Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*) and Sowerby's beaked whales (*Mesoplodon bidens*) off eastern Canada

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Passive acoustic monitoring (PAM) is crucial to expanding the knowledge of beaked whales, including the northern bottlenose whale (*Hyperoodon ampullatus*) and Sowerby's beaked whale (*Mesoplodon bidens*). Existing descriptions of clicks produced by these species are limited by sample size, number of individuals recorded, and geographic scope. Data from multiple encounters in the western North Atlantic are used to provide a quantitative description of clicks produced by these species. Recordings from nine encounters with northern bottlenose whales in Nova Scotia and Newfoundland were analyzed (N = 2239 clicks). The click type described had a median peak frequency of 25.9 kHz (10th–90th percentile range: 22.9–29.3 kHz), and a median inter-click interval (ICI) of 402 ms (N = 1917, 10th–90th percentile range: 290–524 ms). Recordings from 18 Sowerby's beaked whale encounters from Nova Scotia were analyzed (N = 762 clicks). The click type described had a median peak frequency of 65.8 kHz (10th–90th percentile range: 61.5–76.5 kHz), and a median ICI of 237 ms (N = 677, 10th–90th percentile range: 130–315 ms). These results will contribute to the development of methods to detect and classify beaked whale clicks to the species level, improving the effectiveness of PAM and enhancing scientific understanding and conservation efforts for cryptic and at-risk cetaceans. https://doi.org/10.1121/1.5111336

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I. INTRODUCTION

Beaked whales (family Ziphiidae) are a group of cetaceans of which relatively little is known. They inhabit the deep waters of the world's oceans, diving to great depths to forage upon deepwater squid and fish, spending relatively little time at the surface in comparison to other whale species (Barlow, 1999; MacLeod *et al.*, 2006; Tyack *et al.*, 2006; Hooker *et al.*, 2019). As their remote offshore habitat, surfacing behaviour and elusive nature makes these animals challenging to study, there is a lack of information on the abundance, distribution and basic biology of many ziphiid species. Considering that beaked whales are sensitive to some types of anthropogenic noise (e.g., military sonar, which has been linked to mass strandings of beaked whales), ameliorating our knowledge of these species is crucial to mitigation and conservation efforts (Barlow and Gisiner, 2006; Cox *et al.*, 2006; Weilgart, 2007; Miller *et al.*, 2015). There are several species of beaked whales known to occur in the western North Atlantic; two that are regularly encountered off the east coast of Canada are the northern bottlenose whale (*Hyperoodon ampullatus*) and Sowerby's beaked whale (*Mesoplodon bidens*) (Wimmer and Whitehead, 2004; Whitehead, 2013).

Due to historic whaling during the 20th century, as well as a long-term study in the Gully, Nova Scotia, northern bottlenose whales are one of the most well-documented beaked whale species in the western North Atlantic (Whitehead and Hooker, 2012; O'Brien and Whitehead, 2013; Fisheries and Oceans Canada, 2016). There are two genetically distinct populations: one concentrated around the Davis Strait and Baffin Bay, and one inhabiting the Scotian Shelf, primarily the Gully submarine canyon, a Marine Protected Area (MPA) (Reeves *et al.*, 1993; Dalebout *et al.*, 2001; Fisheries and Oceans Canada, 2016). These populations have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as Special Concern and Endangered, respectively (COSEWIC, 2011). The Scotian Shelf population has been designated as Endangered under Canada's Species at Risk Act (SARA) (SARA, 2011). Another aggregation of northern bottlenose whales has recently been discovered off Newfoundland, between these two population centers, and it is not yet known how this aggregation fits into the currently understood population structure (L.J.F., personal observation).

Much less is known about Sowerby's beaked whales as this species is more difficult to spot and identify. They are smaller in size than northern bottlenose whales, produce inconspicuous blows, tend to avoid vessels, and have similar appearances and overlapping distributions with other beaked whales in the genus *Mesoplodon*, including Blainville's beaked whale (*M. densirostris*), Gervais' beaked whale (*M. europaeus*) and True's beaked whale (*M. mirus*) (Barlow, 1999; Barlow *et al.*, 2005; COSEWIC, 2006). Historically,

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Sowerby's beaked whales were known primarily from stranding records. However, they have more recently been observed along the edge of the Scotian Shelf, particularly around the Gully, Shortland and Haldimand submarine canyons (Hooker and Baird, 1999; Whitehead, 2013). They are designated as a population of Special Concern by COSEWIC (2006) and under Canada's SARA (2011).

