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Detection and classification of narrow-band high frequency echolocation clicks from drifting recorders

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ABSTRACT:

In the California Current off the United States West Coast, there are three offshore cetacean species that produce narrow-band high frequency (NBHF) echolocation pulses: Dall's porpoise (*Phocoenoides dalli*) and two species of Kogia. NBHF pulses exist in a highly specialized acoustic niche thought to be outside the hearing range of killer whales and other potential mammal-eating odontocetes. Very little is known about the dwarf and pygmy sperm whales (*K. sima* and *K. breviceps*), including their NBHF pulse characteristics. This paper presents a multivariate clustering method using data from unmanned drifting acoustic recorders and visually verified porpoise recordings to discriminate between probable porpoise and *Kogia* clicks. Using density clustering, this study finds three distinct clusters whose geographic distributions are consistent with the known habitat range for *Kogia* and Dall's porpoise. A Random Forest classification model correctly assigned 97% of the clicks to their cluster. Visually verified Dall's porpoise clicks from towed hydrophones were strongly associated with one of the clusters, while a second cluster tended to be outside the geographic range of Dall's porpoise and unlike the Dall's porpoise cluster. These clicks, presumed to be made by *Kogia*, exhibited greater spectral variance than previous *Kogia* echolocation studies. It is possible that the structure of *Kogia* NBHF pulses may not be as stereotypical as previously described. https://doi.org/10.1121/10.0001229

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I. INTRODUCTION

Odontocetes use echolocation to forage and for navigation. Echolocation click characteristics vary among species in spectral features (Au, 2012). Different species use different frequency ranges and may occupy different acoustic niches, facilitating their co-occurrence in the same region (Tyack and Clark, 2000; Clark et al., 2009). Narrow-band high frequency (NBHF) click types are a highly specialized trait, thought to be above the effective hearing range of most larger predatory odontocetes (e.g., Orcinus orca; Madsen et al., 2005; Morisaka and Connor, 2007; Kyhn et al., 2013). NBHF clicks are above 100 kHz and long in duration (greater than 100 μ s). Four odontocete groups are known to produce NBHF clicks: Phocoenidae (porpoises), dolphins of genus Cephalorynchus, both species in the genus Kogia, and franciscana (Pontoporia blainvillei) of southeastern South America (Madsen et al., 2005; Kyhn et al., 2010; Kyhn et al., 2013).

produce NBHF clicks: Dall's porpoise (Phocoenoides dalli), eastern Pacific harbor porpoise (Phocoena phocoena vomerina), and both species of Kogia: dwarf and pygmy sperm whales (K. sima and K. breviceps, respectively). Dall's porpoise occurs throughout the North Pacific in cooler temperate waters, over the continental shelf and deeper waters (Jefferson, 1988; Forney, 2000; Boyd et al., 2018). Harbor porpoises are found in shallow (<100 m deep), coldtemperate waters (Barlow, 1988; Carretta et al., 2001). *Kogia* is a small (<4 m in length) genus of whale occurring in temperate and tropical offshore waters of the Atlantic, Pacific, and Indian Oceans (Shirihai, 2006). Much of what is known about the distribution of Kogia is inferred from the stranding record. Based on those records, the presumed range of the dwarf sperm whale extends northward to southern Oregon, and the presumed range of the pygmy sperm whale extends farther to northern Washington (Caldwell and Caldwell, 1989; McAlpine, 2018). However, Wade and Gerrodette (1993) reported that all their confirmed sightings of dwarf sperm whales were south of 24 °N, and Barlow and Forney (2007) report that all confirmed sightings off the U.S. West Coast were pygmy sperm whales.

In the California Current there are four species known to

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Kogia are believed to forage for cephalopods in mid- to deep waters, make deep (>250 m), long-duration (~25 min) dives, and spend little time at the surface (Willis and Baird, 1998; Breese and Tershy, 1993; Baird, 2005; MacLeod *et al.*, 2007; McAlpine, 2018). Due to their inconspicuous behavior, small size, and small group sizes (typically 1–2 individuals, but up to 10), they are rarely seen on visual sighting surveys. There have been only 16 *Kogia* sightings during eight National Oceanic and Atmospheric Administration (NOAA) ship-based surveys from 1991 to 2018 in the California Current [Barlow, 2016; Southwest Fisheries Science Center (SWFSC) unpublished data]. The *Kogia* genus is also difficult to discriminate, and many atsea sightings of *Kogia* cannot be identified to species.

Since dwarf and pygmy sperm whales produce echolocation clicks that are distinctive from most other odontocetes, passive acoustic monitoring can be used to study their distribution and relative abundance (Hodge et al., 2018; Hildebrand et al., 2019). To realize this potential, sounds made by Kogia need to be well-characterized in order to discriminate from the few sympatric species that make similar NBHF pulses. Previous studies have shown that NBHF echolocation clicks from the four U.S. West Coast species appear to differ in mean characteristics but have considerable overlap in their acoustic bandwidth (Table I). In its deep-water offshore habitat, Dall's porpoise is the species most acoustically similar to and likely to be confused with the two species of Kogia. Therefore, additional work is needed to discriminate between these echolocation types before they can be used to infer distribution. Here we use acoustic data from drifting acoustic recording systems in conjunction with visually validated recordings to develop a classification algorithm for distinct NBHF click types in the California Current and tentatively assign these types to species.

II. METHODS

A. Click data collection

The Passive Acoustic Survey of Cetacean Abundance Levels (PASCAL) was a dedicated acoustic survey for visually cryptic cetaceans. It was conducted over three legs in 2016 (August 19–23, August 23–September 7, September 11–30) on the NOAA R/V *Bell M. Shimada* along the U.S. West Coast from approximately 50 to 300 nmi offshore (1 141 807 km²) (Keating *et al.*, 2018). Although the focal study group for PASCAL was beaked whales, the study area encompassed regions where both Dall's porpoise and *Kogia* have been well-documented (Barlow, 2016).

