

Passive Acoustic Monitoring for Marine Mammals in the Western Atlantic, June 2017– June 2018

Macey A. Rafter, Ally C. Rice, Bruce J. Thayre, Erin O'Neill, Sean M. Wiggins, Kaitlin E. Frasier, Simone Baumann-Pickering, John A. Hildebrand

> Marine Physical Laboratory, Scripps Institution of Oceanography University of California San Diego, La Jolla, CA 92037

> > Danielle M. Cholewiak, Sofie M. Van Parijs

NOAA NMFS Northeast Fisheries Science Center, Protected Species Branch, Woods Hole, Massachusetts 02543



Long-Beaked Common Dolphins, Photo Credit: Jennifer Trickey

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M.A.R. completed all data analysis and produced all marine mammal and anthropogenic signal weekly and diel plots. A.C.R. compiled, wrote, and edited the report, conducted ambient soundscape analysis, and produced ambient soundscape plots. B.J.T. Coordinated field work logistics and deployed and recovered instruments. E.O. processed all recovered data. S.M.W. and K.E.F. contributed to algorithm development and K.E.F. also managed the project. S.B. and J.A.H. developed the project and determined data analysis approaches. D.M.C. and S.M.V.P. funded data collection and determined instrument locations.

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Executive Summary

Passive acoustic monitoring was conducted in the Western Atlantic (WAT) from June 2017 to June 2018. High-frequency Acoustic Recording Packages (HARPs) were deployed at eight offshore locations: Heezen Canyon (HZ) at 1,100 m depth, Oceanographer Canyon (OC) at 800 m depth, Nantucket Canyon (NC) at 920 m depth, Babylon Canyon (BC) at 1,000 m depth, Wilmington Canyon (WC) at 1,000 m depth, Gulf Stream (GS) at 930 m depth, Blake Plateau (BP) at 940 m depth, and Blake Spur (BS) at 1,000 m depth.

The HARPs recorded underwater sounds between 10 Hz and 100 kHz. Data analysis consisted of analyst scans of long-term spectral averages (LTSAs) and spectrograms, and automated computer algorithm detection when possible. One frequency band was analyzed for the low-frequency ambient soundscape between 10 and 1,000 Hz. Two frequency bands were analyzed for marine mammal vocalizations and anthropogenic sounds: (1) Mid-frequency, between 10 and 5,000 Hz, and (2) High-frequency, between 1 and 100 kHz. For this report there was no analysis for low frequency marine mammal vocalizations, such as those expected from mysticete whales (this analysis was performed separately by NOAA NMFS Northeast Fisheries Science Center).

The ambient soundscape was dominated by anthropogenic sounds, primarily ship traffic and seismic exploration between 10 and 100 Hz at all sites. Between 100 and 1,000 Hz the ambient soundscape was primarily a function of wind and sea state. A seasonal fin whale pattern was seen at all sites during winter months, although it was less pronounced at the three southernmost sites.

Echolocation clicks from eight known odontocete species were detected: Cuvier's beaked whale, Gervais' beaked whale, Sowerby's beaked whale, True's beaked whale, Blainville's beaked whale/northern bottlenose whale, sperm whales, *Kogia* spp., and Risso's dolphins. Detections of Cuvier's beaked whales occurred at all eight sites but were highest at sites HZ and WC. Gervais' beaked whale detections were highest at sites GS, BP, and BS. Sowerby's beaked whale detections were highest at site WC. True's beaked whale detections were highest at site NC. Combined Blainville's beaked whale and northern bottlenose whale detections were highest at site OC. Sperm whale clicks were detected at all eight sites throughout the recording period, but were highest at sites GS and BS. Risso's dolphin click detections were highest at sites NC, BC, and WC. Eight distinct click types that are not yet assigned to a species were also detected.

Four types of anthropogenic sounds were detected: broadband ship sound, explosions, airguns, and echosounders. Broadband ship sounds were detected the most at sites WC, BC, and OC. Explosions were detected at all sites but were highest at site NC. Airgun detections peaked during June at site BS and during July at site GS. Echosounders were detected at all eight sites but were highest at site HZ.

Project Background

In April 2015, a passive acoustic monitoring effort was initiated offshore of the northeast United States in the Western Atlantic (WAT), with support from the National Oceanic and Atmospheric Administration (NOAA), Northeast Fisheries Science Center (NEFSC). The goal of this effort was to characterize vocalizations of marine mammal species recorded in the area and to determine their seasonal presence. This report documents the analysis of sounds recorded by High-Frequency Acoustic Recording Packages (HARPs) from eight sites: Heezen Canyon (HZ), Oceanographer Canyon (OC), Nantucket Canyon (NC), Babylon Canyon (BC), Wilmington Canyon (WC), Gulf Stream (GS), Blake Plateau (BP), and Blake Spur (BS; Figure 1). These sites are all located along the continental slope at water depths of 800–1,100 m. Recording periods for this report were as follows: site HZ recorded from July 2017 to January 2018, site OC recorded form July 2017 to April 2018 (with a gap from 12/10/2017 to 1/4/2018) site NC recorded from July 2017 to June 2018, and sites BC, WC, GS, BP, and BS recorded from June 2017 to June 2018.



Figure 1. Location of High-frequency Acoustic Recording Packages (HARPs) as yellow circles at sites HZ (depth 1,100 m), OC (depth 800 m), NC (depth 920 m), BC (depth 1,000 m), WC (depth 1,000 m), GS (depth 930 m), BP (depth 940 m), and BS (depth 1,000 m).

Methods

High-Frequency Recording Package

HARPs are autonomous underwater acoustic recording devices that, dependent on configuration, can record sounds from 10 Hz up to 160 kHz, and are capable of approximately one year of continuous recording. At all eight sites, the HARPs were deployed in mooring configurations with the hydrophones suspended approximately 20 m above the seafloor. Each HARP hydrophone was calibrated in the laboratory to provide quantitative analysis of the received sound field. Representative data loggers and hydrophones have also been calibrated at the Navy's TRANSDEC facility in the past to verify the laboratory calibrations (Wiggins and Hildebrand, 2007).