Developments in commercially available deep-water passive acoustic monitoring (PAM) technology are expanding our understanding of the spatial and temporal distribution of cetacean species, including beaked whales. Improvements in acoustic signal detection algorithms have allowed for efficient identification of cetacean vocalizations, often down to the genus or species level, and automated detection software is able to process large volumes of data at increasing frequency resolution and sometimes even in near real-time (e.g., Moors-Murphy, 2012; Mellinger *et al.*, 2007; Baumgartner *et al.*, 2008; von Benda-Beckmann *et al.*, 2010; Baumgartner and Mussoline, 2011). PAM has been identified as a crucial tool to monitor beaked whales, a group where traditional (visual) research methods can be challenging to apply, due to the limited amount of time they spend at the surface and the logistical difficulties in conducting offshore field studies (Barlow *et al.*, 2005; MacLeod *et al.*, 2006).

As a family, beaked whales are known to regularly produce stereotypical frequency-modulated (FM) high frequency (>20 kHz) echolocation clicks and to emit short bursts of buzz clicks, presumably to communicate, navigate in their dark underwater world and detect prey (Barlow *et al.*, 2005; Johnson *et al.*, 2004; Madsen *et al.*, 2005; Johnson *et al.*, 2006; Tyack *et al.*, 2006; Johnson *et al.*, 2008; Madsen *et al.*, 2013). Temporal and spectral characteristics of the FM clicks, such as the inter-click interval (ICI), peak frequency, center frequency, bandwidth and upsweep appear distinct between beaked whale species (Baumann-Pickering *et al.*, 2013a). Detailed characterization of beaked whale acoustic signals allows species-specific classification and has informed the development of automated beaked whale click detectors resulting in significant improvements in the interpretation of PAM data for beaked whale monitoring (Dawson *et al.*, 1998; Johnson *et al.*, 2004; Zimmer *et al.*, 2005; Johnson *et al.*, 2006; Tyack *et al.*, 2006; Gillespie *et al.*, 2009; Baumann-Pickering *et al.*, 2010; Rankin *et al.*, 2011; Baumann-Pickering *et al.*, 2013a; Baumann-Pickering *et al.*, 2013b; Yack *et al.*, 2013, Stanistreet *et al.*, 2017, Kowarski *et al.*, 2018).

Detector development requires field-based evidence to associate vocalizations of particular beaked whale species with recorded acoustic signals. Northern bottlenose whale vocalizations (N = 89 clicks) were first recorded and described by Hooker and Whitehead (2002). However, their recordings were made using a sampling rate below 40 kHz, which we now know is too low to capture the full frequency range of beaked whale echolocation clicks. Wahlberg *et al.* (2011) characterized the parameters of on-axis northern bottlenose whale clicks (N = 10) from recordings with a sampling rate of 192 kHz, made north of the Faeroe Islands in the eastern North Atlantic. These on-axis clicks were characterized as having an FM upsweep structure with a center frequency of 43 ± 7 kHz and an inter-click interval of 306 ± 118 ms. This description is limited in sample size and not detailed enough for a full comparison, but it is not consistent with the northern bottlenose whales clicks typically recorded in the western North Atlantic (Moors-Murphy, 2012; Martin and Moors-Murphy, 2013; Stanistreet *et al.*, 2017) or in the eastern north Atlantic, off Ireland (Kowarski *et al.*, 2018).

There is currently only one published description of the vocalizations of Sowerby's beaked whales, based on a single encounter with three groups of animals recorded on a towed hydrophone array (Cholewiak *et al.*, 2013). In this study Cholewiak *et al.* (2013) identified four different FM click types based on median peak frequencies, at 26, 33, 51, and 67 kHz. However, only one of these click types, with a 65–70 kHz peak frequency, has been found in other acoustic datasets, and therefore automated detectors, PAM programs, and analysts looking at data from bottom-mounted recorders have primarily relied on this high-frequency click type to detect and identify Sowerby's beaked whale clicks (Martin, 2016; Stanistreet *et al.*, 2017, Kowarski *et al.*, 2018).

Due to our evolving appreciation of beaked whale click characteristics, additional acoustic data from encounters with northern bottlenose and Sowerby's beaked whales are required to validate and expand our limited knowledge of the click types associated with these two beaked whale species. Clearly, understanding the range of variability associated with vocalizations made by northern bottlenose and Sowerby's beaked whales is also necessary for automated detector development for accurate PAM (whether through use of ship-based, moored, or other PAM systems) of both of these at-risk species. The objective of this study was to quantitatively describe the characteristics of echolocation click types produced by northern bottlenose whales and Sowerby's beaked whales, using recordings made during multiple visual encounters with each species along the continental shelf edge off eastern Canada.

