Description of sounds associated with Sowerby's beaked whales (*Mesoplodon bidens*) in the western North Atlantic Ocean

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Several groups of Sowerby's beaked whales (*Mesoplodon bidens*) were encountered on July 4, 2011, during a shipboard cetacean survey conducted off the eastern seaboard of the United States. Acoustic recordings were collected using a three-element towed hydrophone array. Many echolocation clicks were recorded during the encounter, but no tonal sounds were detected. A total of 2969 echolocation clicks were included in analyses of frequency and temporal characteristics. A Gaussian mixture model with four mixtures was fitted to the histogram of peak frequencies; four subsets of clicks were designated. The majority of clicks ($n = 2048$) contained a median peak frequency of 33 kHz, while the others contained a median peak frequency of 25 kHz ($n = 324$), 51 kHz ($n = 304$), or 67 kHz ($n = 293$). Most clicks did not contain a clear frequency-modulated upsweep, though some clicks exhibited a slight sweep from 30–36 kHz. Seven burst pulses were detected in the encounter, two of which were of high enough quality for detailed analysis. The acoustic characteristics of Sowerby's beaked whales have not previously been described; the current study will facilitate incorporation of these data into passive acoustic monitoring programs in the North Atlantic Ocean. [http://dx.doi.org/10.1121/1.4823843]

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"I was much pleased and astonished when I found, from the extraordinary formation of its mouth, and the situation of its teeth, that this was likely to prove a species not yet described… we know of no whale, with only two teeth in the lower jaw, described by any author."

Sowerby, 1804

I. INTRODUCTION

Mesoplodont beaked whales are the most speciose genera of marine mammals, but also the most poorly known. They are widely distributed, but rarely sighted—some species are still only known from strandings. Within the North Atlantic Ocean, four species of mesoplodont beaked whales are known to occur regularly (MacLeod, 2000; MacLeod *et al.*, 2006). These include Sowerby's (*M. bidens*), Blainville's (*M. densirostris*), Gervais' (*M. europaeus*), and True's beaked whales (*M. mirus*). A single stranding of Gray's beaked whale (*M. grayi*) was reported from the North Sea, but this record is considered extralimital as all other sightings are in the southern hemisphere (MacLeod, 2000). Two other ziphiid species, Cuvier's beaked whales (*Ziphius cavirostris*) and northern bottlenose whales (*Hyperoodon ampullatus*) also range throughout the North Atlantic.

Sowerby's beaked whales (*Mesoplodon bidens*) are one of 14 extant species of mesoplodont beaked whales recognized today. They were documented in 1804, with the first specimen (Sowerby, 1804) becoming the type species for the genus. They range throughout North Atlantic Ocean, with records primarily coming from strandings in the eastern North Atlantic (Mead, 1989). They have also been documented in strandings as well as bycaught in pelagic gillnet fisheries along the western North Atlantic (Waring *et al.*, 2009; Wenzel *et al.*, 2013). A few accounts document their presence in the Norwegian Sea (Carlström *et al.*, 1997; Christensen, 1977), and Leatherwood (1976) mentions their distribution in offshore waters from New England north to the pack ice. The only descriptive record of this species in the wild comes from Hooker and Baird (1999), who describe four encounters with groups in the Gully, Nova Scotia. The groups were comprised of 3–10 animals, with one group including multiple calves and adults of both sexes. Large-scale cetacean surveys conducted by NOAA along the Atlantic coast of the U.S. have also documented their occurrence, but due to the challenges of species identification, these observations are typically grouped within a generic beaked whale category for stock assessments and other reports (Waring *et al.*, 2001; Waring *et al.*, 2009).

Beaked whales are inconspicuous and difficult to see during visual surveys, except in the best of conditions. Little is known about their life history and social structure, but

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recent work is starting to reveal information about their acoustic behavior, critical for expanded passive acoustic monitoring. Thus far, sounds have been attributed to ten different species of beaked whales, and five additional beaked whale-like signals of unknown origin have also been identified (Baumann-Pickering *et al.*, 2010; Baumann-Pickering *et al.*, 2013a, 2013b, 2013c; Caldwell and Caldwell, 1991; Dawson *et al.*, 1998; Gillespie *et al.*, 2009; Johnson *et al.*, 2006; Lynn and Reiss, 1992; Marten, 2000; McDonald *et al.*, 2009; Rankin and Barlow, 2007; Rankin *et al.*, 2011; Rogers and Brown, 1999; Wahlberg *et al.*, 2011; Zimmer *et al.*, 2005). Sowerby's beaked whales are not among them. This paper describes recordings made during an encounter with multiple Sowerby's beaked whales during a shipboard cetacean survey in 2011.

