A description of echolocation clicks recorded in the presence of True's beaked whale (*Mesoplodon mirus*)

Annamaria Izzi DeAngelis[a)]
Integrated Statistics, under contract to the Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), 166 Water Street, Woods Hole, Massachusetts 02543, USA

Joy E. Stanistreet
Fisheries and Oceans Canada, Bedford Institute of Oceanography, 1 Challenger Drive, Dartmouth, Nova Scotia, B2Y 4A2, Canada

Simone Baumann-Pickering
Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, California 92093-0205, USA

Danielle M. Cholewiak
Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), 166 Water Street, Woods Hole, Massachusetts 02543, USA

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True's beaked whales (*Mesoplodon mirus*) were encountered on two separate shipboard surveys on 24 July 2016 and 16 September 2017 in the western North Atlantic Ocean. Recordings were made using a hydrophone array towed 300 m behind the ship. In 2016, three different groups were sighted within 1500 m of the ship; clicks were recorded for 26 min. In 2017, a single group of five whales was tracked over the course of five hours in which the ship maintained a distance <4000 m from the group. A total of 2938 frequency-modulated (FM) clicks and 7 buzzes were recorded from both encounters. Plausible inter-click-intervals (ICIs) were calculated from 2763 clicks, and frequency and duration measurements were calculated from 2150 good quality FM clicks. The median peak frequencies were 43.1 kHz (2016, $n = 718$) and 43.5 kHz (2017, $n = 1432$). Median ICIs were 0.17 s (2016) and 0.19 s (2017). The spectra and measurements of the recorded clicks closely resemble Gervais's beaked whale clicks (*Mesoplodon europaeus*) and distinguishing between the two species in acoustic data sets proves difficult. The acoustic behavior of True's beaked whales was previously unknown; this study provides a description of echolocation clicks produced by this species. © *2018 Acoustical Society of America*. https://doi.org/10.1121/1.5067379

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I. INTRODUCTION

The beaked whale family (Ziphiidae) comprises some of the most difficult to study marine mammal species in the world. Their preferred habitat spans regions of the continental slope and abyssal plains (MacLeod *et al.*, 2006a), which are often found far from shore. They tend to perform long, deep foraging dives (e.g., Tyack *et al.*, 2006) similar to sperm whales (*Physeter macrocephalus*), which limits the opportunity for visual sightings. The physical characteristics that are used to distinguish between species are subtle and often difficult to observe, even in ideal conditions.

Six beaked whale species are known to live in the North Atlantic Ocean: the northern bottlenose whale (*Hyperoodon ampullatus*), Cuvier's beaked whale (*Ziphius cavirostris*), Blainville's beaked whale (*Mesoplodon densirostris*), Sowerby's beaked whale (*Mesoplodon bidens*), Gervais's beaked whale (*Mesoplodon europaeus*), and True's beaked whale (*Mesoplodon mirus*). Of these North Atlantic beaked whale species, True's beaked whale could be considered the least understood. Most documentation has been from stranded animals, and very little data come from live sightings. The distribution of this species is thought to be antitropical, possibly in deep, relatively warm waters away from the slope (MacLeod *et al.*, 2006a; Aguilar de Soto *et al.*, 2017). Recently, True's beaked whales have been sighted in the Azores and Canary Islands, allowing for a better description of the morphological characteristics that define the species (Aguilar de Soto *et al.*, 2017). Aguilar de Soto *et al.* (2017) noted that the physical features of True's are quite similar to Gervais's, with differences lying in the placement of erupted teeth in males, scar patterning, melon coloration and shape, and a striped pattern along the dorsal side of the body (in Gervais's), all of which may or may not be present in all individuals of a species. As beaked whales are typically observed for relatively short periods of time (minutes) between dives, these subtle differences are often difficult to distinguish.

Much research has been done to acoustically record and understand the characteristics of beaked whale signals.

[a)]Electronic mail: annamaria.deangelis@noaa.gov

Research efforts using animal-borne multi-sensor tags have provided the first data linking the diving and acoustic behavior of some species of beaked whales (Johnson *et al.*, 2004; Tyack *et al.*, 2006). Each beaked whale species in these studies was found to produce echolocation clicks containing a frequency-modulated (FM) upsweep; these echolocation clicks, as well as buzzes, were produced during deep dives (>400 m), which suggest that beaked whales forage during these dives (e.g., Johnson *et al.*, 2004). Stomach content analyses of dead specimens, showing diets of meso- and bathypelagic fish and squid (MacLeod *et al.*, 2003; MacLeod *et al.*, 2006b; Wenzel *et al.*, 2013; Hernandez-Milian *et al.*, 2017), also suggest deep-water foraging. In addition to the use of animal-borne sensors, shipboard surveys that combine visual observations and passive acoustic data collection using single or arrayed hydrophones have facilitated the acoustic characterization of the echolocation clicks of multiple species (e.g., Hooker and Whitehead, 2002; Gillespie *et al.*, 2009; Rankin *et al.*, 2011; Cholewiak *et al.*, 2013).

Utilizing the knowledge from these tag and shipboard studies, Baumann-Pickering *et al.* (2013a) analyzed the presence of FM upsweeps across multiple bottom mounted recorders in the Pacific Ocean and Gulf of Mexico, and applied consistent methodology to characterize the FM upsweeps. These FM upsweeps were found to contain species-specific differences in characteristics such as the peak frequency, upsweep shape, and spectral content, along with differences in the inter-click-interval (ICI). The combination of these characteristics (and others) enables species-specific classification of many beaked whale clicks using passive acoustic data. In recent years, bottom-mounted passive acoustic recorders have been widely deployed in the Atlantic and Pacific Oceans and the Gulf of Mexico (Baumann-Pickering *et al.*, 2014; Hildebrand *et al.*, 2015; Stanistreet *et al.*, 2017). These data can be used to monitor the spatial and temporal distributions of beaked whales, among other species. It is usually possible to discriminate between beaked whale FM click types in these long-term acoustic recordings, but sometimes difficult to attribute those signal types to a particular species since validated recordings in which visual sightings data are collected concurrently with the acoustic data do not exist for all beaked whale species (e.g., McDonald *et al.*, 2009), and there is poor understanding of within-species variability.

FM echolocation clicks produced by North Atlantic beaked whale species have been described using acoustic tags for Cuvier's and Blainville's beaked whales (Johnson *et al.*, 2004; Zimmer *et al.*, 2005), and via shipboard surveys using towed hydrophone arrays for northern bottlenose whales (Hooker and Whitehead, 2002; Wahlberg *et al.*, 2011), Sowerby's beaked whales (Cholewiak *et al.*, 2013), and Gervais's beaked whales (Gillespie *et al.*, 2009). To date, no description exists for echolocation clicks produced by True's beaked whale. In 2016 and 2017, True's beaked whales were encountered on two separate shipboard surveys off Georges Bank in the western North Atlantic Ocean. This study provides the first description of True's beaked whale click characteristics, which can aid in efforts to use passive acoustic monitoring to understand beaked whale species distribution in the North Atlantic Ocean.