II. METHODS

A. Data collection

Data were collected by the Whitehead Lab of Dalhousie University during cetacean research trips aboard the 13-metre auxiliary sailing vessel *Balaena*. During the summers of 2015, 2016, and 2017, the vessel travelled along the continental shelf edge from the Hague Line (the border that separates Canadian waters from the waters of the United States) up to southern Labrador surveying for beaked whales and other cetaceans. The vessel spent a substantial amount of time on the slope of the Scotian Shelf, particularly in the Gully MPA, Shortland and Haldimand submarine canyons, as well as off Newfoundland (Fig. 1). The primary purpose of these trips was to collect photographs, videos, biopsies and acoustic recordings of northern bottlenose whales; Sowerby's beaked whales and other species were incidentally sighted. As per methods used in previous photo-identification and acoustic studies of northern bottlenose whales on the Scotian Shelf (Wimmer and Whitehead, 2004; Moors-Murphy,

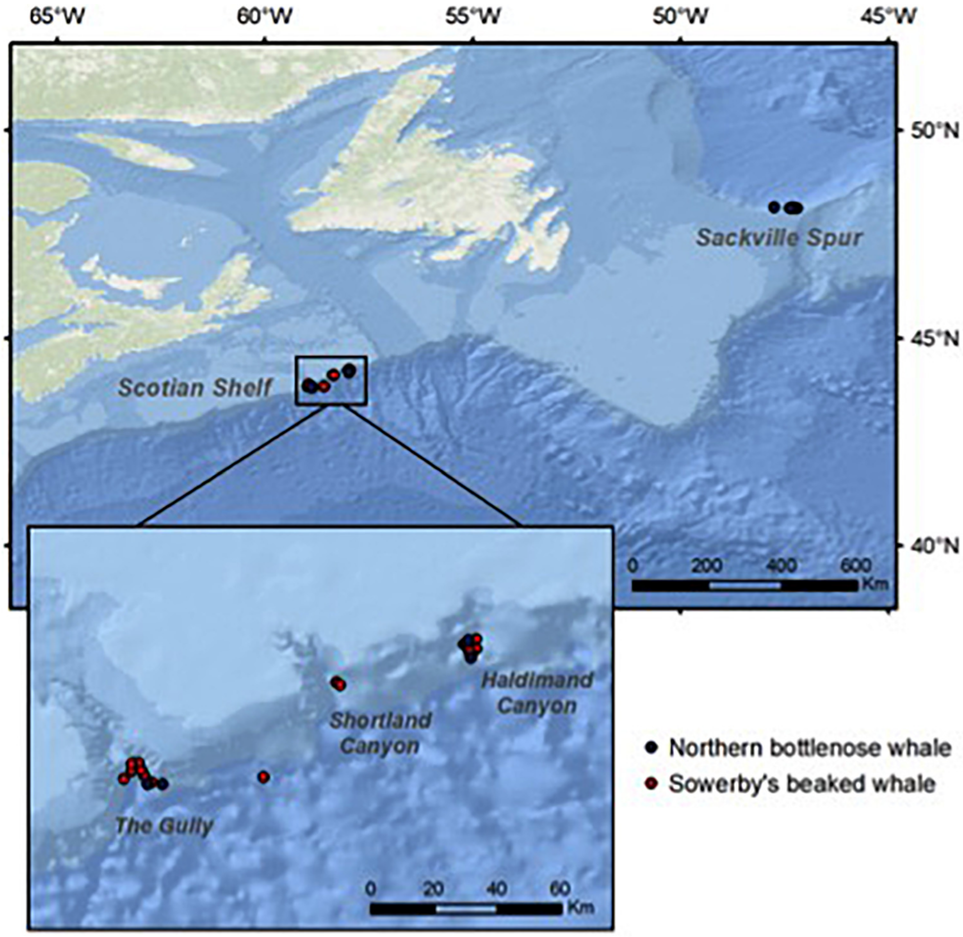

FIG. 1. (Color online) Locations of visual encounters with northern bottlenose whales (blue, N = 9) and Sowerby's beaked whales (red, N = 18) along the Scotian Shelf and in Newfoundland during the summers of 2015, 2016, and 2017 used in this study.

2015), constant watch was kept by at least two observers with the naked eye during all daylight hours and all cetacean sightings were recorded. Metadata collected included location, species, group size, behaviour and environmental conditions for each encounter. Visual encounters began when the whales were first sighted and ended 10 min after they were last seen. For encounters with northern bottlenose whales and Sowerby's beaked whales, depending on the proximity of the whales and field conditions, photographs and biopsies were also collected.

Acoustic data were collected throughout these trips, at a sampling rate of 192 kHz, using a two-element hydrophone array (Benthos AQ4 elements: −204 dBV re: 1 μPa, Magrec HP-02 preamplifier: 29 dB gain) towed approximately 100 m behind the ship. The array was often recording continuously while surveying under sail or motor as well as when following or observing whales, allowing for *post hoc* analysis of acoustic data recorded prior to, during, and after visual encounters with northern bottlenose whales and Sowerby's beaked whales.