During PASCAL, drifting acoustic spar buoy recorders (DASBRs) were deployed at 23 predetermined locations to broadly cover deep waters off the U.S. West Coast (Griffiths and Barlow, 2015; Keating et al., 2018). Details of time, location, and acoustic settings of each DASBR drift are given in supplementary materials, Tables S1 and S2¹. All DASBRs recorded sounds from two hydrophones ~ 100 m deep on a nylon line with 10 m of vertical separation. The line was weighted by a 6.8-kg anchor below the hydrophone array. Fourteen of the deployments were suitable for NBHF research, and each was constructed with an Oceans Instruments' Soundtrap 4300 (ST 4300, Fall City, WA, USA) recorder (sample rate: 288 kHz) and at High Tech, Inc., HTI-96-min hydrophone (with sensitivities of $\sim 165 \text{ dBV}$ re: 1µPa, Long Beach, MS, USA² in the lower hydrophone position. The upper hydrophone was not used in this analysis. The ST 4300 recorders had a 90 kHz low-pass filter that attenuated NBHF signals by ~ 12 dB at 130 kHz. Although the HTI-96-min hydrophone has an advertised flat frequency response of 30 kHz, the usable frequency range is much higher. Frequency spectra in this report have been calibrated for both the hydrophone and recorder as described below. Hydrophones were at least 2 m from the oil-filled ST 4300 recorder, and there were no other reflective surfaces or spaces (e.g., a float) near the sensors, so the recordings are likely free of multipath interference. The hydrophone selection was optimized for beaked whales, which produce much lower frequency pulses, and is not optimal for NBHF signals. However, we did record many NBHF pulses. All ST 4300 recorded 2-min files with a duty cycle of 2 min on and 8 min off. The internal gain for the ST 4300 was set to High, and the high-pass filter was turned off. Acoustic detection locations were plotted using R software, package marmap (Pante and Simon-Bouhet, 2013).

TABLE I. Standard acoustic feature measurements across the four sympatric NBHF click producing species off the US West Coast. Means and [range] are presented. Merkens *et al.* (2018) presented four different data sets, therefore no standard mean could be provided. Range is based on the means of all click types considered normal by the authors, only excluding the captive and ill juvenile animal. Hildebrand *et al.* (2019, Fig. 3) plotted histograms rather than providing the exact range, therefore range should be considered estimates since exact range was not printed. No two studies measure the same feature suite or used the same equipment/methods. Data confirmed to species is visually verified.

Species	Peak frequency (kHz)	Duration (µs)	-3 dB bandwidth (kHz)	Source
P. dalli	134 [N/A]	108 [N/A]	_	Kamminga et al., 1996
P. dalli	137 [121–147]	104 [53-251]	11 [3–23]	Kyhn et al., 2013
P. phocoena	N/A [129–137]	N/A [65-69.5]	_	Kamminga et al., 1996
P. phocoena	140 [137–143]	88 [48-189]	8 [3–19]	Kyhn <i>et al.</i> , 2013
K. breviceps	130 ± 0.7	119 ± 19	8 ± 2.3	Madsen et al., 2005
K. sima	N/A [117–129]	N/A [119–199]	N/A [10–11]	Merkens et al., 2018
Kogia spp.	119 (± 9)	$138(\pm 31)^*$	23 (± 7)	Merkens and Oleson 2018**
Kogia	117~[80–140]	62~[40-90]	19~[5-45]	Hildebrand et al., 2019**

*95% duration provided.

**Recordings taken from bottom-mounted instruments, ~1000 m deep.



We used validated recordings of Dall's porpoise that had been confirmed by two visual observers (J.B. and E.K.) to the DASBR recordings. The recordings were collected in the Kitimat Fjord System of northern mainland British Columbia, Canada, (53.05 °N, 129.28 °W) on June 13, 2015. An oil-filled hydrophone array was towed 100 m behind the S/V Bangarang (37-ft. research sloop under engine power at the time of recording) traveling at approximately 3–5 knots. The array contained an HTI-96-min hydrophone with a built-in 10 Hz high-pass filter and preamplifier. Another preamplifier was added in the array that provided 20 dB gain and a 1-pole Butterworth 480 Hz high-pass filter. Recording hardware included a National Instruments NI-USB-6251 digitizer and a Windows laptop; audio was recorded with a sampling rate of 500 kHz in PAMGuard. The vessel stayed within 70-300 m of a group of approximately 6 animals from 0930 to 1130 a.m., local time. No killer whales, which might have altered Dall's porpoise vocal behavior, were observed in the area during these recordings.

B. Click data extraction

All recordings were processed by PAMGuard open source software (version 1.13.11; Gillespie et al., 2008). NBHF clicks were automatically detected using the click energy detector with a 12 dB threshold and a 6-pole Butterworth high-pass filter set at 70 kHz to exclude other click types. Detection was triggered by the lower hydrophone on DASBR recordings and the single channel for the Dall's porpoise recordings. Visually validated Dall's porpoise recordings were decimated from 500 to 288 kHz to match the sampling rate of the DASBRs. For our click detector, click length was set to 5000 bin samples, with a minimum separation of 1000 samples between clicks. With a sample rate of 288 kHz, PAMGuard binary bin size is 0.0034 ms long. On the energy detections, a PAMGuard click classifier with a frequency sweep was set to search for the peak frequency between 100 and 144 kHz, with a search and integration range of 80-144 kHz (smoothing = 31bins). Two control bands of 80-90 kHz and 90-100 kHz were set with a threshold of 12 and 15 dB, respectively. The feature 'click length' was enabled to limit click lengths to 0.05-0.25 ms (smoothing = 5 bins) with a threshold of 6 dB below the maximum amplitude. Only clicks that met these criteria were included in our analysis. All other clicks detected by the PAMGuard energy detector were discarded. Detections were manually reviewed by ETG to ensure that detections were genuine NBHF clicks rather than noise or static. A series of clicks determined to be biological were assigned to events. Events were defined as bouts of at least three NBHF clicks with a clear peak frequency in the averaged spectrum in sequential files.

To ensure that only clicks with a high signal-to-noise (SNR) ratio were included in analysis, further processing was completed in R (version 3.4.1; see supplementary materials, Table S3)¹. The 5000-bin sample of each click waveform were extracted from the PAMGuard binary files in R

using the package *PamBinaries* (Sakai, 2018). Clicks were then processed individually, independent of which DASBR, event, or channel they were recorded on using the R packages *seewave*, *tuneR*, and *signal* (Sueur *et al.*, 2008; Ligges *et al.*, 2018). Individual clicks were digitally filtered with a 4-pole Butterworth band-pass filter with a pass-band between 100 and144 kHz. The number of digital samples was reduced from 5000 to 512 (1.78 ms), centered around the peak amplitude of the waveform/click.

A 512-bin sample of ambient noise was also taken at either the start or end of the original 5000-bin sample, depending on where the click peak was located within the waveform. If the click was within the first 800 bins of the 5000-bin waveform, the noise sample was taken from the end. If the click was after the first 800 bins, the noise sample was taken from the beginning. If the peak amplitude of the click was not 10 dB (re: 20* log10) above the noise sample at that peak frequency, it was removed from further analysis. Higher SNR thresholds were considered; however, due to the ST-4300 90 kHz low-pass filter stricter thresholds, they yielded inadequate sample sizes for this study.