Data Collected

Eight HARPs were deployed from June 2017 to June 2018 at sites HZ, OC, NC, BC, WC, GS, BP, and BS. The instruments recorded continuously at 200 kHz to provide 100 kHz of effective bandwidth from 189 to 364 days (Table 1).

Deployment	Latitude	Longitude	Depth	Start	End	Recordin	g Duration
Name	(W)	(E)	(m)	Date	Date	(Days)	(Hours)
HZ 03	41° 03.70	66° 21.09	1090	7/9/2017	1/13/2018	189	4,526
OC 03	40° 15.80	67° 59.18	790	7/6/2017	4/16/2018*	258	6,180
NC 03	39° 49.96	69° 58.92	919	7/16/2017	6/9/2018	328	7,867
BC 02	39° 11.43	72° 13.63	1000	6/30/2017	6/3/2018	338	8,110
WC 02	38° 22.43	73° 22.21	1000	6/30/2017	6/2/2018	338	8,110
GS 02	33° 40.02	75° 59.97	930	6/28/2017	6/26/2018	364	8,724
BP 02	32° 06.42	77° 05.41	941	6/27/2017	6/10/2018	348	8,784
BS 02	30° 34.98	77° 23.43	1005	6/2762017	6/23/2018	362	8,678

 Table 1. Passive acoustic monitoring in the Western Atlantic from June 2017 to June 2018.

*There was a gap in OC 03 from about 12/10/2017 to 1/4/2018 due to a disk not being fully imaged.

Data Analysis

The data analysis process is described below in terms of the low-frequency ambient soundscape, major classes of marine mammal calls and anthropogenic sounds in the WAT region, and the procedures used to detect them. For efficiency, the analysis for marine mammal calls and anthropogenic sounds were divided into two frequency bands: (1) Mid-frequency, 10–5,000 Hz, and (2) High-frequency, 1–100 kHz, where the full (high-frequency) band recordings were decimated by a factor of 20 to provide the mid-frequency band data. Analysis of the low-frequency band for marine mammal calls was not within the scope of this report.

To visualize the sound recordings, sound pressure level spectra were calculated for all recordings using a time average of 5 seconds and two frequency bin sizes (10 Hz and 100 Hz, for mid- and high-frequency band analyses, respectively). These spectra were arranged into long-term spectral averages (LTSAs) which were visually examined by analysts as a means to detect marine mammal and anthropogenic sounds. LTSAs were analyst-scanned in source-specific frequency bands and using automatic detection algorithms (described below). During visual analysis, when a sound of interest was identified but its origin was unclear, the corresponding waveform or spectrogram was examined further to classify the sounds to source (e.g., species or anthropogenic source). Signal classification was carried out by comparison to known source-specific spectral and temporal characteristics.

Each band was analyzed for the sounds of an appropriate subset of species or anthropogenic sources. Nearby shipping, explosions, and airguns were categorized as mid-frequency. Beaked whale pulses, sperm whale clicks, *Kogia* spp. clicks, dolphin clicks, and echosounders were categorized as high-frequency.

We summarize and characterize the sounds detected at sites HZ, OC, NC, BC, WC, GS, BP, and BS. We discuss the seasonal occurrence and relative abundance for calls of different species and for anthropogenic sounds that were identified in the acoustic recordings.

Low-frequency Ambient Soundscape

Ocean ambient sound pressure levels tend to decrease as frequency increases (Wenz, 1962). While baleen whales and anthropogenic sources, such as large ships and airguns, often dominate the ambient soundscape below 100 Hz (Širović *et al.*, 2004; McDonald *et al.*, 2006; Wiggins *et al.*, 2016), wind dominates the sound pressure levels from 200 Hz to 20 kHz (Knudsen *et al.*, 1948). To analyze the ambient soundscape, data were decimated by a factor of 100 to provide an effective bandwidth of 10 Hz to 1 kHz. LTSAs were then constructed with 1 Hz frequency and 5 s temporal resolution. To determine low-frequency ambient sound levels, daily spectra were computed by averaging five, 5 s sound pressure spectrum levels calculated from each 75 s acoustic record. System self-noise was excluded from these averages. Additionally, daily averaged sound pressure spectrum levels in 1-Hz bins were concatenated to produce long-term spectrograms for each site.

Odontocetes

Odontocetes (toothed whales) with sounds in the high-frequency range that are found in the Western Atlantic region include Atlantic white-sided dolphins (*Lagenorhynchus acutus*), shortbeaked common dolphins (*Delphinus delphis*), Atlantic spotted dolphins (*Stenella frontalis*), Clymene dolphins (*S. clymene*), striped dolphins (*S. coeruleoalba*), Risso's dolphins (*Grampus griseus*), bottlenose dolphins (*Tursiops truncatus*), rough-toothed dolphins (*Steno bredanensis*), false killer whales (*Pseudorca crassidens*), short-finned pilot whales (*Globicephala macrorhynchus*), long-finned pilot whales (*G. melas*), killer whales (*Orcinus orca*), sperm whales (*Physeter macrocephalus*), dwarf sperm whales (*Kogia sima*), pygmy sperm whales (*K. breviceps*), northern bottlenose whales (*Hyperoodon ampullatus*), Cuvier's beaked whales (*Ziphius cavirostris*), Gervais' beaked whales (*M. bidens*), and True's beaked whale (*M. mirus*).

Odontocete sounds can be categorized as echolocation clicks, burst pulses, or whistles. Echolocation clicks are broadband impulses with peak energy between 5 and 150 kHz, dependent upon the species. Buzz or burst pulses are rapidly repeated clicks that have a creak or buzz-like sound quality; they are generally lower in frequency than echolocation clicks. Dolphin whistles are tonal calls predominantly between 1 and 20 kHz that vary in frequency content, their degree of frequency modulation, as well as duration. These signals are easily detectable in an LTSA as well as in a spectrogram (Figure 2). Echolocation clicks were analyzed as a proxy for odontocete presence because they are currently the most promising call type for species classification in the region. Further analyses might identify distinguishing whistle or burst pulse characteristics.



Figure 2. Generic example demonstrating odontocete signal types in a LTSA (top) and spectrogram (bottom).