B. Acoustic analysis

Visual encounters of northern bottlenose whales and Sowerby's beaked whales with concurrent acoustic data were selected for analysis and included in this study if they met all of the following criteria: (1) all relevant information about time, location, group size, or environmental conditions was available for the encounter; (2) field notes indicated that the whales were less than 1 km away (the estimated average beaked whale click detection range of the hydrophone); (3) visibility was clear, allowing for good sighting conditions with a Beaufort sea-state of 4 or less for northern bottlenose whales, and 5 or less for Sowerby's beaked whales; (4) other odontocetes or beaked whales were not seen within a 30 min window before and a 30 min window after the focal species encounter; and (5) specific to northern bottlenose whale sightings, there were no high-frequency Sowerby's beaked whale clicks detected on the recordings during the encounter.

For the northern bottlenose whale and Sowerby's beaked whale encounters that met these criteria, recordings were first visually analyzed using PAMLAB software (JASCO Applied Sciences, Dartmouth, Nova Scotia) starting 10 min before the sighting until 10 min after the visual encounter ended. Spectrograms of the recordings were scanned visually to find beaked whale clicks and apply screening criteria 5 (above) for northern bottlenose whale recordings, using a window length of 8 s, frequency scale of 0–96 kHz, and FFT settings of 94 Hz frequency step, 0.001 s frame length, 50% overlap and a Hamming window. All clicks with a FM upsweep, occurring in a non-overlapping click train (three or more clicks in a row, spaced approximately equidistantly),

TABLE I. Acoustic recordings selected for analysis from visual encounters with northern bottlenose whales during Whitehead lab cetacean monitoring trips in 2015, 2016, and 2017 off eastern Canada.

Date	Encounter duration (min)	Latitude (° N)	Longitude (° W)	Location	Estimated group size
6/15/15	11	44.2338	57.9708	Scotian Shelf	2
8/23/15	23	44.1848	57.9635	Scotian Shelf	2
8/19/16	11	43.8239	58.8445	Scotian Shelf	2
8/31/16	19	43.8227	58.8854	Scotian Shelf	1
7/14/17	34	48.1364	47.1904	Newfoundland	10–12
7/18/17	58	48.1382	47.2587	Newfoundland	4–10
7/18/17	10	48.1458	47.2903	Newfoundland	4
7/18/17	51	48.1398	47.3573	Newfoundland	7
7/29/17	1	48.1417	47.7241	Newfoundland	3–4

were then viewed individually at an enhanced spectrogram resolution allowing for more detailed examination of the click structure, using a window length of 0.0025 s, frequency scale of 0–96 kHz, and FFT settings of 375 Hz frequency step, 0.000 266 s frame length, 6% overlap and a Hamming window. Clicks were manually selected using the start and end points of the click waveform to draw an annotation box around each click.

These annotated clicks were extracted from the original wav file in MATLAB (R2016b, The Mathworks, Inc., Natick, MA), using methods and code adapted from Baumann-Pickering *et al.* (2013a). A noise sample 3 ms prior to each click annotation was also extracted, and a 10th-order Butterworth band-pass filter with a pass band of 5–95 kHz was applied to both the click and the noise sample. Signal-to-noise ratio (SNR) was calculated by comparing the root-mean-squared (rms) noise level using 512 samples of data from 3 ms preceding the click, and the rms signal level of the extracted click. Clicks with an SNR of 6 dB or lower were deemed to be of too low quality and excluded from further analysis. Power spectra and frequency-based parameters including peak frequency, center frequency, −10 dB bandwidth, and −10 dB lower and upper frequency bounds were calculated for each remaining click [using methods from Au (1993)]. Inter-click interval (ICI) was calculated as the difference in time between the start of one click and the start of the click immediately preceding it within a click train. ICIs of one second or more were removed from the dataset to eliminate intervals between click trains. Measured parameters of northern bottlenose whale clicks were compared between the sites on the Scotian Shelf (the Gully, Shortland, and Haldimand canyons) and Newfoundland.

III. RESULTS

A. Northern bottlenose whales

There were a total of 402 encounters in 2015, 2016, and 2017 where whales were sighted and visually confirmed as northern bottlenose whales; 320 of these had corresponding acoustic recordings. Using the screening criteria described above, nine visual encounters with northern bottlenose whales were selected for acoustic analysis (Table I). Four of these encounters occurred along the Scotian Shelf, in the Gully, Shortland and Haldimand canyons; five occurred off Newfoundland (Fig. 1). Group size ranged from one to an estimated 10–12 animals.