C. Feature extraction

To smooth the sensor frequency sensitivity, a generalized additive model (GAM) was applied to the spectra for both the HTI-96-min (as measured by the National Physical Laboratory in the U.K.) and the ST 4300. Using the R package *gam* (Hastie, 2018), a spline smoothing formula was fit to the frequency sensitivity every 50 Hz to create calibration curves for both instruments, which were applied to each spectrum. A suite of acoustic features was then calculated using *seewave*, *tuneR*, and *signal* for all clicks above the 10dB noise threshold based on a 256-FFT spectrogram.

For each click, five values at the -3 and -6 db thresholds were measured: frequency bandwidth, center frequency, minimum and maximum frequencies, and the resonant quality factor, Q, which estimates the frequency pureness of a time wave at a specific dB level. Q is calculated by dividing the center frequency by the bandwidth, such that a higher Q indicates a lower rate of energy loss relative to the stored energy of the resonator; the oscillations die out more slowly (Au, 2012). Peak frequency was recorded between the -3 dB bandwidth maxima and minima. We also recorded the root mean square (RMS) bandwidth, defined as the spectral standard deviation around the centroid frequency. Click duration was calculated using a Teager-Kaiser (TK) energy operator. The noise floor was established at the 40th energy percentile, consistent with methods from Soldevilla et al. (2008). All waveform samples at least 100 times greater than the noise threshold were summed for duration.

Shoulder frequency, or the presence of a secondary shallow amplitude peak on one side of the peak frequency, was calculated above the -10 dB threshold with at least a 0.1 dB slope on either side of the peak. Shoulder frequencies needed to be ± 5 kHz from the peak frequency to avoid

capturing uncertainty from the peak modal. Both shoulder frequency and amplitude were recorded as a difference from the peak frequency. Clicks that did not exhibit a shoulder frequency were given shoulder frequency and amplitude values of 0 kHz and dB, respectively.

Because reliable inter-click-interval measurements were not available for all events, that measurement was not included in this analysis. Thus, we extracted a total of 16 features for every click. We discarded clicks with a -3 or -6 dB bandwidth frequency maxima of 144 kHz as the sample rate did not capture the full frequency bandwidth for these pulses. Clicks with a peak frequency lower than 100 kHz or a duration greater than 500 μ s were also discarded.

D. Click clustering

Using the above 16 acoustic characteristics, we identified distinct clusters of clicks with similar features recorded from the DASBRs using density clustering (Rodriguez and Laio, 2014). The measurements were first translated to a matrix of pairwise Euclidean distances among clicks. Prior to calculating the distances, we first log-transformed the Q values, click duration, and negative of the shoulder amplitude in order to make them more normally distributed. The distance matrix was then used to compute the density clustering ρ , and δ parameters for each click with the densityClust v0.3 package (Pedersen et al., 2017). Following Rodriguez and Laio (2014), we used the 1.5% quantile of the distribution of pairwise distances for a distance cutoff (dc). Peaks for each cluster were identified as clicks with unusually high values of ρ , δ , and their product, γ , based on a visual inspection of the distribution of these values. Once peaks had been identified, the remaining clicks were assigned to clusters based on their proximity to a peak.

E. Cluster classification and identification

We quantified the robustness of click assignments to clusters by creating a Random Forest (Breiman, 2001) classification model using the randomForest v.4.6-16 package (Liaw and Wiener, 2002) run through the *rfPermute* package (Archer, 2018). The same 16 acoustic features used above were used as predictors for the clusters. Q values, click duration, and shoulder amplitude were not log-transformed as above, as Random Forest is not sensitive to non-normally distributed data. To ensure that the model was not biased toward clusters with larger numbers of clicks, we randomly selected an equal number of clicks from each cluster for each tree in the model. The number of clicks selected from each cluster was half of the smallest cluster size, and clicks were chosen without replacement. The remaining clicks in each cluster were left as "out-of-bag" (OOB) and sent down the tree for prediction. Thus, half or more of the clicks in each cluster were used to validate the model. A total of 8000 trees were built, and the trace of the OOB error rate for trees in the forest was inspected to ensure prediction stability. The mean of the OOB click assignment probabilities to each cluster were also calculated for each event.

The importance of acoustic features for distinguishing clusters was evaluated with the mean decrease in accuracy measure computed by *randomForest*. The significance of feature importance scores was evaluated using *rfPermute*, which randomly permutes cluster assignment in each tree to create a null distribution of the Random Forest predictor importance scores. We conducted 1000 permutations per tree to compute the importance *p*-values.

To evaluate which species might be represented by the DASBR click clusters, we used the above Random Forest model to classify the visually confirmed Dall's porpoise recordings from British Columbia into clusters. Given that only Dall's porpoise and the two *Kogia* species are known to make NBHF clicks in this region, if the clusters identified by the density clustering algorithm are related to distinct click types by each species, the expectation is that a significant majority of Dall's porpoise clicks would strongly classify to one click cluster to the exclusion of the others.

We also examined the relationship of DASBR click cluster assignment probabilities to estimated local Dall's porpoise density. Density estimates (number of animals per km^2) were obtained from a habitat model detailed in Becker *et al.* (2016). Estimates were taken as the mean of 8-day composites derived from 8 surveys conducted between 1991 and 2014. Mean density was computed for 10- km^2 square grids across the study area. Each click was assigned the mean density of the nearest center grid cell center. We expect a higher proportion of clicks within Dall's porpoise habitat to assign to the cluster with visually validated Dall's porpoise clicks.

III. RESULTS

There were 108 NBHF events on 14 DASBR drifts, with a total of 3732 NBHF clicks detected. After filtering out clicks less than 10 dB above the 40% noise threshold, there were 1464 clicks from 84 events (see supplementary material, Table S3). From the towed array, 46 of the 55 Dall's porpoise clicks were 10 dB above the noise threshold. After removing clicks with implausible measurements (e.g., long duration, low peak frequency, incomplete bandwidth), 1186 NBHF clicks from 76 events on 12 DASBR drifts (Fig. 1, Table III), and 23 NBHF Dall's porpoise clicks from the towed array remained.