II. METHODS

A. Data collection

Acoustic and visual data were collected from the NOAA R/V Bigelow, during the Atlantic Marine Assessment Program for Protected Species (AMAPPS) survey off the eastern seaboard of the United States from approximately 42°N to 36°N, during 2 June–1 August 2011. The survey was comprised of sawtooth tracklines covering two main strata: the continental slope and offshore waters. Visual sighting data were collected by two teams operating on different decks of the vessel. Each team consisted of three trained observers; two observers utilized high-powered "big-eye" binoculars (Fujinon, 25×150) to scan from the bow of the ship to 90° port or starboard, while one observer scanned the trackline using hand-held binoculars and naked eye. Target survey speed was 10 knots, and visual data were collected during daylight hours from approximately 06:00–18:00 EDT when sea conditions were less than sea state Beaufort 6.

Acoustic recordings were collected using a three-element oil-filled hydrophone array (Benthos AQ-4 elements: −201 dBV re: 1 μPa, Magrec HP-02 preamplifier: 29 dB gain), towed 300 m behind the ship, at approximately 12 m depth. Acoustic data were routed to a desktop computer via a Magrec HP/27ST monitor box (http://ecologicuk.co.uk, 80 Hz high-pass filter, 30 dB gain) and an external Fireface 400 sound card, with data recorded continuously at a sampling rate of 192 kHz utilizing the software package PAMGUARD [www.pamguard.org (last viewed 23 September 2013)]. Two-channel data were also routed to a second desktop computer via an internal M-Audio soundcard, sampling at 48 kHz, for real-time detection and tracking of vocal animals utilizing the software packages WHALTRAK and ISHMAEL. The hydrophone array was typically deployed from 06:00–18:00 EDT and was retrieved temporarily at midday for oceanographic data collection. The acoustic monitoring team consisted of two or three trained individuals who operated the system in 2-h shifts.

B. Acoustic analysis

1. Click detection and feature characterization

Acoustic data for the current study were manually browsed using the software package RAVEN (Charif *et al.*, 2004), to assess the occurrence of echolocation clicks and tonal sounds. Data were then further post-processed using custom MATLAB (Mathworks, Inc., Natick, MA) routines. Potential echolocation clicks were automatically detected using a two-step approach (Soldevilla *et al.*, 2008). In the first stage, a detection was triggered if 12.5% or more of the frequency bins within a 15–85 kHz frequency range exceeded a signal-to-noise ratio of 10 dB. These detections were refined using the Teager–Kaiser energy operator (Kandia and Stylianou, 2006).

Individual click detections and 1000 points of noise before each click were digitally filtered with a ten-pole Butterworth band-pass filter with a pass-band between 3 and 95 kHz. Filtering was done on 800 sample points centered on the echolocation signal and the associated noise samples. Spectra of each detected click and noise were calculated using 2.56 ms (512 samples) of Hann-windowed data centered on the click and noise. The following variables were measured: center and peak frequencies, −3 and −10 dB bandwidths, and duration. $Q_{3\ \mathrm{dB}}$ was calculated, defined as the peak frequency divided by the −3 dB bandwidth. Signal-to-noise ratio (SNR) was calculated with the root-mean-square level of each click and its preceding noise. Inter-click intervals (ICIs) were calculated from the start of one click to the start of the previous one.

Click detections were manually reviewed for false detections, and criteria were established to remove clicks that were potentially associated with flow noise and bubble noise from within the hydrophone array. Clicks with the following criteria were eliminated from subsequent analyses: $\mathrm{SNR} < 0$ (in the case when two click detections occurred rapidly following one another), peak frequency < 20 kHz, duration > 0.9 ms, inter-click interval < 10 ms or > 500 ms, clicks within trains of ≤ 2 clicks. Inter-click interval criteria were established so that clicks only occurring within identifiable, consecutive click trains were maintained, and to remove potential multipath arrivals or close echoes, keeping the click with maximum amplitude.

A Gaussian mixture model with four mixtures was fitted to the peak frequency histogram to describe distinct peaks in the distribution. Four subsets of clicks were created based on the peak frequency mixtures, using the crossing point of two mixtures as a splitting value. The median, 10th, and 90th percentile of time and frequency parameters were computed over all data as well as separately for each of the four subsets of clicks. For each subset, mean spectra of clicks and noise were produced. Inter-click interval was re-calculated on a subset basis and histograms were computed for each subset.