Click Classification

Odontocete echolocation clicks were detected automatically using an energy detector with a minimum received level threshold of 120 dBpp re: 1 μ Pa (Roch *et al.*, 2011; Fraiser, 2015).

Dominant click types and false positive categories at these sites were identified automatically by dividing detections into successive five-minute windows and determining the impulse signal categories in each window. An automated clustering algorithm was then used to identify recurrent types based on spectral features and inter-click interval (ICI) distributions at each site (Fraiser et al., 2017). Common click types were manually aggregated across all eight sites to form classification training and testing sets for 20 signal types including 17 odontocete signals and three sources of false positives. Click types were attributed to a specific species if known (e.g., beaked whales and Risso's dolphin) or assigned a number if species was unknown. A deep neural network was trained to classify these signal types with 98% classification accuracy on a balanced test set. This trained network was used to classify all five-minute windows across all sites. Classifications were retained if classification certainty exceeded 99% and the classified bin contained at least 50 clicks. Bins containing fewer than 50 detections were ignored and bins with less than 99% classification certainty were classified as "Unidentified Odontocete". This conservative classification strategy was used to minimize misclassifications. Classifier confusion is expected to be highest between sperm whales and ship noise, and possibly between True's and Gervais' beaked whale signals. Further manual verification could be used to improve classification accuracy in the future. Patterns at sites with very low reported encounter rates for a particular species should be interpreted with caution

prior to manual verification. Future work may improve automated classification accuracy by increasing training set sizes and considering temporal structure of detected events.

Beaked Whales

Beaked whales can be identified acoustically by their echolocation signals (Baumann-Pickering *et al.*, 2014; Clarke *et al.*, 2019). These signals are frequency-modulated (FM) upswept pulses, which appear to be species specific and distinguishable by their spectral and temporal features. Identifiable signals are described for all beaked whales known to occur in the region, namely Blainville's, Cuvier's, Gervais', Sowerby's, True's beaked whales, and northern bottlenose beaked whales. Beaked whale FM pulses were detected using the automated energy detector described previously.

Blainville's Beaked Whales / Northern Bottlenose Whales

Blainville's beaked whale echolocation signals (Figure 3) are polycyclic, with a characteristic frequency modulated upsweep, peak frequency around 28 to 39 kHz (Figure 4), with lower peak frequencies occurring at higher latitudes (unpublished results), and inter-pulse interval (IPI) of about 280 ms (Johnson *et al.*, 2006; Baumann-Pickering *et al.*, 2013). Northern bottlenose whales produce echolocation signals with a peak frequency around 26 kHz and an IPI of 400 ms (Clarke *et al.*, 2019) The Blainville's beaked whale/northern bottlenose whale click type shows a bimodal ICI pattern, with peaks at 225 and 335 ms. This bimodality is likely due to these two species being currently grouped into one click type.



Figure 3. Blainville's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at Site BS, May 2016.



Figure 4. Left: Mean frequency spectrum of Blainville's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Cuvier's Beaked Whales

Cuvier's beaked whale echolocation signals (Figure 5) are polycyclic, with a characteristic FM pulse upsweep, peak frequency around 40 kHz (Figure 6), and uniform inter-pulse interval of about 0.5 s (Johnson *et al.*, 2004; Zimmer *et al.*, 2005). An additional feature that helps with the identification of Cuvier's FM pulses is that they have two characteristic spectral peaks around 17 and 23 kHz (Figure 6).



Figure 5. Cuvier's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at site WC, May 2016.



Figure 6. Left: Mean frequency spectrum of Cuvier's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Gervais' Beaked Whales

Gervais' beaked whale signals (Figure 7) have energy concentrated in the 30–50 kHz band (Gillespie *et al.*, 2009), with a peak at 44 kHz (Baumann-Pickering *et al.*, 2013). While Gervais' beaked whale signals sweep up in frequency and are similar to those of Cuvier's and Blainville's beaked whales, the Gervais' beaked whale FM pulses are at a slightly higher frequency than those of the other two species. The IPI for Gervais' beaked whale signals is typically around 275 ms (Baumann-Pickering *et al.*, 2013; Figure 8).



Figure 7. Gervais' beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at site BS, September 2016.



Figure 8. Left: Mean frequency spectrum of Gervais' beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Sowerby's Beaked Whales

Sowerby's beaked whale echolocation signals have energy concentrated in the 50–95 kHz band, with a peak at 67 kHz (Figure 9). Sowerby's beaked whale signals have a characteristic FM upsweep, and are distinguishable from other co-occurring beaked whale signal types by their higher frequency content and a relatively short inter-pulse interval of around 150 ms (Cholewiak *et al.*, 2013; Clarke *et al.*, 2019; Figure 10).



Figure 9. Sowerby's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at site WC, May 2016.



Figure 10. Left: Mean frequency spectrum of Sowerby's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

True's Beaked Whale

True's beaked whale echolocation signals (Figure 11) are FM upswept pulses, with peak frequency around 46 kHz and an inter-pulse interval of about 180 ms (Figure 12). The spectral features of True's beaked whale FM pulses closely resemble those produced by Gervais' beaked whales, and acoustic discrimination between these two species remains challenging (DeAngelis *et al.*, 2018).



Figure 11. True's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at site NC, May 2016.



Figure 12. Left: Mean frequency spectrum of True's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Sperm Whales

Sperm whale clicks contain energy from 2 to 20 kHz, with the majority of energy between 10 and 15 kHz (Møhl *et al.*, 2003; Figure 13). Regular clicks, observed during foraging dives, demonstrate an ICI of 0.25–2s (Goold and Jones, 1995; Madsen *et al.*, 2002a; Figure 14). Short bursts of closely spaced clicks, called creaks, are observed during foraging dives and are believed to indicate a predation attempt (Watwood *et al.*, 2006). Slow clicks are used only by males and are more intense than regular clicks, with long inter-click intervals (Madsen *et al.*, 2002b). Codas are stereotyped sequences of clicks which are less intense and contain lower peak frequencies than regular clicks (Watkins and Schevill, 1977). Effort was not expended to denote whether sperm whale detections were codas, regular, or slow clicks; however, the classifier is most likely to recognize regular clicking.



Figure 13. Sperm whale clicks in LTSA (top) and spectrogram (bottom) recorded at site NC, April 2017.