The density clustering algorithm identified three clusters of clicks in the DASBR recordings (Fig. 2). Approximately two-thirds were assigned to Cluster 1 (795 = 67%), while Cluster 2 had 296 clicks (25%), and Cluster 3 was composed of 95 clicks (8%). The Random Forest model was able to correctly classify 97% of all clicks, with all clusters having approximately the same classification accuracy (Table II). The median OOB assignment probability of clicks to their correct clusters was 0.995, 0.976, and 0.997 for Clusters 1, 2, and 3, respectively (see supplementary material, Fig. S1). In most events, clicks were predominantly in a single cluster. However, when events were composed of clicks from multiple https://doi.org/10.1121/10.0001229



FIG. 1. (Color online) DASBR drifts with NBHF clicks along the West Coast of the United States. Drifts are labelled by station number. Locations of NBHF click events are identified by red points. Dashed line indicates 2000 m isobath.

clusters in large numbers, they tended to be from Clusters 1 and 2 (see supplementary material, Table S3).

All features were found to be significant predictors (p < 0.05) overall in the Random Forest classification model, and most were found to be significantly important for classifying each of the three clusters (Figs. 3 and S2). However, their relative importance to classification accuracy varied.



FIG. 2. Distribution of density clustering (A) ρ and δ , and (B) γ parameters for NBHF clicks. (C) Distributions of clicks on first two dimensions of multi-dimensional scaling transformation of spectral features. Clicks are color coded by cluster number, and numbers are located at the peak click for each cluster.

TABLE II. Confusion matrix of clicks for Random Forest classification model on clusters identified by density clustering.

	Predicted cluster					
Observed cluster	1	2	3	% Correct	CI	Prior
1	772	21	2	97.1	95.7–98.2	67.0
2	2	291	3	98.3	96.1–99.4	25.0
3	1	2	92	96.8	91-99.3	8.0
Overall				97.4	96.3–98.2	51.8

The most important feature (frequency maxima at -3 dB) had an overall mean decrease in accuracy that was four times greater than the least important feature (shoulder amplitude).

Cluster 1 was primarily distinguished from Clusters 2 and 3 by being approximately 10 kHz lower in frequency in important features, such as frequency maxima and center at -3 dB, and the overall peak frequency. The distinguishing characteristics of Cluster 2 were the highest maximum frequency at -3 dB and the lowest Q value at -6 dB. Conversely, Cluster 3 had a Q value at -6 dB that was approximately 1.5 times greater than that of Clusters 1 and 2, and a minimum frequency at -6 dB that was lower in frequency than Clusters 1 and 2 (Figs. 3, 4, and Table III). The bandwidths at -3 and -6 dB and the variability are broad for Clusters 1 and 2 compared to Cluster 3 and Dall's porpoise.

The spatial distribution of the mean OOB Random Forest assignment probabilities to clusters for each event is depicted in Fig. 5. Events composed of clicks with high assignment probability to Cluster 1 tended to predominate in the far offshore region and in the southern portion of the study area off the shelf. Cluster 2 was found principally at the 3 northernmost stations (DASBRs 1, 2, and 3), which ranged from offshore Pt Reyes to central Oregon and in the vicinity of the shelf break. Cluster 3 occurred in a smaller number of events with high probability along the slope between southern Oregon and San Francisco Bay.

Figure 6 shows the relationship between how clicks in each event clustered and the associated estimate of Dall's porpoise density from the habitat models. A majority of the events composed of Cluster 1 clicks were associated with near-zero estimates of Dall's porpoise density. The median estimated Dall's porpoise density for Cluster 1 was 0.001 animals/km,² 0.09 animals/km² for Cluster 2, and 0.12 animals/km² for Cluster 3. Eighty percent of the Cluster 3 clicks were associated with Dall's porpoise densities greater than 0.08 animals/km² and were assigned to that cluster with high probability by our Random Forest model (see supplementary material, Fig. S3). Conversely, 65% of the Cluster 1 clicks were associated with areas of lower Dall's porpoise density, less than 0.08 animals/km², and most clicks had cluster assignment probabilities greater than 90% by our model.

Finally, the Random Forest model predicted all 23 of the known British Columbia Dall's porpoise clicks from the







FIG. 3. Distribution of click acoustic feature values by cluster and Dall's porpoise (Phocoenoides dalli) clicks from towed array. Features are ordered from top left to bottom right by importance in Random Forest classification model. Red underscore indicates p > 0.05.

towed array to belong to Cluster 3. All clicks had assignment probabilities greater than 87% with a median probability of 99.8% (see supplementary material, Fig. S4). The median assignment probability of Dall's porpoise clicks to Clusters 1 and 2 was 0.01% and 0.1%, respectively.

IV. DISCUSSION

Our analysis of the narrow-band high frequency (NBHF) clicks recorded from the 2016 DASBR deployments in the California Current ecosystem indicates the presence of three distinct click types. Given the geographical location of these DASBRs, we can be relatively

y. Dall's porpoise and Cluster 1 by *Kogia*, while the source of Cluster 2 remains uncertain. The evidence that Cluster 3 is Dall's porpoise comes from a combination of comparison of the spectral features of that cluster with known recordings and the spatial distri-

from a combination of comparison of the spectral features of that cluster with known recordings and the spatial distribution of clicks and events strongly assigning to that cluster. All drifts with high probability of assignment to Cluster 3 (Drifts 1, 2, 3, and 20) were in regions of high Dall's porpoise density, which is more heavily concentrated in the

confident that the clicks are most likely to be produced by

Dall's porpoise (*Phocoenoides dalli*), pygmy sperm whales

(*Kogia breviceps*), or dwarf sperm whales (*K. sima*). Our results strongly suggest that Cluster 3 is being produced by





FIG. 4. (Color online) Mean spectra of Cluster 1 (yellow solid), Cluster 2 (blue dash), Cluster 3 (pink dotted dash), and Dall's Porpoise (black dotted) clicks with normalized sensitivity. Gray solid line represents the average noise floor for all three clusters.

TABLE III. Summary of acoustic features for clusters identified by density clustering and British Columbia Dall's porpoise clicks. For each feature, top row is mean (standard deviation), and the bottom row is median (range).