Click detections were imported into Wavesurfer (Sjölander & Beskow, KTH, Sweden), and the pattern of occurrence of 400 clicks from the four subsets was evaluated to determine whether clicks from different subsets occurred within the same click trains. Inter-click intervals were also calculated for 226 consecutive clicks occurring in 33 click trains, to more carefully resolve the ICI distribution.

2. 2-D localization

PAMGUARD (v1.12.05) was used in post-processing to localize individual animals. Clicks were detected using the

PAMGUARD click detector, and were reviewed in the PAMGUARD viewer mode. Click trains were manually identified and marked based on patterns of change in bearing over time, and two-dimensional localizations were computed using algorithms in PAMGUARD's target motion analysis module.

III. RESULTS

A. Field observations

Starting at 07:40 EDT on 4 July 2011, the R/V Bigelow encountered several small groups of Sowerby's beaked whales at 40.78°N, 66.54°W (Fig. 1), just off the continental shelf of the eastern United States, near Georges Bank. Over a period of approximately 25 min during which all visual observers were "on-effort," at least three groups of animals were sighted, some of them multiple times, comprising at least a singleton, a pair, and a group of four or more individuals. Both teams of visual observers were confident of species identification. These groups were distributed along a straight-line distance of 4 km, within 500 m of the trackline, between the 1000 and 2000 m depth contours. During the transit, several animals crossed the survey track line. At 08:00 EDT, one group surfaced and dove approximately 300 m from the vessel, and at 08:04 EDT, acousticians tracked one animal in real-time passing within 800 m of the array. Throughout the encounter, multiple series of echolocation clicks were detected by the acoustic team. After transiting approximately 3.6 km beyond the location of this group, the vessel turned 180° and passed back through the area of the three sightings.

No other species were observed in the immediate area during this period. Within the 30 min (07:10–07:40 EDT) prior to the first Sowerby's sighting, two groups of pilot whales (*Globicephela spp*., $n = 4$ animals and $n = 1$ animal) and three balaenopterid whales were sighted. The pilot whale sightings were 10.7 and 5.6 km, respectively, from the group of Sowerby's beaked whales that were chosen for analysis. Several sperm whales were also detected acoustically.

B. Post-processing acoustic analyses

Thirty minutes of continuous acoustic data (07:55–08:25 EDT) encompassing and following the period of the visual encounter at 08:00 EDT were included in analyses. This period was chosen to maximize the time during which the vessel would be within acoustic range of this group, and minimize the potential detection of other species. Data were reviewed manually for the presence of echolocation click trains and tonal sounds. Echolocation clicks trains were recorded, in some cases from multiple individuals, as evidenced from overlapping sequences. No tonal sounds were recorded.

1. Feature characterization

A total of 4499 clicks were automatically detected using the Teager–Kaiser energy algorithm. After applying criteria to remove potential false detections, a total of 2969 clicks remained in the final dataset. Spectral analyses revealed a multi-modal distribution of peak frequencies. A Gaussian mixture model with four mixtures fit to the distribution of peak frequencies led to four subsets of clicks based on their frequency content (Fig. 2). The majority of the clicks ($n = 2048$) had a median peak frequency of 33 kHz. We refer to these hereafter as the "main" clicks. The remaining 921 clicks fell into one of three subsets: low (peak frequency = 26 kHz, $n = 324$), mid (peak frequency = 51 kHz, $n = 304$), or high (peak frequency = 67 kHz, $n = 293$) (Table I, Fig. 3). However, most clicks contained energy across all of these frequencies. The median −3 dB bandwidth across all clicks was 6 kHz, and the median −10 dB bandwidth was 12 kHz. $Q_{3\ \mathrm{dB}}$ averaged 6.2 for the entire dataset. The median Teager–Kaiser energy click duration was 386 μs (range 224–667 μs, Table I). Most clicks did not exhibit a clear frequency sweep; however, some high-quality clicks contained a subtle sweep from 30–36 kHz (Fig. 4).