II. METHODS

A. Data collection

Acoustic recordings of True's beaked whales were collected during a line-transect cetacean abundance survey in 2016 aboard the National Oceanic and Atmospheric Administration (NOAA) ship *Henry B. Bigelow*, and during a dedicated beaked whale survey in 2017 aboard the research vessel (R/V) *Hugh R. Sharp*. Passive acoustic data were collected using a custom-built hydrophone array towed 300 m behind the vessel. The array included six hydrophone elements with custom-built pre-amplifiers which sampled at 192 kHz, and a depth sensor (Keller America Inc., PA7FLE, Newport News, VA). The depth sensor recorded every 3 s (2016) or 10 s (2017). Acoustic data were routed through a custom-built acoustic recording system. Data were high-pass filtered at 1000 Hz to remove flow noise, and 10 dB gain was added by the acoustic recording system. Signals were acquired using a National Instruments USB-6356 A/D card (Austin, TX), and digitized data were recorded directly to the computer using the software package Pamguard (Gillespie *et al.*, 2008). For the purposes of this study, the last two hydrophone elements were used for detecting beaked whale clicks, and the last hydrophone was used to characterize the detected clicks. This hydrophone was an HTI-96-Min (High Tech, Inc., Long Beach, MS) with a flat frequency response from 1 to 30 kHz (−167 dB re V/μPa ± 1.5 dB). It had a non-linear frequency response across the signal of interest, with an increase in sensitivity of approximately 6 dB from 30 to 70 kHz, which was corrected for during the analysis using custom-written scripts in the program MATLAB (R2017a; MathWorks, Inc., Natick, MA). For further details on array design, see DeAngelis *et al.* (2017).

The 2016 survey occurred from 27 June to 25 August along saw-tooth tracklines spanning 100–4500 m water depths in the western North Atlantic Ocean between 36° and 42° N and 65° and 74° W (Palka *et al.*, 2016). There were two teams of visual observers located on upper and lower decks of the ship, following standard double platform line-transect survey protocols as described in Cholewiak *et al.* (2013). Each observation team was equipped with two sets of high-powered Fujinon binoculars (25 × 150; Fujifilm, Valhalla, NY) and hand-held (10 × 50 or 8 × 42) binoculars. Observers recorded all sightings of marine mammals and sea turtles including information on species, group size, and behavior. Observers also recorded environmental conditions every 30 min and did not operate in sea states greater than Beaufort 6. The towed hydrophone array was monitored by a team of trained acousticians, and was deployed primarily during daylight hours [06:00–18:00 Eastern daylight time (EDT)]. Survey speed was 18–19 km/h and was reduced to 13 km/h during the True's beaked whale encounter. An encounter was defined as the time of the first sighting until the time of the last sighting, or until the ship moved out of the estimated acoustic detection range of the last sighting (~4 km; Zimmer *et al.*, 2008).

In contrast to the 2016 line-transect survey, the 2017 survey was designed to collect fine-scale data on beaked whale distribution and behavior. The survey occurred from 8 to 18 September, covering the region between 38° and 40° N and 67° and 75° W. A single visual observer team was equipped with two Fujinon binoculars (25 × 150) and hand-held (10 × 50 or 8 × 42) binoculars. During exploratory search phases, the observation team was typically comprised of three observers, two of whom scanned from the bow of the ship to 90° port and starboard, while one observer scanned the trackline and recorded data. Survey speed during exploratory phases was 15 km/h. When beaked whales were sighted and the decision was made to initiate focal follow data collection, observer effort changed substantially. Survey speed was reduced to 7–8 km/h or less when tracking a group, and up to five observers scanned 360° around the vessel while collecting detailed data on group surfacings and movements. When conditions allowed, a rigid-hulled inflatable boat was deployed with 3–4 team members on board to collect identification photographs and additional data (e.g., behavioral data, water samples, etc.). A passive acoustics team monitored the towed hydrophone array near-continuously during daytime hours.

B. Acoustic analysis

1. FM clicks

The 2016 data set was post-processed using Pamguard version 1.15.10 with a sixth-order bandpass Butterworth pre-filter from 16 to 90 kHz and a click detector trigger threshold at 10 dB from 20 to 90 kHz. The 2017 data set was processed in Pamguard version 1.15.11 using the same settings, except the trigger threshold was reduced to 8 dB, and the detector was run in real-time as opposed to in post-processing time. Pamguard's bearing-time plot was used to manually identify click trains using a 2 min page window, and the waveform, click spectrum, Wigner-Ville plot, and concatenated spectrogram plots were used to distinguish beaked whale clicks from delphinid clicks, as well as to distinguish between beaked whale species. Within the bearing-time plot, consecutive clicks along the same bearing were grouped together as click trains, and click trains that followed a similar change in bearing over time were grouped together as events (DeAngelis *et al.*, 2017). These events were then localized using the Pamguard Target Motion module's two-dimensional (2D) simplex optimisation algorithm to provide an approximate location of the echolocating group.

Once beaked whale FM clicks were identified in Pamguard, the time series for each detected click, as well as metadata such as the date and time the click was detected, were extracted from Pamguard's binary files using scripts written by the Sea Mammal Research Unit in MATLAB.[1] A signal-to-noise ratio (SNR) threshold detector (Zimmer, 2011) was applied to each detection to extract the part of the click that exceeded the threshold plus 20 sample points (0.104 ms) on either side. The Teager-Kaiser energy detector (Soldevilla *et al.*, 2008; Roch *et al.*, 2011) was then used to identify poor quality clicks. Clicks that did not meet the Teager-Kaiser's adjusted energy threshold for towed array data (35th percentile) were discarded from the analysis. For each click, frequency measurements including the peak frequency, −10 dB upper and lower frequency bounds and −10 dB bandwidth were calculated (*sensu* Au, 1993). The duration of each click was measured based on the Teager-Kaiser energy detector. These measurements were then pooled at an encounter level to determine the median, 10th, and 90th percentiles. Click spectra were computed following methods described in Baumann-Pickering *et al.* (2013a). Clicks from both encounters were pooled to create an overall mean click power spectrum for the species, which was then normalized to the maximum and minimum spectral values, and compared to example spectra from other North Atlantic beaked whale species (Baumann-Pickering *et al.*, 2013a; Cholewiak *et al.*, 2013).

For each event, ICIs from all detected and verified clicks (including poor quality clicks that were rejected from frequency measurements) were calculated using the click start times reported from Pamguard. Grouping click trains that were received on different bearings into separate events (DeAngelis *et al.*, 2017) and calculating ICIs for each event reduced the likelihood of including false ICI measurements due to overlapping click trains. In some cases multiple click trains were received on the same bearing. Every effort was made to separate these events into individual click trains to avoid measuring false ICIs. ICIs > 0.8 s were discarded from analysis, as the largest known ICI range for beaked whales has been reported to be 0.4–0.6 s for Cuvier's, while ICIs for other mesoplodont species are typically 0.2–0.4 s or less (Zimmer *et al.*, 2005; Baumann-Pickering *et al.*, 2013a; Stanistreet *et al.*, 2017). ICIs were then pooled at the encounter level and binned into 0.01 s intervals to create a histogram and identify the modal bin value. The median, 10th, and 90th percentiles were also calculated.

2. Buzz clicks

A buzz was defined as a sequence of non-FM clicks that had ICIs < 0.1 s (Johnson *et al.*, 2006, 2008). Recordings were examined for buzz clicks during times when FM clicks were present using the waveform and spectrogram views in the software Raven Pro 1.5 (Bioacoustics Research Program, 2014). The hydrophone with the strongest SNR was used. Spectrograms were viewed with a window length of 5 s, 1024 point fast Fourier transform (FFT; 5 ms) with a 50% overlap, brightness of 60, and contrast of 65. Once buzzes were identified, they were subjected to both a manual and semi-automated review. For the manual review, a bandpass filter from 28 to 60 kHz was applied in Raven to best view the individual pulses without truncating the energy of the buzz. The number of clicks within a buzz was manually counted in the waveform view with a window length of 0.3 s. A manual buzz duration was measured in the waveform as the time between the peak of the first buzz click to the peak of the last buzz click. To extract the buzz ICI, a semi-automated review was conducted. Sound clips containing just the buzz found in the manual review were imported into MATLAB, where an energy detector was applied with a manually set threshold just above the background noise of each individual buzz sequence. Any detections above the detector threshold that occurred within 50 μs of a click were rejected to eliminate false positives. The detections were then verified using WaveSurfer 1.8.8 (Sjölander and Beskow, 2000), where any remaining false detections were eliminated (i.e., transient signals, multipath reflections). The number of detected clicks per buzz was recorded along with the detected buzz duration (time between the first detected and last detected click) and buzz ICI (time interval between detected clicks).