Feature	Cluster 1 n = 795	Cluster 2 n $= 296$	Cluster $3 n = 95$	Dalls $n = 23$
-3 dB Bandwidth	7.86 (2.29)	11.27 (4.15)	4 (1.13)	3.48 (1)
	7.71 (1.62–14.26)	10.82 (2.23–25.41)	3.74 (2.27-7.6)	3.59 (1.69-6.07)
-6 dB Bandwidth	12.79 (3.5)	17.33 (3.7)	5.85 (1.6)	4.83 (1.21)
	12.41 (3.73–30.21)	17.66 (7.77–30.96)	5.62 (3.41–11.15)	4.65 (2.56–7.57)
RMS Bandwidth	7438.3 (999.23)	8263.63 (827.94)	6861.78 (1336.76)	7022.12 (1235.89)
	7410.44 (4923.58–11295.06)	8170.24 (6742.75–11486.97)	6858.62 (4582.64–11400.52)	6875.93 (5170.04–9149.69)
Center Freq at −3 dB	120.72 (4.43)	131.04 (2.9)	133.23 (2.74)	133.98 (1.35)
	121.44 (108.8–132.6)	130.69 (123.23–141.46)	133.02 (125.88–140.09)	134 (130.08–136.22)
Center Freq at −6 dB	121.42 (4.43)	129.75 (1.77)	133.17 (2.69)	134.03 (1.39)
	121.63 (107.61–131.47)	129.44 (124.97–136.39)	132.98 (125.97–139.5)	134.27 (129.85–136.24)
Duration	117.13 (89.59)	70.03 (44.73)	159.96 (79.38)	156.86 (109.63)
	90.45 (3.48–497.5)	62.62 (3.48–295.72)	156.56 (10.44–375.73)	180.91 (3.48-410.52)
Freq Max at -3 dB	124.65 (4.8)	136.67 (2.42)	135.23 (2.73)	135.72 (1.18)
	125.08 (110.45–139.54)	136.31 (130.2–142.57)	135.33 (127.39–142.19)	135.82 (131.4–137.45)
Freq Max at -6 dB	127.82 (5.35)	138.41 (2.17)	136.1 (2.88)	136.45 (1.21)
	127.5 (110.92–142.88)	138.36 (132.57–142.98)	136.09 (128.1–142.86)	136.48 (132.08–138.43)
Freq Min at -3 dB	116.79 (4.35)	125.4 (4.43)	131.23 (2.86)	132.24 (1.65)
	117.43 (106.2–128.08)	125.28 (114.49–140.34)	131.35 (124.38–138)	132.37 (128.48–135.38)
Freq Min at -6 dB	115.03 (4.1)	121.09 (2.9)	130.25 (2.74)	131.62 (1.77)
	115.29 (102.83–126.75)	120.95 (111.98–132.5)	130.45 (123.84–136.55)	131.65 (127.62–134.96)
Peak Freq	120.29 (4.73)	131.89 (4.1)	133.34 (2.68)	134.1 (1.61)
	121.5 (108.56–132.19)	132.19 (119.81–141.75)	133.31 (126–140.63)	134.44 (129.94–136.69)
Q Value of -3 dB	17.07 (7.41)	14.07 (7.93)	35.93 (9.72)	41.81 (12.87)
	15.53 (8.17–76.58)	12.26 (5.44–63.44)	35.64 (17.31–57.32)	37.28 (21.69-80.76)
Q Value of -6 dB	10.13 (2.89)	7.98 (1.89)	24.41 (6.18)	29.5 (7.84)
	9.72 (4.02–30.12)	7.51 (4.58–17.66)	23.69 (11.96–38.14)	28.79 (17.38-53.18)
Q Value of RMS BW	0.01 (0)	0.01 (0)	0.01 (0)	0.01 (0)
	0.01 (0.01-0.01)	0.01 (0.01–0.01)	0.01 (0.01–0.01)	0.01 (0.01–0.01)
Shoulder Peak Amp	-4.65 (4.04)	-2 (2.43)	-2.58 (4.79)	-1.03 (2.79)
	-3.46 (-14.98-0)	-1.36 (-14.49-0)	0 (-14.72-0)	0 (-9.78-0)
Shoulder Peak Freq	7.41 (7.9)	-4.07 (8.05)	-0.28 (5.8)	0.88 (2.33)
	7.87 (-11.81-30.38)	-6.75 (-22.5-14.62)	0 (-18.56-12.94)	0 (0-7.31)







northern portion of the study area, within 200 nm of the shore (Becker *et al.*, 2016; Boyd *et al.*, 2018). Also, all of the visually confirmed Dall's porpoise clicks from British Columbia were strongly predicted to be Cluster 3.

Our assignment of Kogia to Cluster 1 primarily derives from the observation that it was the most distinct cluster from Cluster 3 and geographically overlapped with extremely low densities of Dall's porpoise derived from a regional habitat model constructed from visual sighting records. Additionally, the location of Cluster 1 events overlaps with the limited sighting records for pygmy sperm whale and Kogia (Barlow, 2016). Although ship-based linetransect surveys have proven effective for estimating habitat use and range for Dall's porpoise (Barlow and Forney, 2007; Boyd et al., 2018; Fig. S4), unfortunately, this small number of sightings does not provide enough information on the full range of *Kogia* within the study area. Between 1991 and 2018 only 16 Kogia sightings were documented during vessel-based surveys conducted by the NOAA's SWFSC in the California Current (1 141 807 km²) (Barlow, 2016; SWFSC unpublished data). Four of the historical Kogia sightings were made in the same geographical location as Drift 9, one of which was a confirmed pygmy sperm whale. Three of the remaining pygmy sperm whale sightings were in waters 500 m or deeper, with no acoustic detection, off the Channel Islands and Big Sur.

The identity of Cluster 2 is equivocal. The spatial distribution of Cluster 2 clicks was more similar to that of

Cluster 3 (probable Dall's porpoise) and tended to occur close in time to events with large Cluster 3 assignment probabilities. The spectral characteristics of Clusters 2, 3, and the British Columbia Dall's porpoise were highly similar, having a distinct, narrow peak between 130 and 136 kHz, and all bandwidth measurements were higher in frequency than Cluster 1 (Table III and Figs. 4 and 5). Cluster 2 has distinctively higher peak and center frequencies than Cluster 1 and other published *Kogia* NBHF pulses with a mean peak frequency at 120 kHz (Merkens *et al.*, 2018; Merkens and Olsen, 2018; Hildebrand *et al.*, 2019). However, the minimum frequency at -3 and -6 dB for Cluster 2 was less than that of Cluster 1. Additionally, Q values at -3 and -6 dB were more similar between Clusters 1 and 2.

Thus, there are three possible origins for the clicks in Cluster 2: 1) They are produced by one of the two *Kogia* species, possibly dwarf sperm whales (*K. sima*) or either species with a shifted frequency bandwidth to avoid predation. 2) They represent added variation in the NBHF repertoire of Dall's porpoise. 3) They are produced by another species not previously known to make NBHF clicks.