To evaluate whether the clicks with different peak frequencies constituted alternate "click types," or whether the variation in peak frequency was more likely related to

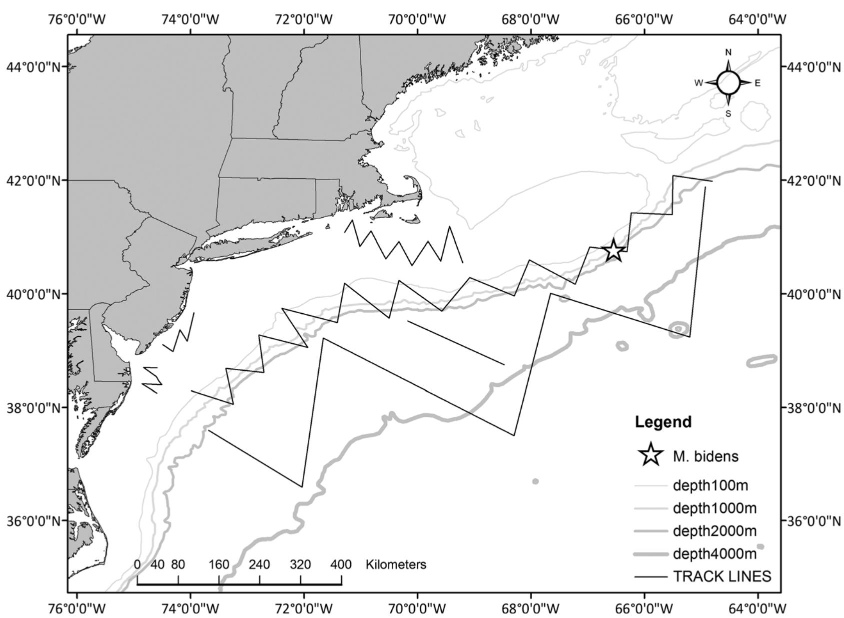

FIG. 1. Location of an encounter with multiple groups of Sowerby's beaked whales (*M. bidens*) on 4 July 2011, during a cetacean, sea turtle, and seabird abundance survey conducted from the NOAA R/V Bigelow along the U.S. east coast. The star indicates the area of the sightings, located at approximately 40.78°N, 66.54°W.

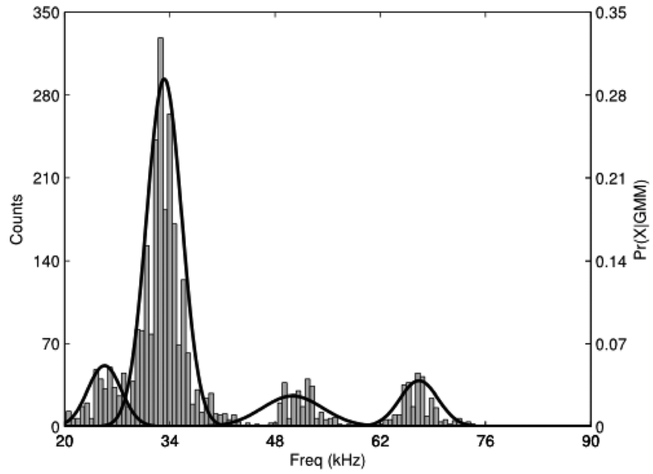

FIG. 2. Distribution of peak frequencies for 2969 echolocation clicks, overlaid with the fit of the Gaussian mixture model with four mixtures. The highest peak corresponds to the "main" clicks; the other peaks represent the "low," "mid," and "high" clicks.

off-axis sound propagation, their patterns of occurrence were evaluated for a subset of 400 clicks. No clear patterns emerged. In approximately half of these clicks, clicks belonging to the low, mid and high frequency subsets were found mixed in varying combinations within click trains. In almost all cases (81%) they were found mixed in trains among the 'main' clicks. There did not appear to be any difference in duration or amplitude of clicks in these alternate categories.

The median inter-click interval (ICI) quantified over the final dataset, excluding ICIs above 500 ms, was 96 ms. ICI was also computed for a subset of 226 clicks occurring in 33 click trains, including only measurements for which there were at least three consecutive clicks clearly identifiable as belonging to the same click train. ICI for this subset was 95 ms, with a generally bimodal distribution. Peaks in ICI were at 40–60 ms and 100–140 ms, suggesting a differentiation between "slow" and "fast" trains (Fig. 5). In addition, several click trains contained "double clicks" (Fig. 6), in which a second click was produced rapidly after a first.

A total of seven burst pulses were found in the dataset. Of these, only two were of high enough amplitude to allow characterization; Fig. 7 shows one example. The first burst pulse contained 82 clicks over approximately 132 ms, with a mean peak frequency of 66.8 kHz. The second burst pulse contained at least 193 clicks over approximately 285 ms, with a mean peak frequency of 35.1 kHz. The first burst pulse had a mean ICI of 1.7 ms (621 clicks per second), while the second had a mean ICI of 1.5 ms (677 clicks per second).

