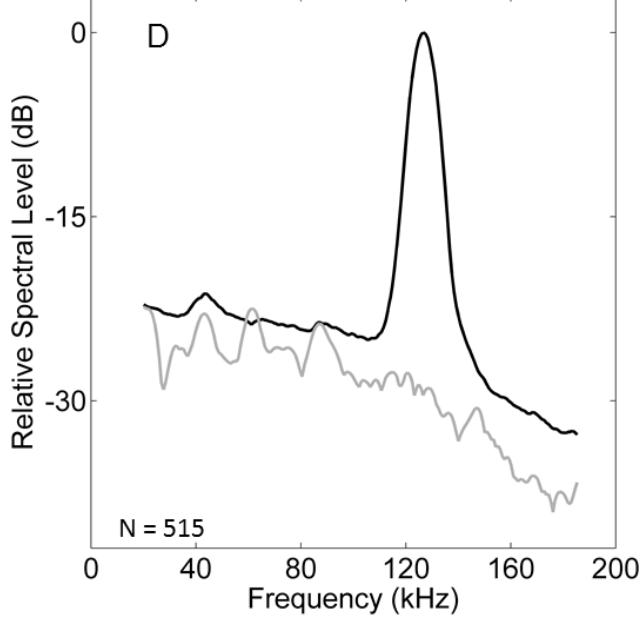


Figure 3. Histograms of peak and centroid frequencies for clicks in the Guam data set, highlighting the usual and lower peak frequency click types. A) Peak frequencies of all clicks, with a primary peak at 127 kHz and a secondary peak at 117 kHz. B) Peak frequencies and C) centroid frequencies of the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