III. RESULTS

A. 2016 True's encounter

On 24 July 2016, visual observers aboard the NOAA ship *Henry B. Bigelow* sighted three groups of True's beaked whales at 40 46.785′ N, 66 34.467′ W (Fig. 1). Sea state was a high Beaufort 4. Groups A and B were sighted at 14:24 EDT, consisted of two and three individuals, and were located approximately 1170 and 730 m away from the ship, respectively [Fig. 2(a)]. Group C was sighted at 14:30 EDT and consisted of one individual located approximately 710 m away from the ship [Fig. 2(a)]. All three groups were seen at the surface for <2 min. Multiple observers saw the three groups and reported features that are consistent with what is known of True's beaked whales, including pale melons, a short rostrum, and a lack of a dorsal stripe on the individuals in groups A and C. These characteristics were difficult to identify in individuals of group B as that group was sighted only by observers on the lower platform, where sighting conditions were more adversely affected by the sea state. No photographs of the animals were taken. Other species sighted in the area were a single sperm whale and an unidentified *Mesoplodon* species, both 7 min before the encounter (4000 m and 2161 m away, respectively). After the three groups of True's beaked whales were sighted, the ship turned 180° to run the trackline in the reverse direction at a slower speed of 13 km/h to attempt to record echolocation clicks [Fig. 2(a)]. During this time the array was at a mean depth of 8 ± 3 m. FM clicks and buzzes were detected on the hydrophone array 7 min after Group C was sighted, and were recorded near-continuously over the next 26 min. The ship made another 180° turn after traveling 3000 m in the opposite direction of the original break in trackline [Fig. 2(a)]. FM clicks and buzzes were no longer detected once the ship returned to the point of the initial turn. Click trains were acoustically localized near the three groups of True's beaked whales that were sighted, and did not appear to originate from the location of the unidentified *Mesoplodon* species sighting.

A total of 882 FM clicks were detected during the 26 min period.[2] Of those, 769 FM clicks had ICIs < 0.8 s, and 718 FM clicks met the energy threshold for the Teager-Kaiser energy detector and were therefore used for frequency and time measurements. A total of four buzzes were recorded during the 26 min period, all of which were of good enough quality to be analyzed.

B. 2017 True's encounter

On 16 September 2017 one group of five True's beaked whales (including 1–2 small animals, potentially calves or juveniles) was sighted at 13:58 EDT at 39 56.098′ N 67 33.631′ W within the Northeast Canyons and Seamounts Marine National Monument (Fig. 1). The initial sea state was a Beaufort 2, and multiple observers using big-eye binoculars were able to confirm the presence of a pale melon and the lack of any apparent stripes on the body. Ship speed was reduced to 4–7 km/h to allow observers to visually track the animals. Over the course of the next five hours, sea state conditions improved to Beaufort 0, and the ship maintained a position 1000–4000 m distant from the group [Fig. 2(b)].

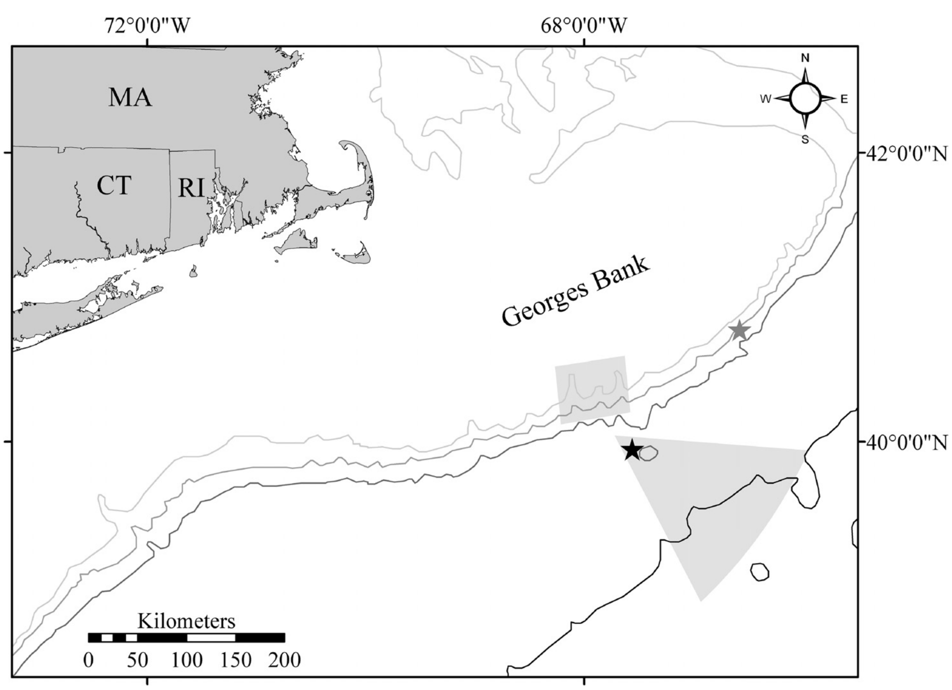

FIG. 1. Locations of 2016 (grey star) and 2017 (black star) encounters with True's beaked whales. The Northeast Canyons and Seamounts Marine National Monument is highlighted in light grey and the 200 m, 1000 m, 2000 m, and 4000 m depth contours are shown as thin lines from light (200 m) to dark (4000 m).

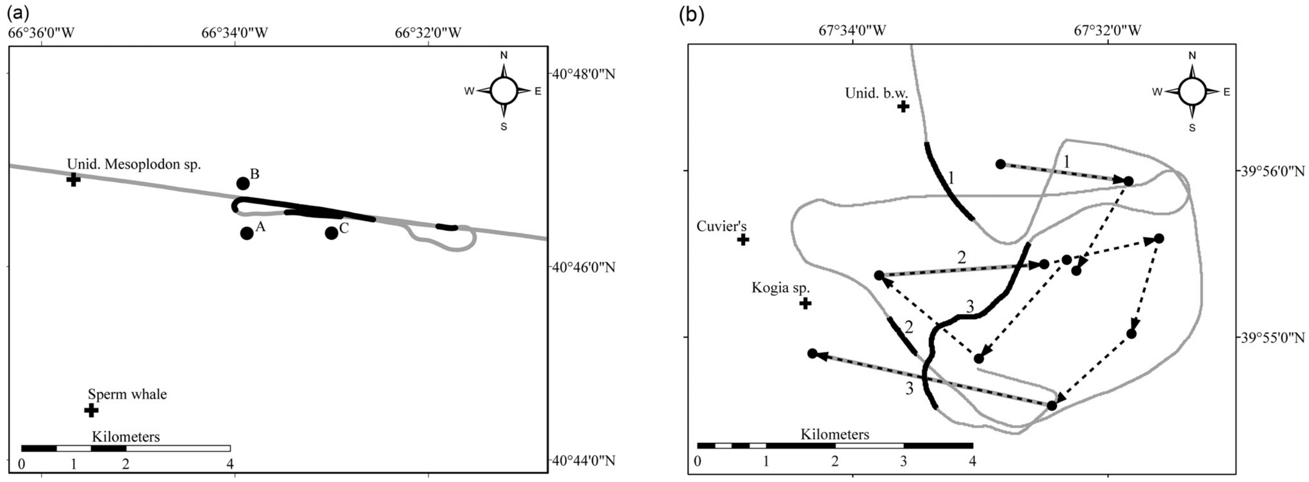

FIG. 2. Detailed view of the ship's track during the 2016 encounter with True's beaked whales (a), where grey indicates times when no beaked whale clicks were detected, and black indicates times when clicks were detected. The three groups of True's beaked whales are shown as circles and are labeled by their group identification (ID). Other species sighted are shown as crosses. A detailed view of the 2017 encounter with a single group of True's beaked whales with the ship's track is shown as a solid line (b). Grey tracklines indicate periods when no beaked whale clicks were detected; black sections of trackline represent periods when clicks were detected, and have been numbered in chronological order. Sequential surfacings of the focal group of True's beaked whales are shown as circles, and the dashed lines show the straight line path between these sightings. For these straight line paths, presumed foraging dives are highlighted in grey and also numbered to match the corresponding section of trackline. Other sightings are shown as crosses.