2. 2-D localization

The bearing-time patterns in click trains from two individuals were clearly distinguishable as they passed the vessel at 08:05 and 08:06 EDT. Two-dimensional radial distances as calculated by PAMGUARD ranged from 325–455 m. One of these is likely the same individual that was localized in real-time during the survey. The bearing-time patterns of other detected clicks could not be clearly associated into long enough trains for localization.

IV. DISCUSSION

This study describes the echolocation clicks recorded in association with visual sightings of multiple Sowerby's beaked whales encountered during a large-scale shipboard survey off the U.S. east coast. Notably, most echolocation clicks do not appear to have a strong frequency-modulated upsweep, unlike those described for most other beaked whale species. The median peak frequency, 33.4 kHz, is similar to that of Blainville's beaked whale (*M. densirostris*, Johnson *et al.*, 2006), but lower than that of Cuvier's beaked whales (*Z. cavirostris*, Zimmer *et al.*, 2005), and the ICI is shorter than other described North Atlantic species. No studies yet document the acoustic characteristics of True's beaked whale (*M. mirus),* the only other beaked whale species found regularly in the western North Atlantic.

The existence of multiple "subsets" of clicks, as defined by differences in peak frequency, is unusual among beaked whales, based on what is currently known. Most species seem to produce a longer FM pulse and a shorter click as part of a buzz sequence. However, Longman's beaked whale (*Indopacetus pacificus*) produces three types of clicks: two short clicks with peak frequencies of 15 and 25 kHz, and a

TABLE I. Parameters of echolocation signals that were recorded during the encounter with Sowerby's beaked whales. Measurements were conducted over all clicks in the final dataset ($n = 2969$), as well as separately for each subset of clicks that contained a peak frequency within the limits determined by the Gaussian mixture model. Frequency bounds for each subset are given above the parameter measurements, and sample size is given below.

		All		Low (peak 1)		Main (peak 2)		Mid (peak 3)		High (peak 4)	
limits (kHz)		20	95	20	28	28	41	41	60	60	95
Parameter	Unit	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range
Peak frequency	kHz	33.4	(27.4–58.1)	25.5	(22.1–27.4)	33.0	(30.4–36.0)	51.4	(43.1–54.4)	67.1	(64.5–70.1)
Center frequency	kHz	38.0	(32.4–50.9)		(24.0–43.7)	36.7	(33.0–45.0)	47.0	(41.0–53.1)	54.7	(47.3–63.3)
−3 dB bandwidth	kHz	5.6	(3.8–9.0)	6.0	(3.8–11.3)	5.6	(3.8–8.6)	6.4	(3.8–10.9)	6.0	(3.4–9.4)
−10 dB bandwidth	kHz	12.0	(7.1–20.7)	13.5	(7.9–20.6)	11.6	(6.8–18.8)	15.0	(7.8–28.5)	12.4	(7.1–20.7)
Duration	us	386	(224–667)	349	(203–567)	401	(224–672)	364	(224–698)	375	(229–698)
Inter-click interval	ms	96	(16–216)	76	(28–310)	110	(19–220)	111	(38–288)	114	(16–318)
Q		6.2	(1.4–28.1)	4.3	(1.4–9.4)	5.9	(1.7–14.5)	7.9	(1.9–22.8)	10.8	(5.0–28.1)
Sample	*n*	2969		324		2048		304		293	