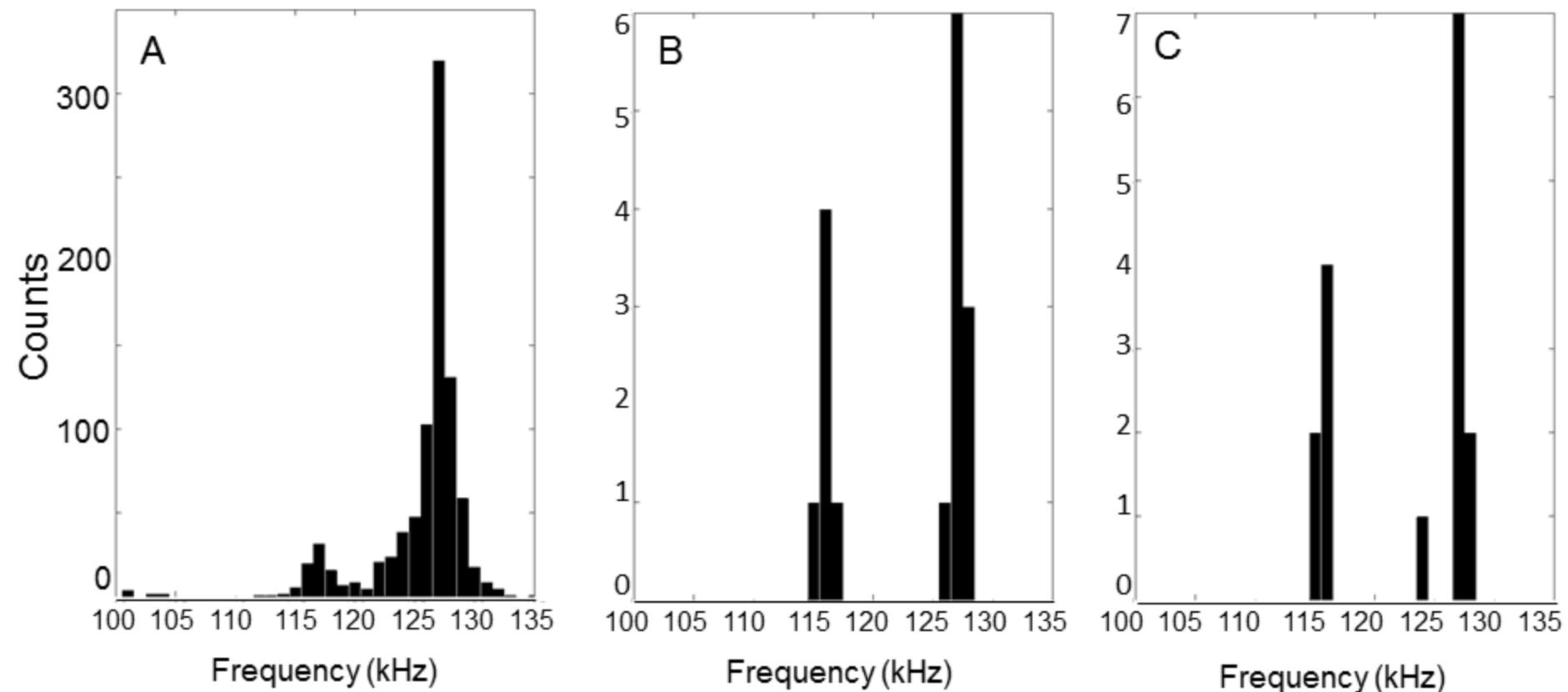


Figure 2. Examples of the burst-pulse clicks (A,B) and the lower frequency clicks (C, D) from Guam, including an example spectrogram (A) and time series (B) of the burst-pulse clicks and an example spectrogram (C) and waveform (D) of the lower frequency clicks. The burst-pulse is visible in A and B between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

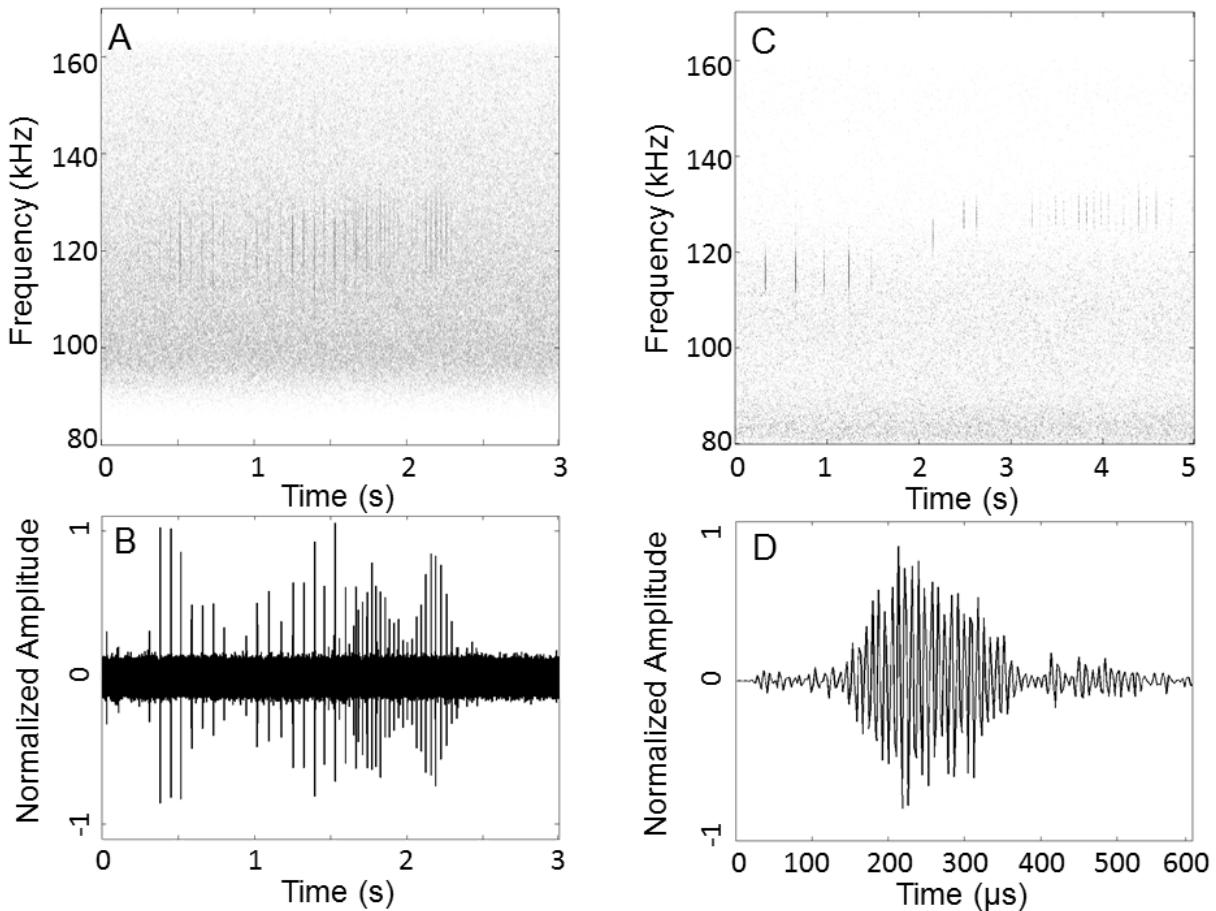


Figure 4. Histogram of click duration in the recording of free-ranging *K. sima* from The Bahamas. Grey bars indicate first mode (duration < 235  $\mu$ s), likely comprised of single clicks. Black bars indicate second mode (duration > 235  $\mu$ s), likely comprised of clicks-plus-reverberations. Dashed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