Figure 14. Left: Mean frequency spectrum of sperm whale clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Kogia spp.

Dwarf and pygmy sperm whales emit echolocation signals which have peak energy at frequencies near 130 kHz (Au, 1993). While this is above the upper frequency band recorded by HARPs during these deployments, energy from *Kogia* clicks can be recorded within the 100 kHz HARP bandwidth (Figure 15). The observed signal may result both from the low-frequency tail of the *Kogia* echolocation click spectra, and from aliasing of energy from above the Nyquist frequency of 100 kHz (Figure 16).



Figure 15. Kogia spp. clicks in LTSA (top) and spectrogram (bottom) recorded at site BS, July 2016.



Figure 16. Left: Mean frequency spectrum of Kogia spp. clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Delphinid Click Types

Risso's dolphin clicks and at least eight other delphinid click types were identified across the eight recording sites; the click types were labeled 2–10. Some reported click types may contain multiple subtypes. Further analysis will be required to refine click types and reduce classification confusion between similar types.

Risso's Dolphin

Risso's dolphin clicks (Figure 17) have frequency peaks at approximately 22, 26, and 33 kHz. These clicks have a modal ICI of approximately 150 ms (Figure 18). Past studies have shown that spectral properties of Risso's dolphin clicks have slight variations with geographic region (Soldevilla *et al.*, 2017), although the multiple sharp frequency peaks and average ICI found at these northwestern Atlantic sites are similar to what has been found elsewhere.



Figure 17. Risso's dolphin clicks in LTSA (top) and spectrogram (bottom) recorded at site NC, April 2017.



Figure 18. Left: Mean frequency spectrum of Risso's dolphin click cluster (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with primary peak at 33 kHz; Right: Distribution of inter click intervals within cluster with modal peak at 0.15 seconds.

Click type 2 (Figure 19) has a narrow spectral peak at 22 kHz and a broad peak from 32 to 43 kHz. These clicks have a modal ICI of approximately 130 ms (Figure 20).



Figure 19. Click type 2 in LTSA (top) and spectrogram (bottom) recorded at site NC, June 2016.



Figure 20. Figure 16. Left: Mean normalized received sound pressure spectrum level of click type 2 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 22 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 130 ms.

Click type 3 (Figure 21) has a peak frequency of approximately 32 kHz, and a modal ICI of 65 ms (Figure 22).



Figure 21. Click type 3 in LTSA (top) and spectrogram (bottom) recorded at site NC, October 2016.



Figure 22. Left: Mean normalized received sound pressure spectrum level of click type 3 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 32 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 65 ms.

Click Type 4/6

Click types 4 & 6 are not consistently distinguishable across all sites and have been combined due to their similarities in inter-click interval and spectra. The combined click type 4/6 (Figure 23) has a peak frequency of approximately 19 kHz, and a modal ICI of 145 ms (Figure 24).



Figure 23. Click type 4/6 in LTSA (top) and spectrogram (bottom) recorded at site WC, May 2016.



Figure 24. Left: Mean normalized received sound pressure spectrum level of click type 4/6 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 19 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 145 ms.

Click type 5 (Figure 25) has a main peak frequency between 34 and 51 kHz, and two minor spectral peaks at 19 and 27 kHz. This click type has a modal ICI of 65 ms (Figure 26).



Figure 25. Click type 5 in LTSA (top) and spectrogram (bottom) recorded at site NC, August 2016.



Figure 26. Left: Mean normalized received sound pressure spectrum level of click type 5 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with primary peak between 34 and 51 kHz; Right: Distribution of inter-click intervals within cluster with modal peak at 65 ms.



Click type 7 (Figure 27) has a peak frequency of 28 kHz and a modal ICI of 70 ms (Figure 28).

Figure 27. Click type 7 in LTSA (top) and spectrogram (bottom) recorded at site HZ, September 2016.



Figure 28. Left: Mean normalized received sound pressure spectrum level of click type 7 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 28 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 70 ms.

Click type 8 (Figure 29) has a peak frequency at approximately 41 kHz and a modal ICI of 55 ms (Figure 30).



Figure 29. Click type 8 in LTSA (top) and spectrogram (bottom) recorded at site WC, May 2016.



Figure 30. Left: Mean normalized received sound pressure spectrum level of click type 8 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 41 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 55 ms.

Click type 9 (Figure 31) has a main peak frequency at approximately 26 kHz, and a minor spectral peak at 16 kHz (Figure 32). This click type has a modal ICI of 175 ms (Figure 32).

Figure 31. Click type 9 in LTSA (top) and spectrogram (bottom) recorded at site WC, September 2016.

Figure 32. Left: Mean normalized received sound pressure spectrum level of click type 9 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 26 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 175 ms.

Click type 10 (Figure 33) has a peak frequency of approximately 26 kHz and a modal ICI of 200 ms (Figure 34).

Figure 34. Left: Mean normalized received sound pressure spectrum level of click type 10 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 26 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 200 ms.

Anthropogenic Sounds

Several anthropogenic sounds were monitored for this report: broadband ships, explosions, airguns, and echosounders. Manual effort was expended for broadband ship sound and echosounders (Table 2), and the start and end of each individual sound or overall session was logged and their durations were added to estimate cumulative hours per week. An automated detector was used for the explosion and airgun analyses, described below. For explosions and airguns, individual signals were detected and are reported as weekly totals.

Sound Type	LTSA Search Parameters		
sound Type	Plot Length (hr)	Frequency Range (Hz)	
Broadband Ships	3	10–5,000	
Echosounders	1	5,000–100,000	

Broadband Ships

Broadband ship sound occurs when a ship passes within a few kilometers of the hydrophone. Ship sound can occur for many hours at a time, but broadband ship sound typically lasts from 10 min up to 3 h. Ship sound has a characteristic frequency-range dependent interference pattern in the LTSA (McKenna *et al.*, 2012). The combination of sound wave direct paths and surface reflected paths produce constructive and destructive interference (bright and dark bands) in the LTSA that varies by frequency and distance between the ship and the receiver (Figure 35, top). Noise can extend above 10 kHz, although sound levels typically decrease rapidly above a few kHz. Broadband ship analysis effort consisted of manual scans of the LTSA set at 3 hours with a frequency range of 10–5,000 Hz.