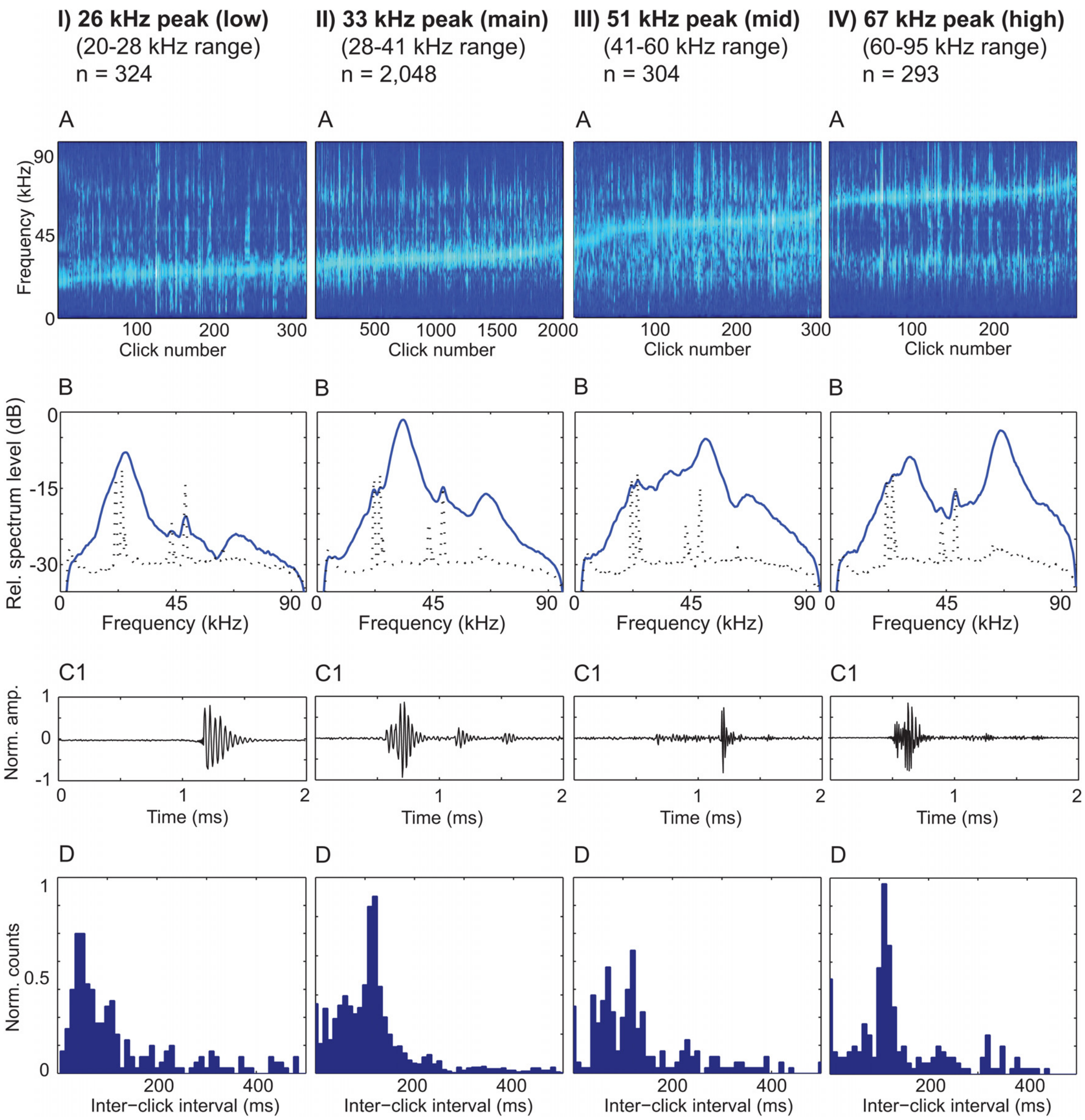

FIG. 3. (Color online) Description of click subsets (I–IV) with (a) concatenated spectrograms of all clicks per category sorted by peak frequency, (b) mean spectra (solid line) and mean noise preceding clicks (dashed line), (c) example time series of each subset, and (d) normalized distribution of inter-click interval.

longer FM pulse (Rankin *et al.*, 2011). Clicks recorded from northern bottlenose whales (*Hyperoodon ampullatus*) also varied in spectral characteristics based on whether they were "surface" or "deep water" clicks (Hooker and Whitehead, 2002). The variation in peak frequencies observed in the current study has not been reported for other mesoplodon species. No clear pattern within click trains was found in the occurrence of clicks from different peak frequency subsets; specifically, higher amplitude clicks were not necessarily in the "high" frequency subset, and vice versa, as might be expected if this variation was primarily due to propagation effects. Therefore, whether the different subsets of clicks comprise functional categories, or whether their occurrence is due to a production or propagation mechanism, is unknown.

The broad, but generally bimodal distribution of inter-click intervals found in the Sowerby's beaked whale recordings suggests a differentiation between "slow" and "fast" click trains. This pattern has also been described in some delphinids (Lammers *et al.*, 2004). Among beaked whales, this pattern has only been documented among two species. The northern bottlenose whale exhibited variation in ICI between "surface" and "deep water" click trains (Hooker and Whitehead, 2002). The Palmyra beaked whale, a presumed mesoplodon species, also exhibits a bimodal distribution in ICI, where most pulses were found to have an interval of 120–340 ms, but a second peak at 430 ms was also found (Baumann-Pickering *et al.*, 2010).