Verification photographs were collected by observers on the ship, as well as by a separate team of observers operating in a rigid-hulled inflatable boat on the water. The group of True's beaked whales was observed across ten dives during this time. On three of those dives, FM clicks were detected on the towed array 4–11 min after the group was last sighted at the surface and the ship was between 600 and 2400 m from the previous sighting during clicking periods [Fig. 2(b)]. The duration of the three acoustic periods ranged from 6 to 16 min, for a total of 37 min with echolocation clicks. During this time, due to the slow movement of the ship, the array was at a mean depth of 43 ± 13 m.

One group of five unidentified beaked whales was sighted 18 min before the focal group of True's beaked whales. At the start of the encounter, 25 FM clicks were detected for <1 min from a different bearing from that of the focal group. These clicks were not included in further analysis since they clearly did not come from the focal group. Other species sighted during this time were an unidentified *Kogia* species and Cuvier's beaked whale(s). Cuvier's beaked whale clicks were also detected during the encounter and were not examined in this analysis. Common dolphins (*Delphinus* sp.) were sighted for 29 min before the encounter, but were not sighted for 11 min before the start of the encounter.

A total of 2056 FM clicks were detected during all 3 foraging dives, with the most clicks recorded on the third dive (1164 clicks). Of the 2056 FM clicks, 1994 FM clicks had ICIs < 0.8 s, and 1432 FM clicks met the Teager-Kaiser energy threshold and were therefore used for frequency and time measurements. A total of three buzzes were recorded, one on the second dive and two on the third dive. The buzz on the second dive was of poor quality and was not analyzed.

C. FM click characteristics

An exemplar FM click recorded in the presence of True's beaked whales is shown in Fig. 3. The median peak frequency was 43.1 kHz (40.5 kHz and 47.6 kHz, 10th and 90th percentiles, respectively) for clicks recorded in the 2016 encounter and 43.5 kHz (37.5 kHz and 49.5 kHz, 10th and 90th percentiles, respectively) for clicks recorded in

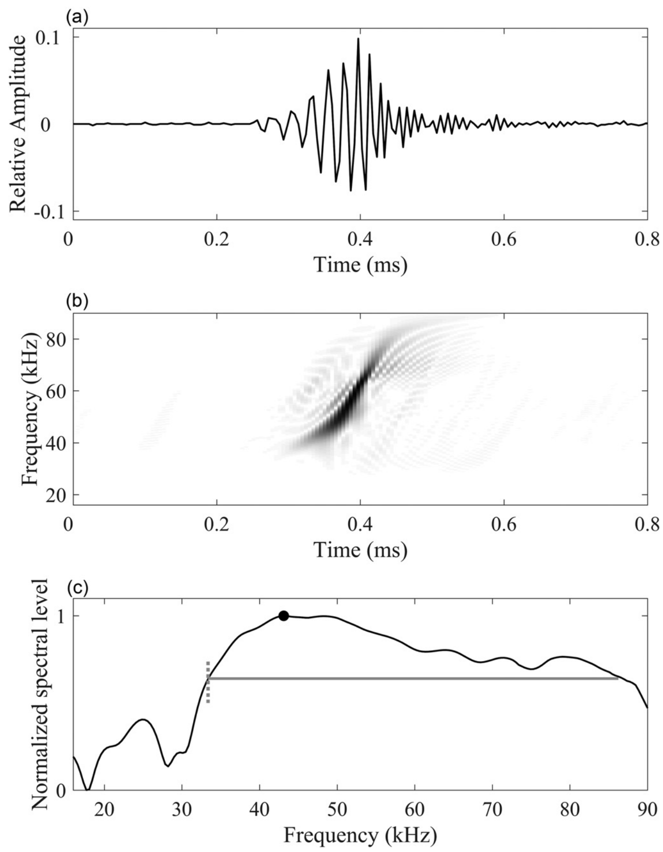

FIG. 3. Exemplar click recorded during the 2017 encounter with True's beaked whales shown as the waveform (a), Wigner-Ville plot (b), and normalized power spectrum (c). The peak frequency in the power spectrum is denoted by the circle, the −10 dB lower frequency bound is denoted by a dashed line, and the −10 dB bandwidth is shown as a solid grey line.

TABLE I. Characteristics of True's beaked whale FM clicks recorded during the two encounters in this study. All measurements are reported as medians with 10th and 90th percentiles in parentheses.

	2016 encounter	2017 encounter
Sample size (time and frequency measurements)	718	1432
Peak frequency (kHz)	43.1 (40.5, 47.6)	43.5 (37.5, 49.5)
−10 dB lower endpoint (kHz)	34.5 (31.5, 37.9)	34.5 (30.4, 40.5)
−10 dB bandwidth (kHz)	19.5 (14.6, 31.1)	20.6 (9.4, 32.3)
Duration (us)	239 (183, 344)	271 (198, 390)
Sample size (ICI)	769	1994
ICI (s)	0.17 (0.15, 0.23)	0.19 (0.13, 0.38)

2017 (Table I). The median −10 dB lower frequency bound was the same in both encounters (34.5 kHz). The higher frequency is less consistent than the lower frequency due to the influences of absorption and directionality of the signal; therefore, the upper −10 dB frequency bound is not reported here. The modal ICI bin was 0.16–0.17 s in 2016 and 0.18–0.19 s in 2017 (Fig. 4). The modal ICI corresponded well with the median ICI, which was 0.17 s (0.15 s and 0.23 s, 10th and 90th percentiles, respectively) and 0.19 s (0.13 s and 0.38 s, 10th and 90th percentiles, respectively), respectively (Table I).

When all clicks recorded in both encounters were combined, the resulting mean spectrum was different from click spectra previously reported for other North Atlantic beaked whale species, occupying a frequency range between reported Gervais's beaked whale and Sowerby's beaked whale click spectra (Fig. 5). The mean spectrum calculated for True's beaked whale clicks is most similar to the mean spectrum for Gervais's clicks described by Baumann-Pickering *et al.* (2013a). It should be noted that the Gervais's clicks reported in Baumann-Pickering *et al.* (2013a) were not confirmed by visual sightings since they were collected with long-term bottom-mounted recorders, but had characteristics matching the visually confirmed data reported in Gillespie *et al.* (2009), thus are presumed to belong to Gervais's beaked whale. ICIs were shorter for True's FM click trains than reported for Gervais's (Fig. 4). The frequency characteristics of True's clicks recorded in both years overlapped with the range of values reported for Gervais's in Baumann-Pickering *et al.* (2013a).