Figure 35. Broadband ship sound in the LTSA (top) and spectrogram (bottom) recorded at site BC.

Explosions

Effort was directed toward detecting explosive sounds in the recordings including military explosions, shots from sub-seafloor exploration, and seal bombs used by the fishing industry. An explosion appears as a vertical spike in the LTSA that, when expanded in the spectrogram, has a sharp onset with a reverberant decay (Figure 36). Explosions were detected automatically using a matched filter detector on data decimated to a 10 kHz sampling rate. The timeseries was filtered with a 10th order Butterworth bandpass filter between 200 and 2,000 Hz. Cross-correlation was computed between 75 s of the envelope of the filtered timeseries and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the match filter signal. The cross-correlation was squared to 'sharpen' peaks of explosion detections. A floating threshold was calculated by taking the median cross-correlation value over the current 75 s of data to account for detecting explosions within noise, such as shipping. A cross-correlation threshold of 3*10-6 above the median was set. When the correlation coefficient reached above threshold, the timeseries was inspected more closely.

Consecutive explosions were required to have a minimum time distance of 0.5 s to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end times above the threshold were determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and root-mean-square (rms) received sound pressure levels (RL) were computed over the potential explosion period as well as a timeseries of the length of the explosion template before and after the explosion. The potential explosion was classified as a false detection and deleted if 1) the dB difference of pp and rms levels between signal and time AFTER the detection was less than 4 dB or 1.5 dB respectively; 2) the dB difference of pp and rms levels between signal and time BEFORE the signal was less than 3 dB or 1 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 0.55 s of duration. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. A trained analyst subsequently verified the remaining potential explosions for accuracy. Explosions have energy as low as 10 Hz and often extend up to 2,000 Hz or higher, lasting for a few seconds including the reverberation.

Figure 36. Explosion example in the LTSA (top) and spectrogram (bottom) recorded at site BP.

Airguns

Airguns are regularly used in seismic exploration to investigate the ocean floor and what lies beneath it. A container of high-pressure air is momentarily vented to the surrounding water, producing an air-filled cavity which expands and contracts several times (Barger and Hamblen, 1980). Airgun blasts have energy as low as 10 Hz and can extend up to 250 Hz or higher, lasting for a few seconds including the reverberation. While most of the energy produced by an airgun array falls below 250 Hz, airguns can produce significant energy at frequencies up to at least 1 kHz (Blackman *et al.*, 2004). Source levels tend to be over 200 dB re 1 μ Pa-m (Amundsen and Landro, 2010), and have been measured up to 260 dB rms re 1 μ Pa-m (Hildebrand, 2009). These blasts typically have an inter-pulse interval of approximately 10 s and bouts can last from several hours to days (Figure 37).

Airguns were detected automatically using a matched filter detector on data decimated to a 10 kHz sampling rate. The timeseries was filtered with a 10th order Butterworth bandpass filter between 25 and 200 Hz. Cross correlation was computed between 75 s of the envelope of the filtered timeseries and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the matched filter signal. The cross correlation was squared to 'sharpen' peaks of airgun blast detections. A floating threshold was calculated by taking the median cross correlation value over the current 75 s of data to account for detecting airguns within noise, such as shipping. A cross correlation threshold of $2*10^{-6}$ above the median was set. When the correlation coefficient reached above this threshold, the timeseries was inspected more closely.

Consecutive airgun blasts were required to have a minimum start time difference of 2 s to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end times above the threshold were marked when the energy rose by more than 2 dB above the median energy across the detection. The pp and rms RLs were computed over the potential blast period as well as a timeseries of the length of the airgun blast template before and after the explosion. The potential airgun blast was classified as a false detection and deleted if 1) the signal dB difference of pp and rms during and AFTER the detection was less than 4 dB or 0.5 dB respectively; 2) the dB difference of pp and rms between signal and time BEFORE the signal was less than 3 dB or 0.5 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 10 s. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. Airgun blast interpulse intervals were used to discard potential airgun detections that were not part of a sequence. A trained analyst subsequently verified the remaining potential airgun detections for accuracy.

Figure 37. Airgun example in the LTSA (top) and spectrogram (bottom) and recorded at site GS.

Echosounders

Echosounding sonars transmit short pulses or frequency sweeps, typically in the high-frequency (above 5 kHz) band (Figure 38), although echosounders are occasionally found in the mid-frequency range (2–5 kHz). Many large and small vessels are equipped with echosounding sonar for water depth determination, fish detection, or other ocean sensing; typically these echosounders are operated much of the time a ship is at sea, as an aid for navigation and fishing operations. Presence of high-frequency echosounders was manually detected by analysts reviewing LTSA plots.

Figure 38. Echosounders in the LTSA (top) and spectrogram (bottom) recorded at site HZ.

Results

The results of acoustic data analysis at all eight sites are summarized below. We describe the low-frequency ambient soundscape, the seasonal occurrence and relative abundance of several marine mammal acoustic signals, as well as detected anthropogenic sounds.

Ambient Soundscape

Daily-averaged ambient soundscape spectra were processed into monthly-averages and plotted using the same monthly color scheme for each of the deployments so that months from different sites and years can be compared. If more than a year of data is present, dashed lines are used for months in the second year. Partial months, those with less than 90% of total days recorded, include an asterisk (*) in the color legend and more detail is provided in Table 3.