The existence of what seemed to be sporadic "doublets" in some of the click trains appears to be unusual, and their function is unknown. These instances of double clicks do not seem to be the product of propagation or a second animal, as the amplitude and phase of both clicks are similar. The production of double clicks is common among some other echolocating taxa, such as swiftlets, with the evolution of single echolocation clicks occurring in only a few species (Price *et al.*, 2004). The production of double

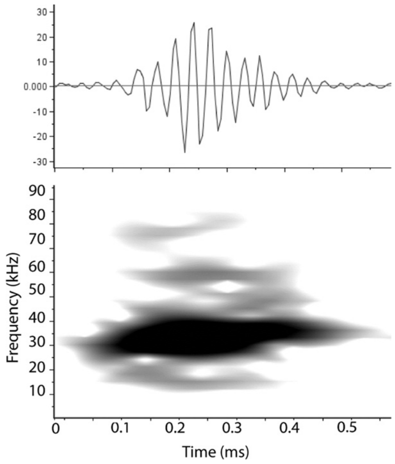

FIG. 4. Sample click showing slight frequency sweep from 30–36 kHz. Top panel shows the time series and bottom panel shows the spectrogram (Hann window, 56 pt. FFT, 98% overlap).

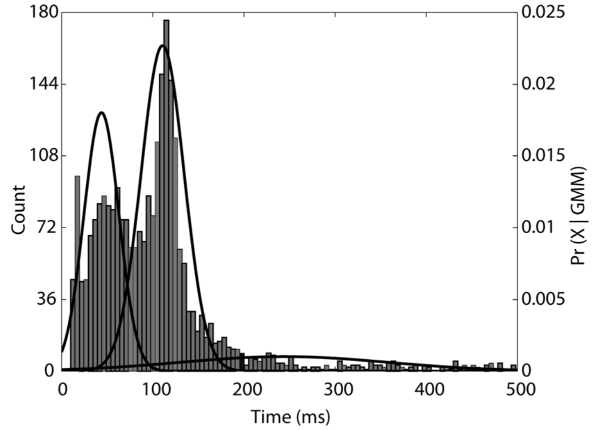

FIG. 5. Distribution of inter-click intervals measured from all 2969 clicks, overlaid with a Gaussian mixture model.

clicks is also common in some bat species, where a change in echo frequency is thought to trigger a switch from single to double echolocation calls (Smotherman and Metzner, 2005). While the production of double echolocation clicks is not commonly reported among odontocetes, beluga whales (*Delphinapterus leucas*) are known to produce "packets" of clicks (Turl and Penner, 1989), which is hypothesized to be related to their detection and signal processing strategies.

It is not known whether the features of the clicks described in this study are characteristic of the species as a whole. Based on the number of animals, distribution, and composition of groups (one of which included a mother with calf), it seems possible that the echolocation clicks recorded here could be associated with social rather than foraging behavior. Although the depth of the vocalizing animals in our study is unknown, the radial distances of tracked individuals was approximately 450 m from the array. Preliminary 3-D analysis incorporating the timing of surface-reflected clicks with the maximum 2-D range from PAMGUARD suggests that these individuals may actually be vocalizing at relatively shallow depths ($<$ 100 m), unlike what is currently reported for Cuvier's beaked whales and other mesoplodon species. In studies of northern bottlenose whales, Hooker and Whitehead (2002) found that echolocation clicks were produced both by animals at the surface as well as presumably deeper, foraging animals. We speculate that Sowerby's beaked whales may also produce echolocation clicks in multiple contexts, possibly with differing functions.

Additionally, the majority of the clicks recorded via our towed array are almost certainly off-axis, leading to distortion of spectral characteristics. This could be related to