D. Buzz click characteristics

Buzzes with the highest SNR were recorded on a hydrophone in which the full frequency response was unknown; therefore, frequency measurements were not calculated for buzz clicks. An example buzz sequence from the 2016 encounter is shown in Fig. 6. Buzzes were sometimes seen following a FM click train, although not always (three out of seven times). Characteristics of six buzz sequences can be found in Table II. The number of clicks manually counted per buzz sequence ranged from 48 to 586 clicks. The detector was unable to detect all the clicks that were manually counted, predominantly missing clicks located at the beginning of the buzz sequence in four out of six sequences, although in one case it also missed clicks in discrete sections toward the end of the buzz (2017 encounter buzz 2). This meant that the durations calculated using the detector were smaller than the manually derived durations. Durations of buzz sequences calculated manually ranged from 0.17 s to 1.94 s. Median buzz ICIs calculated using the detector ranged from 3.0 ms (2016 encounter buzz 4, 10th = 2.7 ms, 90th = 4.3 ms) to 5.3 ms (2016 encounter buzz 2, 10th = 4.7 ms, 90th = 5.6 ms). All but one buzz sequence exhibited a decrease in buzz ICI over the length of the buzz (Fig. 7). The beginning ICI ranged from ~5.0 ms to ~10.5 ms in these cases, and decreased to as small as 2.6 ms

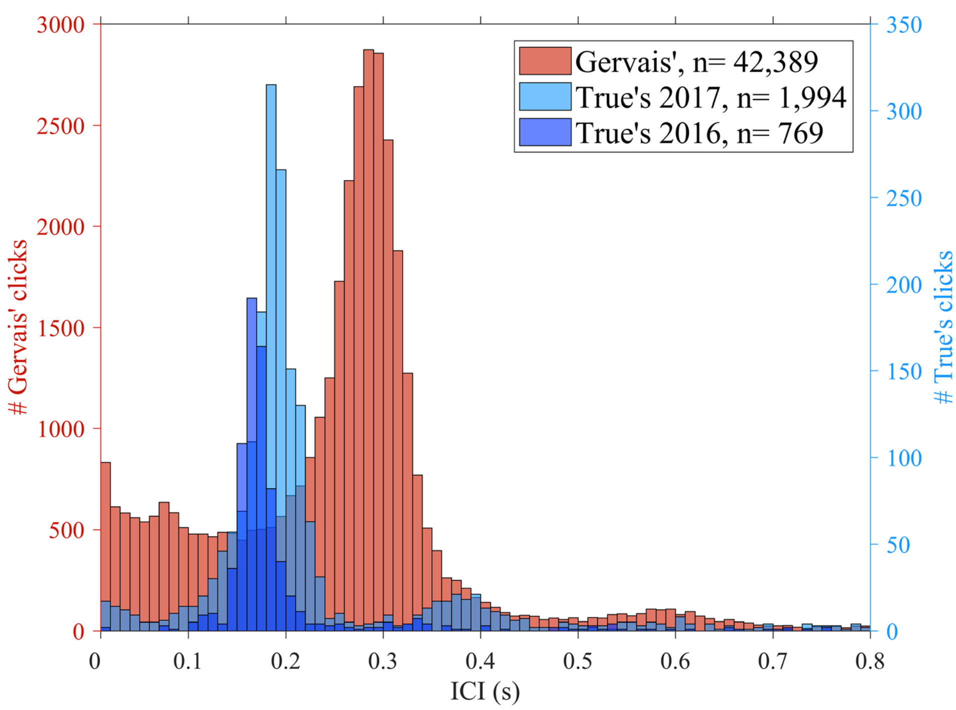

FIG. 4. (Color online) ICIs of True's beaked whale clicks recorded in this study (light blue = 2016 and dark blue = 2017) and presumed Gervais's beaked whale clicks recorded in Baumann-Pickering *et al.* (2013a; orange). Note the different *y* axes values for each species.

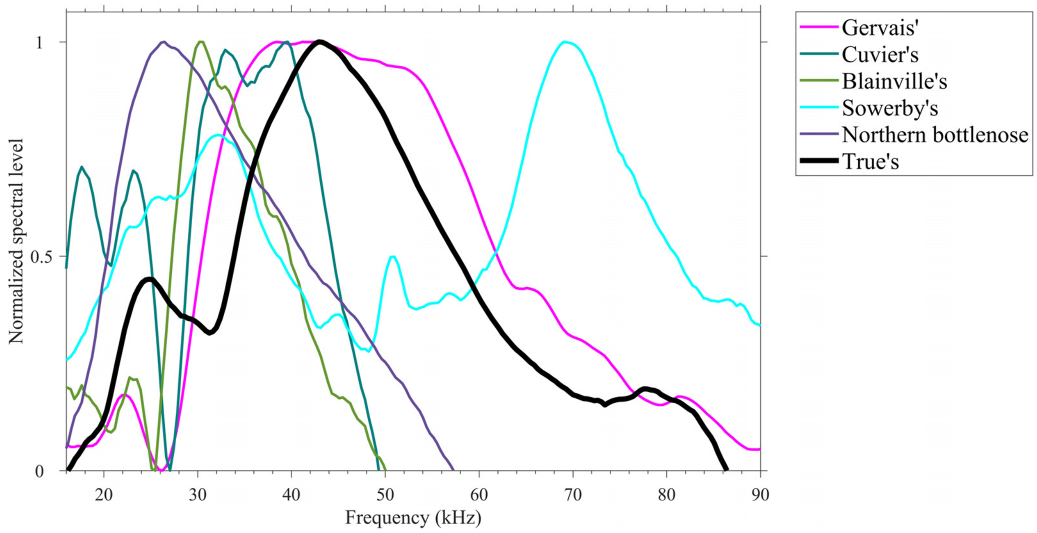

FIG. 5. (Color online) Power spectral densities of all North Atlantic beaked whale species normalized to the same spectral scale. Example spectra for Cuvier's, Gervais's, and Blainville's beaked whale clicks come from data reported in Baumann-Pickering *et al.* (2013a) from bottom-mounted recorders; the example spectrum for northern bottlenose whale clicks comes from data collected in The Gully, Nova Scotia, using bottom-mounted recorders, and the example spectrum for Sowerby's beaked whale clicks come from the "high" click subset reported in Cholewiak *et al.* (2013) from a towed hydrophone array.

by the end of a buzz. The one buzz sequence that did not follow this pattern (2016 encounter buzz 3) started with an ICI of ~3.5 ms and ended with an ICI of ~8.5 ms.

IV. DISCUSSION

Recordings collected in both 2016 and 2017 contained clicks that were recorded in the presence of True's beaked whales. In 2016, the presence of multiple beaked whale groups close to the ship provided good evidence that the recorded clicks came from at least one of the three groups. Additionally, the acoustic localizations of click trains during this encounter were closer to the three groups of True's than to the unidentified *Mesoplodon* species that was sighted 7 min prior to the encounter. With a sea state of Beaufort 4 during the 2016 encounter, it is possible that other groups of beaked whales were present but visually missed due to the unfavorable sea state. During the 2017 encounter, conditions were better suited for sighting beaked whales (initially a Beaufort 2, decreasing to a Beaufort 0), and a single group of True's beaked whales was tracked for ~5 h. All of the FM clicks recorded in 2017 occurred during dives that were approximately 40 min long, and no clicks were recorded from the focal group during shorter dives (~17 min between surfacings). The occurrence of FM clicks during these longer dives is consistent with data collected via tags deployed on Cuvier's and Blainville's beaked whales (Tyack *et al.*, 2006), where clicking corresponded to foraging activity (Johnson *et al.*, 2004, 2006; Madsen *et al.*, 2005). Combined visual and acoustic data from these two separate encounters with True's