Previous studies have recorded *Kogia* echolocation clicks as unimodal, or having one strong spectral peak chiefly between 125 and 130 kHz (Madsen *et al.*, 2005; Merkens *et al.*, 2018). In the current study, the peak frequency of clicks from Cluster 1 ranged from 109 to 132 kHz, while the peak frequency of clicks in Clusters 2 and 3



Clicks

FIG. 6. NBHF click sequences in each event (right) with corresponding mean Dall's porpoise density estimated from habitat models in Becker *et al.* (2016) on left. Events are ordered from highest Dall's porpoise density at the top to lowest on the bottom. Clicks are ordered by their temporal occurrence in each event from left to right and color coded by cluster.

was higher (120–142 kHz, Table III, and Figs. 3 and 4). Our reported peak and center frequencies are lower than previous studies for *Kogia* with visually confirmed recordings. Merkens *et al.* (2018) opportunistically recorded dwarf sperm whales in the Bahamas and Guam with hydrophones at 2 m and 30 m deep, respectively. While this could be regional variation, the clicks recorded on the deeper hydrophone recorded a lower peak frequency, including a small subset of clicks with a peak frequency of 117 (\pm 3) kHz. Clicks recorded on the 2 m deep hydrophone had a peak frequency of 129 (\pm 2) kHz. Additionally, presumed *Kogia* clicks from bottom-mounted recorders (~1000 m) in the Gulf of Mexico and off the Kona coast of Hawai'i Island recorded a mean peak frequency closer to this study, 117 kHz (Hildebrand *et al.*, 2019) and 119 kHz (Merkens and

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Oleson, 2018). A depth of 100 m may allow us to record acoustic behavior or beam pattern flexibility in relation to depth not documented by animals recorded at the surface or captive animals (Madsen *et al.*, 2005; 130 ± 0.7 kHz).

We found, anecdotally, that some of our offshore detections shifted in spectral parameters within the same NBHF event. For example, in Event 11 on Drift 9, a NBHF click train started with a peak frequency of 115 kHz and a shoulder frequency of 129 kHz. The event lasted 50 s and displayed highly variable spectral features (Fig. 7). The peak frequency, bandwidth, and shoulder frequency shifted dramatically (± 5 kHz). A shoulder frequency was detected on most clicks in the encounter; however, the initial shoulder modal became the peak modal within the first 10 s of the event. The aspect angle of the animal in relation to the





FIG. 7. (Color online) NBHF click train event from drift 9, event #11. Top panel: a 60 s PAMGuard Bearing Time Display, with bearing measurements enlarged. Bottom panel: eight click spectrums from this event with associated times and peak and shoulder frequencies. Click train in Bearing Time Display from a presumed *Kogia* shows the animal traveling from above the DASBR array (above 90°) to around 100 m deep before the detection stops. Bearing was determined from the time difference of arrival between the DASBR's upper hydrophone (either an HTI-92WB or HTI-96min, see Table SM2). Event is approximately 50 s long within the time window starting at 11:32:34 UTC. Click selected in the bearing time window was at 11:32:43 UTC; the same click in the first spectral plot of the bottom panel. In each plot of the bottom panel is the click spectrum between 90 and 144 kHz, with the relative amplitude (dB), and time the click occurred (title). Blue triangles and brown diamonds indicate the peak and shoulder frequencies, respectively. Shoulder frequency will not be present if the amplitude slope threshold (0.1 dB) is not met.

cylindrical hydrophone may contribute to this variation. However, the first 4 spectra in Fig. 7 were within the first 10 s of the event, and maintained a similar bearing angle $(\sim 20^{\circ})$ in relation to the hydrophone. These clicks demonstrate a dramatic shift in peak and shoulder frequency and amplitude. As this event progresses and the animal dives deeper, the variation may be attributed to the aspect angle or a combination of the aspect and bearing angles. Variation in Cluster 1 may capture shifts in *Kogia* beam pattern when demonstrating different acoustic behaviors (e.g., sweeping the head while foraging) or sharing an acoustic niche with con- and/or heterospecifics. In summary, *Kogia* may adjust their beam pattern to higher frequencies due to unknown environmental conditions and animal behavior.

While spectral shoulders were not reported in previous studies of NBHF vocalizations, they were detected in 93% of clicks in this study, tending to occur most often in Cluster 1. In this cluster, the shoulders had a higher frequency than

the peak, and were noticeably lower in amplitude with a median of -3.5 dB (Table III). When a spectral shoulder was present in Cluster 2, the frequency was commonly lower than the peak frequency and close in amplitude with a median of -1.2 dB. In some of the clicks illustrated in Fig. 8, this spectral shoulder appears to be a variation on a bimodal frequency pattern.

Bimodal frequencies in echolocation clicks have been recorded in beluga whales (Lammers and Castellote, 2009), Risso's dolphins (Soldevilla *et al.*, 2008), and bottlenose dolphins (Starkhammar *et al.*, 2011). Like most odontocetes these species possess two pairs of phonic lips (Cranford *et al.*, 1996; Cranford *et al.*, 2000). The two separately controlled phonic lips are capable of producing sonar clicks either independently or simultaneously (Cranford *et al.*, 2000), which can lead to bimodal characteristics (Lammers and Castellote, 2009). Members of the *Physeteroid* superfamily, sperm whales (*Physeter macrocephalus*) and both

species of *Kogia*, have only one pair of phonic lips and a spermaceti organ (Cranford *et al.*, 1996). Therefore, NBHF clicks with bimodal spectra are probably not being produced using the same mechanism as by other well-studied echolocating species.

In harbor porpoises, there is evidence of flexibility in the sonar beam due to changes in the melon. This is supported by an asymmetrical beam pattern in part caused by skull structure (Koblitz et al., 2012). Additionally, porpoises will alter their beamwidth to track prey while foraging (Wisniewska et al., 2015). The diameter of the head is considered indicative of radiating aperture size (Au et al., 1999). It is possible that *Kogia* also have an asymmetrical beam pattern, despite only having one pair of phonic lips, due to their asymmetrical skull (MacLeod et al., 2007; Thornton et al., 2015). Species producing bimodal clicks demonstrate variation in spectral energy distribution depending on the distance and angle the receiver is to the signal source (Lammers and Castellote, 2009; Starkhammar et al., 2011), and have been documented controlling the directionality of their beamwidth (Moore et al., 2008). In this study, we did not know the distance of the signal source to the receiver. NBHF clicks recorded on the DASBRs were probably closer to on-axis because narrow-band signals are highly focused and directional. Off-axis clicks likely had a lower probability of being recorded, though there is no way we could know this with the scope of this study.