A total of 2239 northern bottlenose whale clicks were annotated in the recordings associated with these nine encounters. A few buzzes were observed but are not described further here. The clicks generally had a clear, consistent upsweep shape. The median peak frequency of all northern bottlenose whales clicks measured was 25.9 kHz (10th–90th percentile range: 22.9–29.3 kHz) and the −10 dB lower frequency bound was 20.3 kHz (10th–90th percentile range: 15.8–23.6 kHz) (Table II). The frequency parameters of clicks recorded on the Scotian Shelf and Newfoundland were similar (Table II). The shape of the mean power spectra of the annotated clicks were also similar between regions [Fig. 2(a)]. Other frequency parameters are reported in Table II. ICI was typically consistent, but some variation between click trains and occasionally within click trains was qualitatively observed. The overall median ICI was 402 ms (10th–90th percentile range: 290–524 ms), and the median ICI for the Scotian Shelf was slightly higher than the median ICI in Newfoundland, but clicks from both regions exhibited a largely overlapping range

TABLE II. Characteristics of echolocation clicks recorded during nine encounters with northern bottlenose whales. Median and 10th–90th percentile range of each parameter are given for clicks recorded in the Scotian Shelf and Newfoundland regions and for all clicks combined.

Parameter	Scotian Shelf	Newfoundland	All clicks
Sample size	968	1271	2239
Peak frequency (kHz)	26.3 (24.0–30.8)	25.5 (21.8–28.5)	25.9 (22.9–29.3)
Center frequency (kHz)	28.6 (25.2–32.8)	26.4 (22.6–30.2)	27.4 (23.5–31.8)
−10 dB bandwidth (kHz)	13.9 (9.8–22.5)	13.1 (8.6–21.8)	13.5 (9.4–22.1)
−10 dB lower frequency bound (kHz)	21.0 (18.4–23.6)	19.5 (15.0–22.9)	20.3 (15.8–23.6)
Sample size for ICI	842	1075	1917
Inter-click interval (ms)	414 (320–562)	394 (254–498)	402 (290–524)

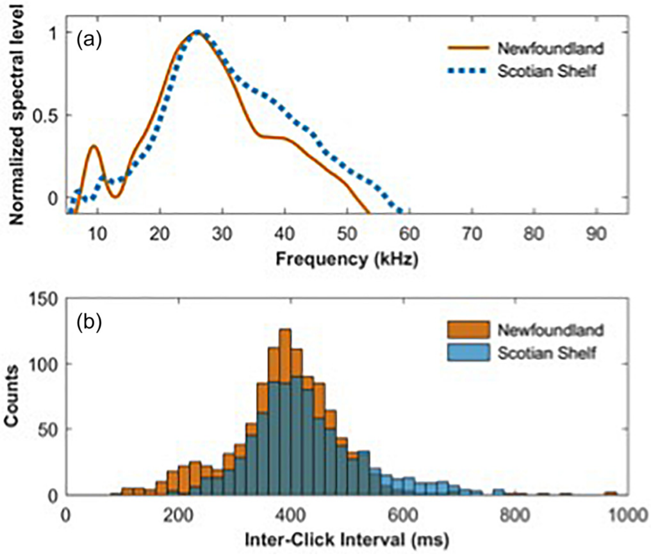

FIG. 2. (Color online) (a) Mean power spectra and (b) inter-click intervals (ICIs) of northern bottlenose whale clicks recorded on the Scotian Shelf and off Newfoundland between 2015 and 2017. Mean click spectra have been normalized to the same amplitude scale.

of variation in ICI [Fig. 2(b), Table II]. An example northern bottlenose whale click is shown in Fig. 3.

B. Sowerby's beaked whales

Of 41 visual encounters with Sowerby's beaked whales in 2015 and 2016, 40 had corresponding acoustic recordings, 18 of which were selected for acoustic analysis based on the screening criteria described above. Acoustic recordings during these 18 encounters were analyzed and 762 clicks were annotated (Table III). All of these encounters occurred along

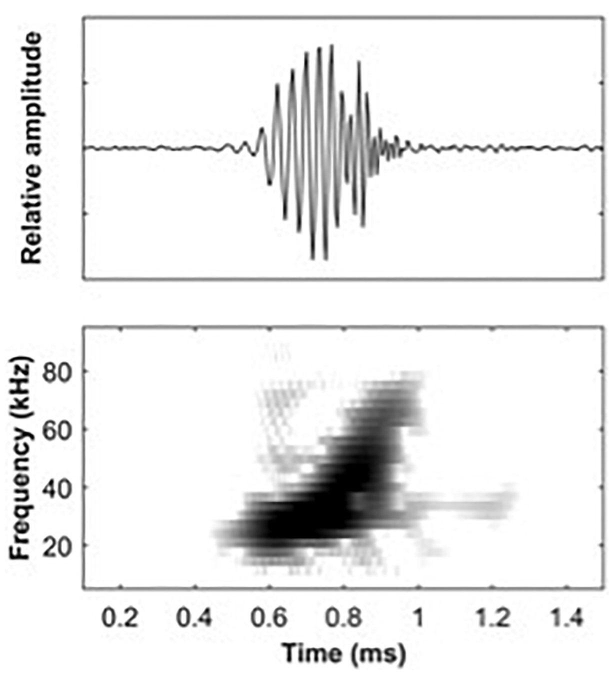

FIG. 3. Example northern bottlenose whale click. Top panel shows the waveform and bottom panel shows the spectrogram (sampling frequency 192 kHz, 60-point FFT, Hamming window, 98% overlap).