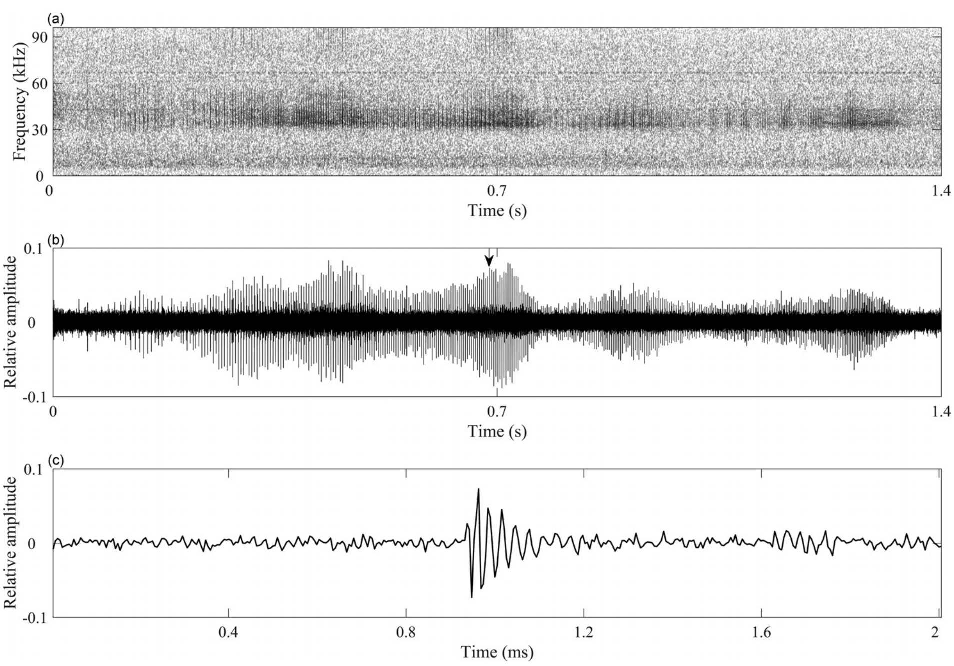

FIG. 6. Example buzz sequence shown as the spectrogram (a), waveform (b), and the waveform of a single click within the sequence (c). The arrow in (b) indicates the click shown in (c). Note that the *x* axis in (c) is on a different scale.

TABLE II. Characterization of buzz click sequences recorded during the two encounters in this study. Number of clicks per buzz and duration of buzz were calculated manually and using a click detector. Buzz ICIs are reported as medians with 10th and 90th percentiles in parentheses.

	nClicks manual	nClicks detector	Manual buzz duration (s)	Detected buzz duration (s)	Buzz ICI (ms)
2016 buzz 1	272	242	0.98	0.89	3.469 (2.883, 4.617)
2016 buzz 2	98	87	0.50	0.45	5.287 (4.731, 5.636)
2016 buzz 3	48	35	0.24	0.17	4.475 (3.506, 7.474)
2016 buzz 4	388	381	1.31	1.26	3.000 (2.700, 4.306)
2017 buzz 1	186	140	0.70	0.53	3.521 (3.174, 4.839)
2017 buzz 2	586	376	2.43	1.94	4.344 (3.172, 6.672)

beaked whales in 2016 and 2017 provide clear evidence that the clicks described in this study were produced by True's beaked whales.

Six buzz sequences recorded in the presence of True's beaked whales were analyzed, and five demonstrated a patterned decrease in buzz ICI similar to what has been measured for Blainville's beaked whales (Johnson *et al.*, 2006). The initial buzz ICI could not be compared between this study and those reported for Blainville's in other studies as the start of the buzz sequence was difficult to find in many cases when multiple whales were clicking, and the energy detector used in this study missed the beginning in almost all cases. Buzz 4 from the 2016 encounter exhibited a rapid change in initial ICI, similar to that noted by Johnson *et al.* (2006) and Johnson *et al.* (2008), where the buzz ICI rapidly changed from ~10 ms to ~4.5 ms in the first 0.2 s. Beaked whale clicks were likely recorded from multiple individuals within a group, and it is likely that snippets of FM click trains and buzzes, rather than entire click sequences, were

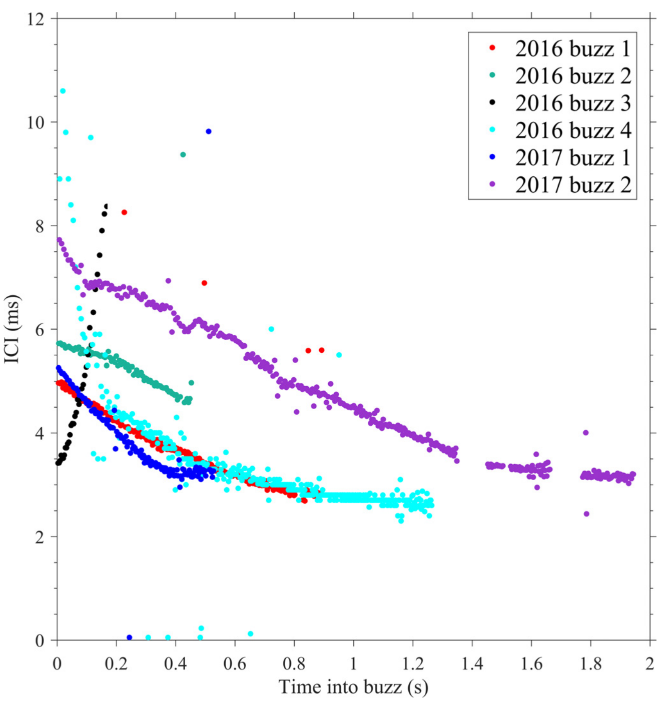

FIG. 7. (Color online) Change in buzz ICI for the six buzzes that were analyzed between the two True's beaked whale encounters.

recorded from multiple animals. Buzz 3 from the 2016 encounter exhibited a different pattern from the other measured buzz sequences with an increase in ICI. This was also the shortest buzz in the sample, with the fewest clicks. It is possible that only the end of the buzz sequence was recorded, or this buzz was used for social communication rather than foraging. Social communication in beaked whales is poorly understood, but burst pulses, non-FM clicks, and tonal sounds have been documented from multiple species (Dawson and Ljungblad, 1998; Rankin and Barlow, 2007; Aguilar de Soto *et al.*, 2011; Rankin *et al.*, 2011).

Given that most beaked whale species seem to have fairly distinct species-specific click characteristics (e.g., Baumann-Pickering *et al.*, 2013a), it is interesting that among North Atlantic beaked whale species, True's beaked whale clicks closely resemble clicks attributed to Gervais's beaked whales. This similarity also exists in the morphological characteristics of these two species; Aguilar de Soto *et al.* (2017) identified the two species as strikingly similar. Baumann-Pickering *et al.* (2013a) hypothesized that there may be a relationship between body size and peak frequency of echolocation clicks for beaked whales. A weak correlation was found between the maximum body size and the centroid frequency of signals from beaked whales with known echolocation click descriptions, although this relationship appeared to be heavily influenced by Baird's beaked whale (*Berardius bairdii*). The data in this paper do not seem to support this hypothesis; among the beaked whale species in the North Atlantic Ocean, True's, Gervais's, and Sowerby's beaked whales are all of similar size, yet Sowerby's produce much higher-frequency echolocation clicks than the other two species. A phylogenetic study by Dalebout *et al.* (2008) suggested that True's and Gervais's beaked whales are sister taxa, and Sowerby's beaked whale is more distantly related. This could be a contributor to the greater similarity between True's and Gervais's echolocation and morphological traits. The evolutionary drivers behind echolocation behavior and acoustic signal characteristics in beaked whales are unknown, but may include physiological or environmental factors. How prey selection has influenced frequency content in echolocation clicks, for example, is unclear. Ecological niche separation has been examined between *Mesoplodon* sp., Cuvier's beaked whale, and *Hyperoodon* sp., but not within the genus *Mesoplodon* (MacLeod *et al.*, 2003) as most aspects of the biology and ecology of beaked whale species remain unknown.