We have potentially three sympatric NBHF species in the offshore California current, although Dall's porpoise and the pygmy sperm whale may be the only common species. Due to this, having a robust method to discern between species vocalizations is necessary to improve monitoring efforts. Other studies have used acoustic features to discern different species, or groups of species (Kyhn et al., 2013; Rankin et al., 2017). However, what acoustic features to use is less clear; no two studies have measured the same feature suite. Standard features include peak frequency, duration, inter-click-interval (ICI), -3/-10 dB bandwidth, and center frequency (Madsen et al., 2005; Soldevilla et al., 2009; Kyhn et al., 2013; Merkens et al., 2018; Merkens and Oleson, 2018). Other features, such as Q factor (Madsen et al., 2005; Kyhn et al., 2013; Merkens et al., 2018) and notch frequency (Soldevilla et al., 2009), have only started to be discussed as diagnostic when discerning between groups. Peak frequency and ICI are often discussed when discerning between species groups, but these features can shift due to the signal source location to the receiver or if the animal is tracking prey (Koblitz et al., 2012; Wisniewska et al., 2015). We included the shoulder frequency and amplitude features as they appeared subjectively prominent when initially reviewing the data, and the presence of a spectral shoulder had not been documented in previous Kogia studies. Developing spectral templates for each species, rather than relying on extracted feature measurements may improve classification results. However, any template would need to be flexible enough to capture the high variability of our presumed Kogia clicks. Additional research needs to be completed with visual confirmation of *Kogia* presence to test our assessment.

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²Use of named products does not constitute endorsement by the United States government.

- Archer, E. (2018). "rfPermute: Estimate permutation p-values for Random Forest importance metrics [R package version 2.1.8]," https://github.com/ EricArcher/rfPermute.
- Au, W. W. (2012). *The Sonar of Dolphins* (Springer Science and Business Media, Berlin).
- Au, W. W., Kastelein, R. A., Rippe, T., and Schooneman, N. M. (1999). "Transmission beam pattern and echolocation signals of a harbor porpoise (Phocoena phocoena)," J. Acoust. Soc. Am. 106(6), 3699–3705.
- Baird, R. W. (**2005**). "Sightings of Dwarf (*Kogia sima*) and Pygmy (*K. breviceps*) sperm whales from the Main Hawaiian Islands," Paci. Sci. **59**(3), 461–467.
- Barlow, J. (1998). "Harbor porpoise, Phocoena phocoena, abundance estimation for California, Oregon, and Washington: 1. Ship surveys," Fish. B. 86(3), 417–432.
- Barlow, J. (2016). "Cetacean Abundance in the California Current Estimated from Ship-based Line-transect Surveys in 1991–2014," Administrative report IJ-12-01. (Southwest Fisheries Science Center, National Marine Fisheries Service, La Jolla, California, USA).
- Barlow, J., and Forney, K. A. (2007). "Abundance and population density of cetaceans in the California Current ecosystem," Fish. B. 105(4), 509–526.
- Becker, E., Forney, K., Fiedler, P., Barlow, J., Chivers, S., Edwards, C., and Redfern, J. (2016). "Moving towards dynamic ocean management: How well do modeled ocean products predict species distributions?," Remote Sens. 8(2), 149.
- Boyd, C., Barlow, J., Becker, E. A., Forney, K. A., Gerrodette, T., Moore, J. E., and Punt, A. E. (2018). "Estimation of population size and trends for highly mobile species with dynamic spatial distributions," Divers. Distrib. 24(1), 1–12.
- Breese, D., and Tershy, B. R. (1993). "Relative abundance of cetacea in the Canal de Ballenas, Gulf of California," Mar. Mammal Sci. 9(3), 319–324.
 Breiman, L. (2001). "Random forests," Mach. Learn. 45(1), 5–32.
- Caldwell, D. K., and Caldwell, M. C. (1989). "Pygmy sperm whale, Kogia breviceps (de Blainville, 1838): Dwarf sperm whale, Kogia simus (Owen, 1866)," Handbook of Marine Mammals 4, 235–260.

¹See supplementary material at https://doi.org/10.1121/10.0001229 for information about the PASCAL DASBR deployments (SM1 and SM2) and how each click clustered per event according to the density clustering model (SM3); and the clicks were extracted from the PAMGuard binaries, how each click was selected and filtered, how the feature measurements for each click were extracted; and how the Random Forest model was used to verify our results.



- Carretta, J. V., Taylor, B. L., and Chivers, S. J. (2001). "Abundance and depth distribution of harbor porpoise (*Phocoena phocoena*) in northern California determined from a 1995 ship survey," Fish. B. **99**(1), 29–29.
- Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., and Ponirakis, D. (2009). "Acoustic masking in marine ecosystems: Intuitions, analysis, and implication," Mar. Ecol. Prog. Series. 395, 201–222.
- Cranford, T. W., Amundin, M., and Norris, K. S. (1996). "Functional morphology and homology in the odontocete nasal complex: Implications for sound generation," J. Morphol. 228(3), 223–285.
- Cranford, T. W., Elsberry, W. R., Blackwood, D. J., Carr, J. A., Kamolnick, T., Todd, M., and Decker, E. C. (2000). "Two independent sonar signal generators in the bottlenose dolphin: Physiologic evidence and implications," J. Acoust. Soc. Am. 108(5), 2613–2614.
- Forney, K. A. (2000). "Environmental models of cetacean abundance: Reducing uncertainty in population trends," Conserv. Biol. 14(5), 1271–1286.
- Gillespie, D., Mellinger, D. K., Gordon, J., Mclaren, D., Redmond, P., McHugh, R., and Thode, A. (2008). "PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans," J. Acoust. Soc. Am. 30(5), 54–62.
- Griffiths, E. T., and Barlow, J. (2015). Equipment Performance Report for the Drifting Acoustic Spar Buoy Recorder (DASBR), NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-543.
- Hastie, T. (**2018**). "GAM: Generalized Additive Models [R package version 1.16]," https://CRAN.R-project.org/package=gam.
- Hildebrand, J. A., Frasier, K. E., Baumann-Pickering, S., Wiggins, S. M., Merkens, K. P., Garrison, L. P., and McDonald, M. A. (2019). "Assessing seasonality and density from passive acoustic monitoring of signals presumed to be from pygmy and dwarf sperm whales in the Gulf of Mexico," Frontiers in Mar. Sci. 6, 66.
- Hodge, L. E., Baumann-Pickering, S., Hildebrand, J. A., Bell, J. T., Cummings, E. W., Foley, H. J., and Waples, D. M. (2018). "Heard but not seen: Occurrence of *Kogia* along the western North Atlantic shelf break," Mar. Mammal Sci. 34, 1141–1153.
- Jefferson, T. A. (1988). "Phocoenoides dalli," Mammalian Species 319, 1–7.
- Kamminga, C., Cohen, S., and Silber, G. K. (1996). "Investigations on cetacean sonar XI: Intrinsic comparison of the wave shapes of some members of the Phocoenidae family," Aquatic Mammals 22, 45–56.
- Keating, J. L., Barlow, J., Griffiths, E. T., and Moore, J. E. (2018). Passive Acoustics Survey of Cetacean Abundance Levels (PASCAL-2016) Final Report. (US Department of the Interior, Bureau of Ocean Energy Management, OCS Study BOEM, Honolulu, HI), 25, 22.
- Koblitz, J. C., Wahlberg, M., Stilz, P., Madsen, P. T., Beedholm, K., and Schnitzler, H. U. (2012). "Asymmetry and dynamics of a narrow sonar beam in an echolocating harbor porpoise," J. Acoust. Soc. Am. 131(3), 2315–2324.
- Kyhn, L. A., Jensen, F. H., Beedholm, K., Tougaard, J., Hansen, M., and Madsen, P. T. (2010). "Echolocation in sympatric Peale's dolphins (Lagenorhynchus australis) and Commerson's dolphins (Cephalorhynchus commersonii) producing narrow-band high-frequency clicks," J. Exp. Biol. 213(11), 1940–1949.
- Kyhn, L. A., Tougaard, J., Beedholm, K., Jensen, F. H., Ashe, E., Williams, R., and Madsen, P. T. (2013). "Clicking in a killer whale habitat: Narrowband, high-frequency biosonar clicks of harbour porpoise (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*)," PloS one 8(5), e63763.
- Lammers, M. O., and Castellote, M. (2009). "The beluga whale produces two pulses to form its sonar signal," Biol. Letters 5(3), 297–301.
- Liaw, A., and Wiener, M. (2002). "Classification and regression by randomForest," R News 2(3), 18–22.
- Ligges, U., Krey, S., Mersmann, O., and Schnackenberg, S. (2018). "tuneR: Analysis of Music and Speech," https://CRAN.R-project.org/ package=tuneR.
- MacLeod, C. D., Reidenberg, J. S., Weller, M., Santos, M. B., Herman, J., Goold, J., and Pierce, G. J. (2007). "Breaking symmetry: The marine