the Scotian Shelf, located in the Gully, Shortland, and Haldimand canyons (Fig. 1). Group size ranged from one to six animals.

The median peak frequency of the 762 annotated Sowerby's beaked whale clicks was 65.8 kHz (10th–90th percentile range: 61.5–76.5 kHz), and the −10 dB lower frequency bound was 55.1 kHz (10th–90th percentile range: 52.6–71.9 kHz) (Table IV). A clear FM upsweep shape was visible in most Sowerby's beaked whale clicks. The mean power spectra of all the annotated clicks was most similar to the "high-frequency" click type described in Cholewiak *et al.* (2013). Mean click spectra from that study, the only published reference on Sowerby's beaked whale clicks, are included in Fig. 4(a) for comparison. Other frequency parameters are reported in Table IV. The ICI had a broad and almost bimodal distribution; with a wide peak around 150–250 ms and a steep peak at 315 ms [Fig. 4(b)]. Median ICI was 237 ms (10th–90th percentile range: 130–315 ms) (Table IV). An example of a Sowerby's beaked whale click is shown in Fig. 5.

IV. DISCUSSION

The northern bottlenose whale clicks described in this study are consistent with clicks previously found in bottom-mounted recordings from the Gully (Martin and Moors-Murphy, 2013; Stanistreet *et al.*, 2017) and Ireland (Kowarski *et al.*, 2018). We found this click type in recordings made in the presence of northern bottlenose whales, not only in the Gully and other submarine canyons along the Scotian Shelf, but also off Newfoundland. This is in contrast to the higher center frequency and shorter ICI documented for on-axis clicks produced by northern bottlenose whales in the Faeroe Islands (Wahlberg *et al.*, 2011). Differences between our description of northern bottlenose whale clicks and these previously published values could simply be due to sample size, as Wahlberg *et al.* (2011) had a limited sample size of 10 clicks, compared to N = 2239 in this study. Other factors that can influence the variation in acoustic parameters are the specific environmental context in which they were recorded, such as the whale's range and orientation relative to the hydrophone, propagation effects, or differences in recording systems. However, the click parameters reported here are consistent with northern bottlenose clicks found in other large acoustic datasets from the Scotian Shelf and Ireland, which include both towed array and bottom-mounted recordings, suggesting that the frequency characteristics we describe are not unique to the environmental context or recorder characteristics of this study (Stanistreet *et al.*, 2017; Kowarski *et al.*, 2018). While we focused on describing the general characteristics of clicks produced by two beaked whale species, it is also important to consider intraspecific variation. In Blainville's beaked whales, Keating *et al.* (2016) found changes in peak frequency, center frequency and −10 dB bandwidth of clicks within an encounter (although duration and ICI did not vary). While we observed little variation in click parameters between encounters, and this was not the focus of our analysis, the collection of additional recordings along with

TABLE III. Acoustic recordings selected for analysis from visual encounters with Sowerby's beaked whales in the Gully, Shortland Canyon, and Haldimand Canyon during Whitehead lab cetacean monitoring trips in 2015 and 2016.

Date	Encounter duration (min)	Latitude (° N)	Longitude (° W)	Location	Estimated group size
6/18/15	10	44.2225	57.9847	Haldimand	3
6/18/15	10	44.2255	57.9761	Haldimand	3
6/18/15	10	44.2366	57.95	Haldimand	1
8/04/15	23	43.8283	58.875	Gully	3–5
8/15/15	10	43.8470	58.8974	Gully	3
8/20/16	10	44.2025	57.9686	Haldimand	1
8/21/16	16	44.1127	58.3487	Shortland	2
8/24/16	10	44.1963	57.9611	Haldimand	2
8/24/16	10	44.2081	57.9496	Haldimand	1
8/24/16	10	44.2023	57.9670	Haldimand	1
8/25/16	10	44.1066	58.339	Shortland	2–3
8/29/16	10	43.8375	58.9536	Gully	2
8/31/16	10	43.8622	58.9046	Gully	2
8/31/16	10	43.8843	58.9262	Gully	2
8/31/16	10	43.8436	58.5565	Gully	3
9/01/16	10	43.8615	58.9324	Gully	4
9/01/16	14	43.8839	58.9115	Gully	6
9/01/16	11	43.8800	58.9320	Gully	3

behavioural observations in a dedicated study could allow for comparisons between clicks produced in different social contexts to understand if there are more subtle differences in acoustic behaviour between encounters. As we learn more about the aggregation of northern bottlenose whales in Newfoundland, differences in acoustic behaviour between this group of whales, the Scotian Shelf population, and other distinct populations, such as the Davis-Strait-Baffin Bay-Labrador Sea population, have the potential to provide new insights into the population structure of this species.