The high directionality of beaked whale clicks presents a challenge when towing an array above a whale that is infrequently oriented toward the surface, resulting in a low probability that on-axis clicks will be recorded. Beaked whale clicks recorded off-axis tend to vary in frequency characteristics more than on-axis clicks. Shaffer *et al.* (2013) reported that the off-axis clicks of Blainville's beaked whales were longer in duration, narrower in −3 dB bandwidth, and lower in centroid frequency and apparent source level than on-axis clicks. Baumann-Pickering *et al.* (2013b) compared recordings of Baird's beaked whales collected with a towed array to recordings collected on a bottom-mounted high-frequency acoustic recording package

(HARP) and found that the peak frequency on the highest frequency click subtype (IV) was higher on the HARPs than the towed array. This subtype falls in a similar frequency range to clicks recorded from True's and Gervais's beaked whales in the North Atlantic and Gulf of Mexico, respectively. When comparing click spectra of True's clicks recorded with a towed hydrophone array (this study) and clicks classified as Gervais's recorded with bottom-mounted recorders (Baumann-Pickering *et al.*, 2013a), there are many similarities between the FM click measurements. Assuming that most of the clicks recorded in this study are off-axis, it is possible that mostly off-axis True's FM clicks may be indistinguishable from combined on- and off-axis Gervais's FM clicks. Peak frequency may be useful to describe clicks in a general sense, but for signals that have a relatively flat peak across a broad frequency range (e.g., True's and Gervais's beaked whale clicks) it can be considered a poor metric to use alone. The overall shape of the click spectra and the -10 dB lower frequency bound will be more informative in differentiating between beaked whale species. ICI will also be a better metric to use as it is not as influenced by the effects of signal propagation and click directionality. While there is overlap between the distributions of ICIs reported for the two species, the median ICIs were quite different with True's beaked whale clicks generally having a lower ICI (Fig. 4). It should be noted that the sample size used to calculate the ICI of True's clicks (this study) was 6.5% of the sample size used to calculate the ICI of presumed Gervais's clicks (Baumann-Pickering *et al.*, 2013a), therefore, it would be beneficial to obtain a larger sample size of True's clicks to assess whether this difference in ICI is consistent.

Much focus has been placed on interspecific differences in beaked whale echolocation clicks, but it is also important to consider intraspecific variation. Keating *et al.* (2016) examined FM clicks emitted by a group of Blainville's beaked whales and found shifts in frequency measurements such as peak frequency, center frequency, and -10 dB bandwidth within an encounter. Without acoustic localization and visual confirmation of the species identification, the authors state that the significant differences in frequency measurements would have led them to attribute those clicks to a new beaked whale species. Data from this study demonstrate that True's beaked whale clicks could easily be misidentified as Gervais's beaked whale clicks since the differences in click characteristics between the species may fall within the range of intraspecific variation. These results highlight the importance of quantifying both inter- and intraspecific variation. With limited data on True's beaked whales, it is hard to understand the level of intraspecific variation based on this study alone. More data are needed to better understand the individual level of variation in beaked whale signals.

The presumed Gervais's beaked whale clicks discussed as a point of comparison in this study were collected without associated visual sightings data, however, they do match characteristics of visually verified clicks recorded from Gervais's beaked whales by Gillespie *et al.* (2009). True's beaked whales have not been found in the Gulf of Mexico (MacLeod *et al.*, 2006a) where Baumann-Pickering *et al.* (2013a) recorded presumed Gervais's beaked whale clicks. Multiple Gervais's beaked whale strandings have been recorded in the Gulf of Mexico, whereas there are neither strandings nor sightings of True's in the Gulf of Mexico. However, species uncertainty remains in datasets collected without other forms of species confirmation (such as visual sightings or genetics), and it is possible that the clicks recorded by Baumann-Pickering *et al.* (2013a) may not be solely produced by Gervais's beaked whales, or may not be representative of Gervais's beaked whale clicks in the North Atlantic. Little is known about possible regional differences in echolocation clicks within the same beaked whale species.

This study contributes to a growing body of knowledge on beaked whale acoustic behavior. With the description provided in this study, an initial acoustic characterization has now been provided for all beaked whale species that are known to live in the North Atlantic Ocean. However, our results indicate a broad overlap in acoustic characteristics between True's and Gervais's beaked whale clicks. Uncertainty in species classification will exist in data collected without visual species confirmation in regions where both species are present, at least until future studies are able to further quantify the degree of inter- and intraspecific variation, along with any differences due to recording platform (e.g., towed array and bottom-mounted recorders). Despite these challenges, this study contributes valuable information for passive acoustic monitoring of beaked whales. With large-scale monitoring programs that can describe broad patterns in beaked whale occurrence (e.g., Stanistreet *et al.*, 2017) and the development of methodologies to estimate density based on acoustic presence data (e.g., Küsel *et al.*, 2011), passive acoustic monitoring continues to fill data gaps for many beaked whale species.

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[1]Available at https://conservationcoding.com/2017/09/10/the-new-pamguard-matlab-library/ (Last viewed January 30, 2018).

[2]See supplementary material at https://doi.org/10.1121/1.5067379 for a sound clip containing True's FM clicks and a buzz recorded from the HTI-96-Min (High Tech, Inc., Long Beach, MS).

Aguilar de Soto, N., Madsen, P. T., Tyack, P., Arranz, P., Marrero, J., Fais, A., Revelli, E., and Johnson, M. (**2011**). "No shallow talk: Cryptic strategy in the vocal communication of Blainville's beaked whales," Mar. Mammal Sci. **28**(2), E75–E92.

Aguilar de Soto, N., Martín, V., Silva, M., Edler, R., Reyes, C., Carrillo, M., Schiavi, A., Morales, T., García-Ovide, B., Sanchez-Mora, A., Garcia-Tavero, N., Steiner, L., Scheer, M., Gockel, R., Walker, D., Villa, E.,