environment, prey size, and the evolution of asymmetry in cetacean skulls," Anatom. Rec. 290(6), 539-545.

- Madsen, P. T., Carder, D. A., Bedholm, K., and Ridgway, S. H. (2005). "Porpoise clicks from a sperm whale nose: Convergent evolution of 130 kHz pulses in toothed whale sonars?," Bioacoustics 15(2), 195–206.
- McAlpine, D. F. (2018). "Pygmy and dwarf sperm whales: Kogia breviceps and K. sima," in Encyclopedia of Marine Mammals (Academic Press, Cambridge, MA), pp. 786–788.
- Merkens, K., Mann, D., Janik, V. M., Claridge, D., Hill, M., and Oleson, E. (2018). "Clicks of dwarf sperm whales (*Kogia sima*)," Mar. Mammal Sci. 34(4), 963–978.
- Merkens, K. P., and Oleson, E. M. (2018). Comparison of high-frequency echolocation clicks (likely Kogia) in two simultaneously collected passive acoustic data sets sampled at 200 kHz and 320 kHz. NOAA Technical Memorandum NMFS-PIFSC-74.
- Moore, P. W., Dankiewicz, L. A., and Houser, D. S. (2008). "Beamwidth control and angular target detection in an echolocating bottlenose dolphin (*Tursiops truncatus*)," J. Acoust. Soc. Am. 124(5), 3324–3332.
- Morisaka, T., and Connor, R. C. (2007). "Predation by killer whales (*Orcinus orca*) and the evolution of whistle loss and narrow-band high frequency clicks in odontocetes," J. Evol. Biol. 20(4), 1439–1458.
- National Marine Fisheries Service, U.S. Department of Commerce (2017). Marine Mammal Health and Stranding Response Database [Data File].
- Pedersen, T. L., Hughes, S., and Qiu, X. (2017). "densityClust: Clustering by Fast Search and Find of Density Peaks [R package version 0.3]," https://CRAN.R-project.org/package=densityClust.
- Pante, E., and Simon-Bouhet, B. (2013). "marmap: A package for importing, plotting and analyzing bathymetric and topographic data in R," PLoS ONE 8(9), 73051.
- Rankin, S., Archer, F., Keating, J. L., Oswald, J. N., Oswald, M., Curtis, A., and Barlow, J. (2017). "Acoustic classification of dolphins in the California Current using whistles, echolocation clicks, and burst pulses," Mar. Mammal Sci. 33(2), 520–540.
- Rodriguez, A., and Laio, A. (2014). "Clustering by fast search and find of density peaks," Science 344(6191), 1492–1496.
- Sakai, T. (2018). "PamBinaries, GitHub repository," https://github.com/ TaikiSan21/PamBinaries.
- Shirihai, H. (2006). Whales, Dolphins, and Seals: A Field Guide to the Marine Mammals of the World (A. and C. Black, London).
- Soldevilla, M. S., Henderson, E. E., Campbell, G. S., Wiggins, S. M., Hildebrand, J. A., and Roch, M. A. (2008). "Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks," J. Acoust. Soc. Am. 124(1), 609–624.
- Starkhammar, J., Moore, P. W., Talmadge, L., and Houser, D. S. (2011). "Frequency-dependent variation in the two-dimensional beam pattern of an echolocating dolphin," Biology Letters 7(6), 836–839.
- Sueur, J., Aubin, T., and Simonis, C. (2008). "Seewave, a free modular tool for sound analysis and synthesis," Bioacoustics 18(2), 213–226.
- Thornton, S. W., Mclellan, W. A., Rommel, S. A., Dillaman, R. M., Nowacek, D. P., Koopman, H. N., and Ann Pabst, D. (2015). "Morphology of the nasal apparatus in pygmy (*Kogia Breviceps*) and dwarf (*K. sima*) sperm whales," Anatomical Record 298(7), 1301–1326.
- Tyack, P. L., and Clark, C. W. (2000). "Communication and acoustic behavior of dolphins and whales," in *Hearing by Whales and Dolphins* (Springer, New York), pp. 156–224.
- Wade, P. R., and Gerrodette, T. (1993). "Estimates of Cetacean Abundance and Distribution in the Eastern Tropical Pacific," Report of the International Whaling Commission 43, 477–493.
- Willis, P. M., and Baird, R. W. (**1998**). "Status of the dwarf sperm whale, Kogia simus, with special reference to Canada," Can. Field. Nat. **112**(1), 114–125.
- Wisniewska, D. M., Ratcliffe, J. M., Beedholm, K., Christensen, C. B., Johnson, M., Koblitz, J. C., Wahlberg, M., and Madsen, P. T. (2015). "Range-dependent flexibility in the acoustic field of view of echolocating porpoises (Phocoena phocoena)," Elife 4, e05651.