- For all sites, levels between 10 and 100 Hz were dominated by anthropogenic sounds, primarily ship traffic and seismic exploration (Hildebrand, 2009). In this band, levels across most sites are within ~5 dB of one another. Site GS shows levels ~10 dB higher in winter (Figure 44), site BP shows levels ~10 dB higher (Figure 45), and site BS shows levels ~10–20 dB higher (Figure 46).
- Between 100 and 1000 Hz, sound pressure spectrum levels are largely a function of wind and sea state. The highest levels are found at site OC in March 2018 (Figure 40), and the lowest during summer at site BS (Figure 46). In general, spectrum levels are highest during winter months, and lowest during summer months.
- A seasonal 20 Hz fin whale signal is present at all eight sites, although it is not as pronounced at sites GS, BP, and BS as during the previous reporting period (Rafter *et al.*, 2018). Highest levels were measured at site NC in January 2018 (Figure 41).
- High levels at low frequencies (10–20 Hz) at sites GS (Figure 44), BP (Figure 45), and BS (Figure 46) may be due to strong currents that result in hydrophone cable strumming.
- There is a year-round presence of a fish call that down sweeps signal from about 800 to 400 Hz at site HZ that can be clearly seen in the summer and fall monthly sound pressure spectrum level averages (Figure 39). In September 2017, the signal has its highest signal-to-noise ratio (SNR) due to otherwise particularly low ambient sound levels, with signal levels in that band reaching ~2.5 dB above ambient levels.
- These results are generally consistent with previous monitoring periods (Varga *et al.*, 2017; Rafter *et al.*, 2018).

Deployment	Month / Year	Days of Data / Days in Month
HZ 03	July 2017	23/31
	January 2018	13/31
OC 03	July 2017	26/31
	December 2017	10/31
	January 2018	28/31
	April 2018	16/30
NC 02	July 2017	16/31
NC 05	June 2018	09/30
BC 02	June 2018	03/30
WC 02	June 2018	02/30
GS 02	June 2017	03/30
	April 2018	26/30
BB 02	June 2017	04/30
DP 02	June 2018	10/30
BS 02	June 2017	04/30
	June 2018	23/30

Table 3. Incomplete months included in the ambient soundscape analysis during this recording period.

Figure 39. Low-frequency ambient soundscape at site HZ from July 2017 to January 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site HZ from July 2017 to January 2018 (bottom).

Figure 40. Low-frequency ambient soundscape at site OC from July 2017 to April 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site OC from July 2017 to April 2018 (bottom).


Figure 41. Low-frequency ambient soundscape at site NC from July 2017 to June 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site NC from July 2017 to June 2018 (bottom).



Figure 42. Low-frequency ambient soundscape at site BC from July 2017 to June 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site BC from July 2017 to June 2018 (bottom).



Figure 43. Low-frequency ambient soundscape at site WC from July 2017 to June 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site WC from July 2017 to June 2018 (bottom).



Figure 44. Low-frequency ambient soundscape at site GS from June 2017 to April 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site GS from June 2017 to April 2018 (bottom).



Figure 45. Low-frequency ambient soundscape at site BP from June 2017 to June 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site BP from June 2017 to June 2018 (bottom).



Figure 46. Low-frequency ambient soundscape at site BS from June 2017 to June 2018 (top). Legend gives color-coding by month. Months with an asterisk (*) have partial recording effort. Long-term spectrograms using daily-averaged spectra for site BS from June 2017 to June 2018 (bottom).

Odontocetes

Beaked Whales

Cuvier's, Gervais', and Blainville's beaked whale/northern bottlenose whale echolocation clicks were detected at all eight sites. True's beaked whale echolocation clicks were detected at all sites except BS and Sowerby's beaked whale echolocation clicks at all sites but GS and BP. If detections are sparse for a particular species and site combination, presence should be interpreted with caution prior to manual verification. More details of each species' presence at all eight sites are given below.

Cuvier's Beaked Whales

- Cuvier's beaked whale echolocation clicks were detected throughout the monitoring period at sites HZ, BC, and WC, and intermittently at all other sites (Figure 47; Figure 48).
- Presence was highest at site HZ during the winter (Figure 47) and at site WC during the winter and spring (Figure 48).
- There were consistent detections throughout the monitoring period at site BC (Figure 47), though in lower numbers than at sites HZ and WC.
- There was no diel pattern for Cuvier's beaked whale echolocation clicks (Figure 49; Figure 50).



Figure 47. Weekly presence (black bars) of Cuvier's beaked whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week. *Note: Axis change for sites HZ and BC due to a higher amount of Cuvier's beaked whale echolocation detections compared to the rest of the sites*.



Figure 48. Weekly presence (black bars) of Cuvier's beaked whale echolocation clicks between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of Cuvier's beaked whale echolocation detections compared to the rest of the sites*.



Figure 49. Cuvier's beaked whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Gray vertical shading denotes nighttime, and light purple horizontal shading denotes absence of acoustic data.



Figure 50. Cuvier's beaked whale echolocation clicks in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Gervais' Beaked Whales

- Gervais' beaked whale echolocation clicks were primarily detected at the southernmost sites, with detections occurring mainly during the fall at site BP and during fall and winter at site GS (Figure 51; Figure 52). Gervais' beaked whale detections at northern sites are likely to be misclassified True's beaked whale.
- There was no diel pattern for Gervais' beaked whale echolocation clicks (Figure 53; Figure 54).



Figure 51. Weekly presence (black bars) of Gervais' beaked whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 52. Weekly presence (black bars) of Gervais' beaked whale echolocation clicks between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Different axes due to the variable amount of Gervais' beaked whale echolocation detections at these sites.*



Figure 53. Gervais' beaked whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 54. Gervais' beaked whale echolocation clicks in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Sowerby's Beaked Whales

- Sowerby's beaked whale echolocation clicks were detected at all sites except GS and BP. Detections were most common at sites HZ, BC, and WC, with WC having the highest presence overall and a peak in detections during August 2017 (Figure 55; Figure 56).
- There was no diel pattern for Sowerby's beaked whale echolocation clicks (Figure 57; Figure 58).



Figure 55. Weekly presence (black bars) of Sowerby's beaked whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Axis change for site HZ due to a higher amount of Sowerby's beaked whale echolocation detections compared to the rest of the sites*.



Figure 56. Weekly presence (black bars) of Sowerby's beaked whale echolocation clicks between June 2017 and June 2018 at sites WC and BS. Effort markings are described in Figure 47. *Note: Different axes due to a higher amount of Sowerby's beaked whale echolocation detections at site WC*.



Figure 57. Sowerby's beaked whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 58. Sowerby's beaked whale echolocation clicks in five-minute bins (blue bars) at sites WC and BS. Effort markings are described in Figure 49.