The Sowerby's beaked whale clicks reported here are most similar to the high frequency clicks (N = 293) described by Cholewiak *et al.* (2013), one of four click types reported from a single encounter with Sowerby's beaked whales. While the peak frequencies are similar (~65 kHz), the mean spectra of the high frequency clicks recorded by Cholewiak *et al.* (2013) had a second lower energy peak around 33 kHz, which was not observed in the present study. Notably clicks from the encounter with Sowerby's beaked whales analysed by Cholewiak *et al.* (2013) occurred at the same time other odontocete species were sighted at the surface from the same vessel, which could have inadvertently affected the results of their analyses. We used visual sightings of other species as a criterion to exclude recordings from analysis in this study to reduce the probability of recording other species; however, it is difficult to control for the possibility of recording other species that were not seen. While this study made efforts to restrict the data analyzed through our field methods and analysis criteria, given the ranges over which acoustic signals recorded in an open ocean environment may travel and the amount of time that many cetacean species spend vocalizing at depth it is possible that there may have been other species present in the distance and on the recordings. The distribution of ICIs for

TABLE IV. Characteristics of echolocation clicks recorded during 18 encounters with Sowerby's beaked whales. Median and 10th–90th percentile range of each parameter are given for all clicks.

Parameter	All clicks
Sample size	762
Peak frequency (kHz)	65.8 (61.5–76.5)
Center frequency (kHz)	65.8 (61.4–71.3)
−10 dB bandwidth (kHz)	25.1 (9.8–30.8)
−10 dB lower frequency bound (kHz)	55.1 (52.6–71.9)
Sample size for ICI	677
Inter-click interval (ms)	237 (130–315)

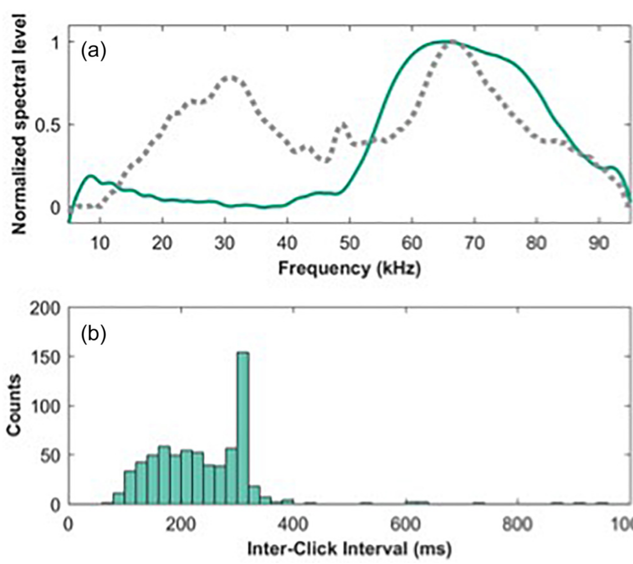

FIG. 4. (Color online) (a) Mean power spectra (solid line) and (b) inter-click intervals (ICIs) of Sowerby's beaked whale clicks recorded on the Scotian Shelf during 2015 and 2016. Dashed line in (a) represents the mean click spectra of the high frequency click type recorded during a single encounter with Sowerby's beaked whales off the eastern US, using data from Cholewiak *et al.* (2013). Mean click spectra have been normalized to the same amplitude scale.

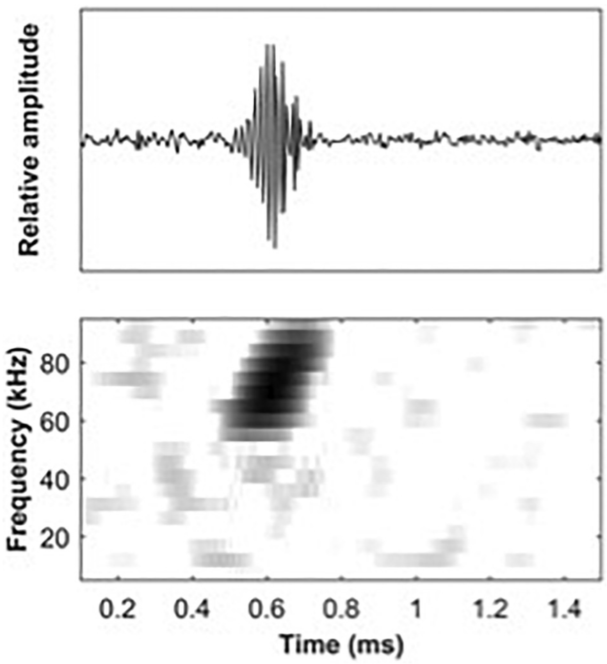

FIG. 5. Example Sowerby's beaked whale click. Top panel shows the waveform and bottom panel shows the spectrogram (sampling frequency 192 kHz, 60-point FFT, Hamming window, 98% overlap).