Szlama, P., Eriksson, I. K., Tejedor, M., Perez-Gil, M., Quaresma, J., Bachara, W., and Carroll, E. (**2017**). "True's beaked whale (*Mesoplodon mirus*) in Macaronesia," PeerJ **5**, 3059.
Au, W. W. L. (**1993**). *The Sonar of Dolphins* (Springer, New York).
Baumann-Pickering, S., McDonald, M. A., Simonis, A. E., Solsona Berga, A., Merkens, K. P. B., Oleson, E. M., Roch, M. A., Wiggins, S. M., Rankin, S., Yack, T. M., and Hildebrand, J. A. (**2013a**). "Species-specific beaked whale echolocation signals," J. Acoust. Soc. Am. **134**, 2293–2301.
Baumann-Pickering, S., Roch, M. A., Brownell, R. L., Jr., Simonis, A. E., McDonald, M. A., Solsona-Berga, A., Oleson, E. M., Wiggins, S. M., and Hildebrand, J. A. (**2014**). "Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific," PLoS One **9**, e86072.
Baumann-Pickering, S., Yack, T. M., Barlow, J., Wiggins, S. M., and Hildebrand, J. A. (**2013b**). "Baird's beaked whale echolocation signals," J. Acoust. Soc. Am. **133**, 4321–4331.
Bioacoustics Research Program. (**2014**). *Raven Pro: Interactive Sound Analysis Software* (The Cornell Lab of Ornithology, Ithaca, NY).
Cholewiak, D., Baumann-Pickering, S., and Van Parijs, S. (**2013**). "Description of sounds associated with Sowerby's beaked whales (*Mesoplodon bidens*) in the western North Atlantic Ocean," J. Acoust. Soc. Am. **134**, 3905–3912.
Dalebout, M. L., Steel, D., and Baker, C. S. (**2008**). "Phylogeny of the beaked whale genus *Mesoplodon* (Ziphiidae: *Cetacea*) revealed by nuclear introns: Implications for the evolution of male tusks," Syst. Biol. **57**, 857–875.
Dawson, S., and Ljungblad, D. (**1998**). "Sounds recorded from Baird's beaked whale, *Berardius bairdii*," Mar. Mammal Sci. **14**, 335–344.
DeAngelis, A. I., Valtierra, R., Van Parijs, S. M., and Cholewiak, D. (**2017**). "Using multipath reflections to obtain dive depths of beaked whales from a towed hydrophone array," J. Acoust. Soc. Am. **142**, 1078–1087.
Gillespie, D., Dunn, C., Gordon, J., Claridge, D., Embling, C., and Boyd, I. (**2009**). "Field recordings of Gervais' beaked whales *Mesoplodon europaeus* from the Bahamas," J. Acoust. Soc. Am. **125**, 3428–3433.
Gillespie, D., Mellinger, D. K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X. Y., and Thode, A. (**2008**). "PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans," Proc. Inst. Acoust. **30**, 54–62.
Hernandez-Milian, G., Lusher, A., O'Brian, J., Fernandez, A., O'Connor, I., Berrow, S., and Rogan, E. (**2017**). "New information on the diet of True's beaked whale (*Mesoplodon mirus*, Gray 1850), with insights into foraging ecology on mesopelagic prey," Mar. Mammal Sci. **33**, 1245–1254.
Hildebrand, J. A., Baumann-Pickering, S., Frasier, K. E., Trickey, J. S., Merkens, K. P., Wiggins, S. M., McDonald, M. A., Garrison, L. P., Harris, D., Marques, T. A., and Thomas, L. (**2015**). "Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico," Sci. Rep. **5**, 1–15.
Hooker, S. K., and Whitehead, H. (**2002**). "Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*)," Mar. Mammal Sci. **18**, 69–80.
Johnson, M., Hickmott, L. S., Soto, N. A., and Madsen, P. T. (**2008**). "Echolocation behaviour adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*)," Proc. Biol. Sci. **275**, 133–139.
Johnson, M., Madsen, P. T., Zimmer, W. M. X., de Soto, N. A., and Tyack, P. L. (**2004**). "Beaked whales echolocate on prey," Proc. Biol. Sci. **271**, S383–S386.
Johnson, M., Madsen, P. T., Zimmer, W. M. X., de Soto, N. A., and Tyack, P. L. (**2006**). "Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation," J. Exp. Biol. **209**, 5038–5050.
Keating, J. L., Barlow, J., and Rankin, S. (**2016**). "Shifts in frequency-modulated pulses recorded during an encounter with Blainville's beaked whales (*Mesoplodon densirostris*)," J. Acoust. Soc. Am. **140**, EL166–EL171.
Küsel, E. T., Mellinger, D. K., Thomas, L., Marques, T. A., Moretti, D., and Ward, J. (**2011**). "Cetacean population density estimation from single fixed sensors using passive acoustics," J. Acoust. Soc. Am. **129**, 3610–3622.
MacLeod, C. D., Perrin, W. F., Pitman, R., Barlow, J., Ballance, L., D'Amico, A., Gerrodette, T., Joyce, G., Mullin, K. D., Palka, D. L., and Waring, G. T. (**2006a**). "Known and inferred distributions of beaked whale species (Cetacea: *Ziphiidae*)," J. Cetacean Res. Manage. **7**, 271–286.
MacLeod, C. D., Santos, M. B., López, A., and Pierce, G. J. (**2006b**). "Relative prey size consumption in toothed whales: Implications for prey selection and level of specialisation," Mar. Ecol. Prog. Ser. **326**, 295–307.
MacLeod, C. D., Santos, M. B., and Pierce, G. J. (**2003**). "Review of data on diets of beaked whales: Evidence of niche separation and geographic segregation," J. Mar. Biol. Assoc. U. K. **83**, 651–665.
Madsen, P. T., Johnson, M. P., Aguilar De Soto, N., Zimmer, W. M. X., and Tyack, P. L. (**2005**). "Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*)," J. Exp. Biol. **208**, 181–194.
McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., Johnston, D. W., and Polovina, J. J. (**2009**). "An acoustic survey of beaked whales at Cross Seamount near Hawaii," J. Acoust. Soc. Am. **125**, 624–627.
Palka, D., Cholewiak, D., Broughton, E., and Jech, M. (**2016**). "Appendix A: Northern leg of shipboard abundance survey during 27 June–25 August 2016: Northeast Fisheries Science Center," Annual Report of a Comprehensive Assessment of Marine Mammal, Marine Turtle, and Seabird Abundance and Spatial Distribution in US Waters of the Western North Atlantic Ocean- AMAPPS II, pp. 10–60, available at https://www.nefsc.noaa.gov/psb/AMAPPS/docs/Annual%20Report%20of%202016%20AMAPPS_final.pdf.
Rankin, S., and Barlow, J. (**2007**). "Sounds recorded in the presence of Blainville's beaked whales, *Mesoplodon densirostris*, near Hawai'i," J. Acoust. Soc. Am. **122**, 42–45.
Rankin, S., Baumann-Pickering, S., Yack, T., and Barlow, J. (**2011**). "Description of sounds recorded from Longman's beaked whale, *Indopacetus pacificus*," J. Acoust. Soc. Am. **130**, EL339–EL344.
Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S., and Hildebrand, J. A. (**2011**). "Classification of echolocation clicks from odontocetes in the Southern California Bight," J. Acoust. Soc. Am. **129**, 467–475.
Shaffer, J. W., Moretti, D., Jarvis, S., Tyack, P., and Johnson, M. (**2013**). "Effective beam pattern of the Blainville's beaked whale (*Mesoplodon densirostris*) and implications for passive acoustic monitoring," J. Acoust. Soc. Am. **133**, 1770–1784.
Sjölander, K., and Beskow, J. (**2000**). "Wavesurfer—An open source speech tool," in *ICSLP-2000*, Beijing, China, pp. 464–467.
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**, 609–624.
Stanistreet, J. E., Nowacek, D. P., Baumann-Pickering, S., Bell, J. T., Cholewiak, D. M., Hildebrand, J. A., Hodge, L. E. W., Moors-Murphy, H. B., Van Parijs, S. M., and Read, A. J. (**2017**). "Using passive acoustic monitoring to document the distribution of beaked whale species in the western North Atlantic Ocean," Can. J. Fish. Aquat. Sci. **74**, 2098–2109.
Tyack, P. L., Johnson, M., Soto, N. A., Sturlese, A., and Madsen, P. T. (**2006**). "Extreme diving of beaked whales," J. Exp. Biol. **209**, 4238–4253.
Wahlberg, M., Beedholm, K., Heerfordt, A., and Mohl, B. (**2011**). "Characteristics of biosonar signals from the northern bottlenose whale, *Hyperoodon ampullatus*," J. Acoust. Soc. Am. **130**, 3077–3084.
Wenzel, F. W., Polloni, P. T., Craddock, J. E., Gannon, D. P., Nicolas, J. R., Read, A. J., and Rosel, P. E. (**2013**). "Food habits of Sowerby's beaked whales (*Mesoplodon bidens*) taken in the pelagic drift gillnet fishery of the western North Atlantic," Fish. Bull. **111**, 381–389.
Zimmer, W. M. X. (**2011**). *Passive Acoustic Monitoring of Cetaceans* (Cambridge University Press, New York).
Zimmer, W. M. X., Harwood, J., Tyack, P. L., Johnson, M. P., and Madsen, P. T. (**2008**). "Passive acoustic detection of deep-diving beaked whales," J. Acoust. Soc. Am. **124**, 2823–2832.
Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P. L. (**2005**). "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)," J. Acoust. Soc. Am. **117**, 3919–3927.