True's Beaked Whales

- True's beaked whales echolocation clicks were detected at all sites except BS and were most common at site NC between January and March 2018 (Figure 59; Figure 60). It is possible that detections at southern sites may be misclassified Gervais' detections (Figure 60).
- There was no diel pattern for True's beaked whale echolocation clicks (Figure 61; Figure 62).



Figure 59. Weekly presence (black bars) of True's beaked whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 60. Weekly presence (black bars) of True's beaked whale echolocation clicks between June 2017 and June 2018 at sites WC, GS, and BP. Effort markings are described in Figure 47.



Figure 61. True's beaked whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 62. True's beaked whale echolocation clicks in five-minute bins (blue bars) at sites WC, GS, and BP. Effort markings are described in Figure 49.

Blainville's Beaked Whales/Northern Bottlenose Whale

- Blainville's beaked whale/northern bottlenose whale echolocation clicks occurred intermittently throughout the monitoring period at all sites (Figure 63; Figure 64).
- Highest detections occurred during the summer at site OC, and the majority, if not all, of these detections were likely from northern bottlenose whales. Effort is being given towards better classifying clicks from these two species for future monitoring periods.
- Most detections occurred during the daytime at site OC, while during the nighttime at site BS (Figure 65; Figure 66). These differences could be a result of these detections being a mix of Blainville's beaked whales further south and northern bottlenose whales further north.



Figure 63. Weekly presence (black bars) of Blainville's beaked whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 64. Weekly presence (black bars) of Blainville's beaked whale echolocation clicks between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47.



Figure 65. Blainville's beaked whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 66. Blainville's beaked whale echolocation clicks in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Sperm Whales

- Sperm whale click detections occurred at all sites (Figure 67; Figure 68) with highest detection rates at the most northern sites, particularly sites HZ and NC (Figure 67).
- Detections were lowest at site BP (Figure 68).
- There were more click detections during the day at sites HZ, NC, GS, and possibly at OC and BC (Figure 69; Figure 70).



Figure 67. Weekly presence (black bars) of sperm whale echolocation clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 68. Weekly presence (black bars) of sperm whale echolocation clicks between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of sperm whale echolocation detections compared to the rest of the sites*.



Figure 69. Sperm whale echolocation clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 70. Sperm whale echolocation clicks in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.
Kogia spp.

- *Kogia* spp. clicks were detected at five of the eight sites (Figure 71; Figure 72) and were highest at the southernmost sites, GS, BP, and BS (Figure 72). There were no detections at sites OC, BC, or WC.
- There was no diel pattern for *Kogia* spp. clicks (Figure 73; Figure 74).



Figure 71. Weekly presence (black bars) of *Kogia* spp. echolocation clicks between June 2017 and June 2018 at sites HZ and NC. Effort markings are described in Figure 47.



Figure 72. Weekly presence (black bars) of *Kogia* spp. echolocation clicks between June 2017 and June 2018 at sites GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site GS due to a higher amount of Kogia spp. echolocation detections compared to the rest of the sites*.



Figure 73. *Kogia* spp. echolocation clicks in five-minute bins (blue bars) at sites HZ and NC. Effort markings are described in Figure 49.



Figure 74. *Kogia* spp. echolocation clicks in five-minute bins (blue bars) at sites GS, BP, and BS. Effort markings are described in Figure 49.

Delphinid Click Types

Risso's Dolphins

- Risso's dolphins were detected at all eight sites with highest detection rates at the most northern sites, particularly NC, BC, and WC (Figure 75; Figure 76).
- At sites HZ and OC, detections occurred mainly during the fall, while at NC, BC, and WC the detections peaked during the spring (Figure 75; Figure 76).
- There were distinct diel patterns for Risso's dolphins with detections occurring primarily during nighttime in the fall and primarily during the daytime in the spring (Figure 77; Figure 78).



Figure 75. Weekly presence (black bars) of Risso's dolphin clicks between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 76. Weekly presence (black bars) of Risso's dolphin clicks between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher quantity of Risso's dolphin click detections compared to the rest of the sites*.



Figure 77. Risso's dolphin clicks in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 78. Risso's dolphin clicks in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Click Type 2

- Click type 2 was detected throughout the monitoring period at all sites, but was highest at the more northern sites, particularly during the spring at sites BC and WC (Figure 79; Figure 80).
- The majority of click type 2 detections occurred during nighttime hours (Figure 81; Figure 82).
- Manual analysis on a subset of data shows that click type 2 is often hard to distinguish from click type 9 due to natural variability within each type. These two types have similar distinctive spectral features and modal inter-click intervals, suggesting that they may be produced by the same species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 79. Weekly presence (black bars) of click type 2 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 80. Weekly presence (black bars) of click type 2 detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of click type 2 detections compared to the rest of the sites*.



Figure 81. Click type 2 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 82. Click type 2 detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

- Click type 3 was detected across all eight sites, but was highest at sites WC and BC (Figure 83; Figure 84). Detections typically peaked during the summer and fall.
- The majority of click type 3 detections occurred during nighttime hours, though at the sites with the most detections (WC and BC), detections occurred throughout the day as well (Figure 85; Figure 86).
- Manual analysis on a subset of data shows that click type 3 is often recorded concurrently with Click type 7. These two types have similar spectral content, modal inter-click intervals, diel patterns, and geographic distributions, suggesting that they may be produced by the same species. Alternatively, these types may capture a continuum of generic mid-frequency clicks with peak frequencies ranging from ~28 kHz to ~32 kHz, which may be produced by more than one species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 83. Weekly presence (black bars) of click type 3 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Axis change for site BC due to a higher amount of click type 3 detections compared to the rest of the sites*.



Figure 84. Weekly presence (black bars) of click type 3 detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of click type 3 detections compared to the rest of the sites*.



Figure 85. Click type 3 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 86. Click type 3 detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

- Click type 4/6 was detected at all sites except BS, with the highest detections occurring at sites BC and WC, particularly during the fall (Figure 87; Figure 88).
- The majority of click type 4/6 detections occurred during nighttime hours (Figure 89; Figure 90).
- Manual analysis on a subset of data shows that click type 4/6 is often hard to distinguish from click type 10 due to natural variability within each type. These two types have similar spectral content, modal inter-click intervals, diel patterns, and geographic distributions, suggesting that they may be produced by the same species. Alternatively, these types may capture a continuum of generic low-frequency clicks with peak frequencies ranging from ~18 kHz to ~25 kHz, which may be produced by more than one species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 87. Weekly presence (black bars) of click type 4/6 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 88. Weekly presence (black bars) of click type 4/6 detections between June 2017 and June 2018 at sites WC, GS, and BP. Effort markings are described in Figure 47.