Sowerby's beaked whales in this study were highly variable (Fig. 4), with a similar range to Cholewiak *et al.* (2013). It is possible that some clicks within a click train were not recorded due to propagation effects or attenuation at the high frequencies characteristic of Sowerby's beaked whale clicks, which may result in measuring longer ICIs. However, the variability in ICI observed in this study did not appear to be due to missing clicks, and it is more likely that the ICI of Sowerby's click trains is inherently variable in the context they were recorded. Perhaps Sowerby's beaked whales produce slower click trains in some contexts (i.e., at the surface). The Sowerby's beaked whale clicks described here are similar to the putative Sowerby's clicks found by Stanistreet *et al.* (2017) in bottom-mounted recordings collected along the shelf edge off the northeastern United States and within the Gully. The geographic occurrence of this click type reflects the presumed range of Sowerby's beaked whales (MacLeod *et al.*, 2006). Furthermore, this click type is distinct from clicks attributed to all other known beaked whales in the North Atlantic, including Cuvier's beaked whale (*Ziphius cavirostris*), Blainville's beaked whale, Gervais' beaked whale, and True's beaked whale (Zimmer *et al.*, 2005; Johnson *et al.*, 2006; Gillespie *et al.*, 2009; DeAngelis *et al.*, 2018.).

Previous studies on beaked whale acoustic behaviour have described FM clicks using a variety of time and frequency parameters, which are often measured inconsistently and therefore difficult to compare across studies. Peak frequency is a measure often reported; however, it only indicates one point on the power spectrum of a click and may not adequately represent the distribution of energy across frequencies, particularly for broadband clicks that do not exhibit a narrow peak. Center frequency is often reported, but may also belie the shape of the click spectra. In this study, we also report the -10 dB lower frequency bound from the peak frequency, to provide additional information that may be useful in differentiating between beaked whale click types, as suggested by DeAngelis *et al.* (2018). Moving toward more consistent and representative reporting of beaked whale vocalizations will enable more accurate comparisons between studies and contribute to a better understanding of how these acoustic signals vary among species and regions.

Due to the nature of PAM using a towed array at the surface, directional clicks are often recorded off-axis which may result in distortion and greater variability in their spectral characteristics. Although the hydrophone and recording settings were consistent throughout the study, the results include clicks recorded during nine separate northern bottlenose whale encounters and 18 separate Sowerby's beaked whale encounters at different locations. This analysis did not account for salinity, water temperature, and various other factors that may have affected sound propagation. It was not possible to acoustically localize individual whales, since vessel speed and heading were highly variable during encounters and the precise orientation and depth of the hydrophone array was unknown. Thus, this analysis did not account for range, depth, and orientation of whales relative to the hydrophone array and likely recorded on- and off-axis clicks from a variety of angles. However, the variability of clicks produced by northern bottlenose whales and Sowerby's beaked whales reported here represents the characteristics of their clicks as received by towed array systems, providing a useful reference for detection from vessel platforms and as a baseline for future studies.

This study provides a quantitative description of northern bottlenose whale clicks from towed array recordings along the Scotian Shelf and in Newfoundland, as well as a description of Sowerby's beaked whale clicks recorded along the Scotian Shelf. While both species have previously been recorded, this is the first detailed description of a large sample of their echolocation clicks from a variety of contexts in the western North Atlantic. This study characterizes the most frequently recorded click types for both species but does not preclude the existence of other click types that may be less frequently recorded. Quantitative information on click characteristics is critical for improving automated click detection algorithms and the effectiveness of PAM for beaked whales, which ultimately provides the ability to confidently detect northern bottlenose whales and Sowerby's beaked whales from platforms without visual observers, including an extensive network of bottom-mounted PAM recorders that have been and continue to be deployed off eastern Canada and United States (e.g., Stanistreet *et al.*, 2017). A detailed appreciation for the acoustic behaviour of beaked whales based on live encounters is critical for gaining insight into their distribution, abundance, and overlap with current or proposed anthropogenic activities. Such an understanding contributes to the effective management and mitigation of the impacts of disturbance from these activities, and supports the recovery of these species at risk.

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