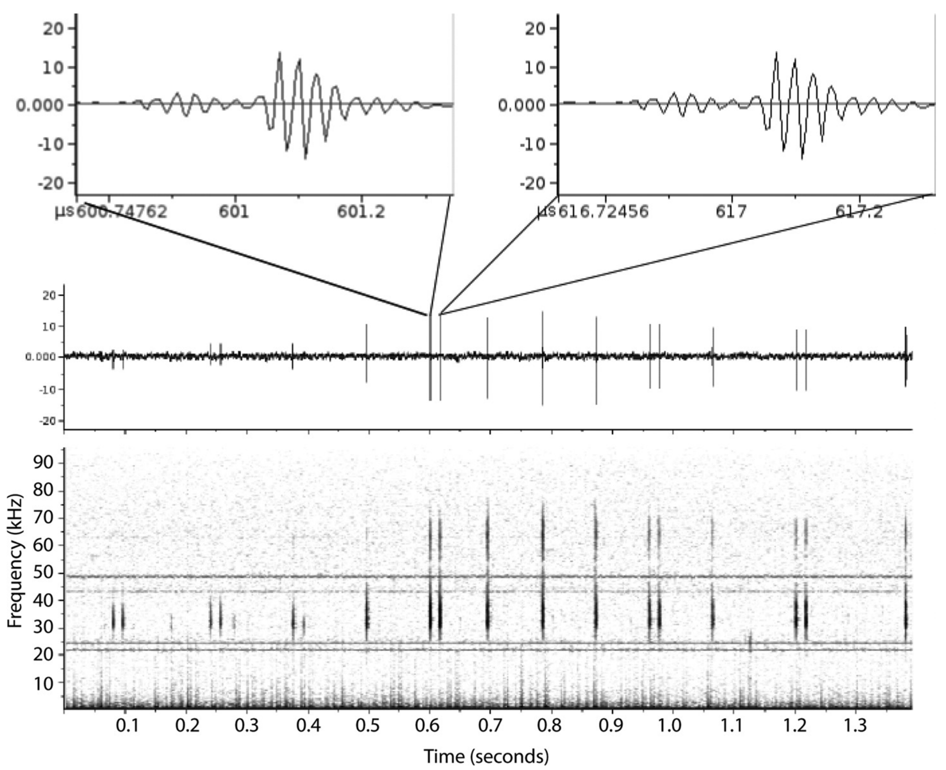

FIG. 6. Example of click train with irregularly interspersed "double clicks." Top panels show the waveforms of two consecutive clicks, bottom panel shows the spectrogram of the click train (Hann window, 512 pt. FFT, 50% overlap). Note that the amplitude and phase of the second click in each doublet is similar to the first click.

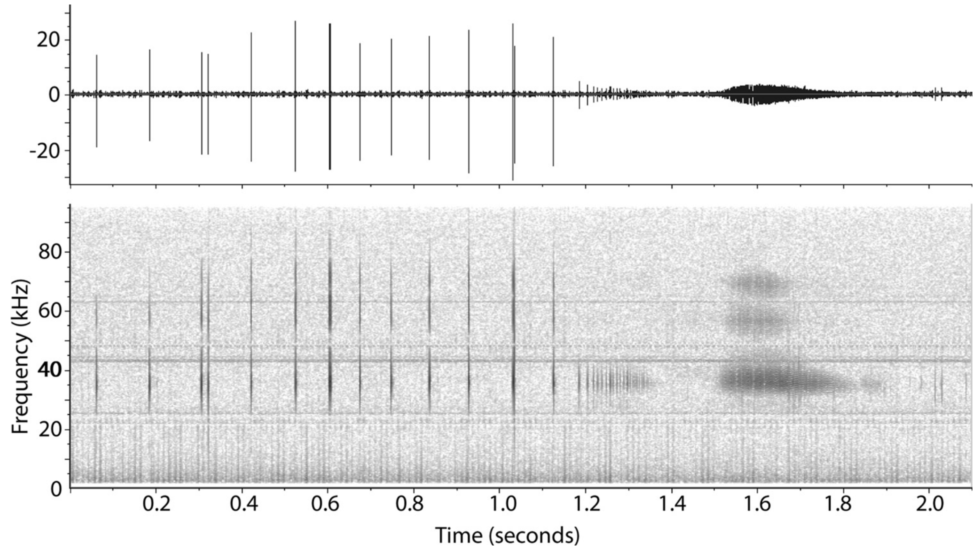

FIG. 7. Examples of one click train and burst pulse. Top panel shows the waveform, bottom panel shows the spectrogram (Hann window, 1024 pt. FFT, 50% overlap). Note that one "double click" is apparent in this example as well as in Fig. 5.

some of the variability found in peak and center frequencies and bandwidths. However, as most studies utilizing towed hydrophone arrays will likely record more off-axis clicks than on-axis ones, we feel it is useful to describe the range of variation in clicks that are captured in these studies.

Passive acoustic data are being collected throughout the oceans at an increasing rate, from both towed hydrophone arrays as well as stationary recorders. We hope the results of this study will allow for the expanded detection and classification of Sowerby's beaked whale sounds among the many odontocete species' vocalizations recorded in the North Atlantic Ocean, ultimately leading to improved knowledge of the distribution and behavior of this species.

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