Figure 89. Click type 4/6 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 90. Click type 4/6 detections in five-minute bins (blue bars) at sites WC, GS, and BP. Effort markings are described in Figure 49.

Click Type 5

- Click type 5 was detected intermittently at the five most northern sites and was not detected at sites GS, BP, or BS (Figure 91; Figure 92). Detections were highest at site OC.
- Click type 5 occurred primarily during nighttime hours (Figure 93; Figure 94).



Figure 91. Weekly presence (black bars) of click type 5 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 92. Weekly presence (black bars) of click type 5 detections between June 2017 and June 2018 at site WC. Effort markings are described in Figure 47.



Figure 93. Click type 5 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 94. Click type 5 detections in five-minute bins (blue bars) at site WC. Effort markings are described in Figure 49.

- Click type 7 was detected at all eight sites, but was most common at the five most northern sites. Detections peaked at WC during the fall and at OC during the spring (Figure 95; Figure 96).
- Click type 7 occurred primarily during nighttime hours (Figure 97; Figure 98).
- Manual analysis on a subset of data shows that click type 7 is often recorded concurrently with click type 3. These two types have similar spectral content, modal inter-click intervals, diel patterns, and geographic distributions, suggesting that they may be produced by the same species. Alternatively, these types may capture a continuum of generic mid-frequency clicks with peak frequencies ranging from ~28 kHz to ~32 kHz, which may be produced by more than one species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 95. Weekly presence (black bars) of click type 7 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 96. Weekly presence (black bars) of click type 7 detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of click type 7 detections compared to the rest of the sites*.



Figure 97. Click type 7 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 98. Click type 7 detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Click Type 8

- Click type 8 was detected at all eight sites with the highest detections occurring at sites WC and BC (Figure 99; Figure 100).
- Click type 8 was detected more during daytime hours at sites BC and WC, but there was no clear diel pattern at the other sites (Figure 101; Figure 102).



Figure 99. Weekly presence (black bars) of click type 8 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Axis change for sites HZ and OC due to a lower amount of click type 8 detections compared to the rest of the sites*.


Figure 100. Weekly presence (black bars) of click type 8 detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for sites BP and BS due to a lower amount of click type 8 detections compared to the rest of the sites*.



Figure 101. Click type 8 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 102. Click type 8 detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Click Type 9

- Click type 9 was detected at all sites except GS. Detections were intermittent at most sites but occurred in high numbers throughout the monitoring period at site BS, relative to the other sites (Figure 103; Figure 104).
- Click type 9 showed no clear diel pattern at any site (Figure 105; Figure 106).
- Manual analysis on a subset of data shows that click type 9 is often hard to distinguish from click type 2 due to natural variability within each type. These two types have similar distinctive spectral features and modal inter-click intervals, suggesting that they may be produced by the same species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 103. Weekly presence (black bars) of click type 9 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 104. Weekly presence (black bars) of click type 9 detections between June 2017 and June 2018 at sites WC, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site BS due to a higher amount of click type 9 detections compared to the rest of the sites*.



Figure 105. Click type 9 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 106. Click type 9 detections in five-minute bins (blue bars) at sites WC, BP, and BS. Effort markings are described in Figure 49.

- Click type 10 occurred regularly across all eight sites, with detections highest during April at site OC (Figure 107; Figure 108).
- There was no diel pattern for click type 10 (Figure 109; Figure 110).
- Manual analysis on a subset of data shows that click type 10 is often hard to distinguish from click type 4/6 due to natural variability within each type. These two types have similar spectral content, modal inter-click intervals, diel patterns, and geographic distributions, suggesting that they may be produced by the same species. Alternatively, these types may capture a continuum of generic low-frequency clicks with peak frequencies ranging from ~18 kHz to ~25 kHz, which may be produced by more than one species. In future analyses, combination of these two types should be considered, unless other evidence comes to light supporting their attribution to separate species.



Figure 107. Weekly presence (black bars) of click type 10 detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Axis change for site OC due to a higher amount of click type 10 detections compared to the rest of the sites*.



Figure 108. Weekly presence (black bars) of click type 10 detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47.



Figure 109. Click type 10 detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 110. Click type 10 detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Unclassified Odontocete Clicks

Signals that had characteristics of odontocete clicks but could not be classified to species were labeled as unclassified odontocetes. Clicks were left unclassified if too few clicks were detected in a time bin (< 20 clicks / minute), if they did not match any documented click types, or if detected clicks were of poor quality (e.g., low amplitude or masked).

- Unclassified clicks were detected throughout the recording period at all eight sites, but were highest at the five most northern sites (Figure 111; Figure 112).
- At most sites there was no discernible diel pattern for unclassified clicks, but at sites OC, BC, and WC there were more clicks during nighttime hours in the winter (Figure 113; Figure 114).



Figure 111. Weekly presence (black bars) of unclassified click detections between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47.



Figure 112. Weekly presence (black bars) of unclassified click detections between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47.



Figure 113. Unclassified click detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 114. Unclassified click detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Anthropogenic Sounds

Four types of anthropogenic sounds were detected: broadband ship sounds, explosions, airguns, and echosounders. There were also occasional HFA and communication signals detected although we did not have analysis effort for these signal types during this reporting period. Site GS had two instances of communication signals on August 30, 2017 and March 27, 2018, while site BP had one instance on September 25, 2017. Site BS had one instance of communication signals on December 24, 2017 and two instances of HFA sonar on February 23, 2018 and May 26, 2018.

Broadband Ships

- Broadband ship sounds were detected at all eight sites during the recording period. Sites WC, BC, and OC had the highest amount of ship detections (Figure 115; Figure 116).
- There was no diel pattern for broadband ship sounds at most sites, but site WC showed higher detections of broadband ship sounds during the day (Figure 117; Figure 118).



Figure 115. Weekly presence (black bars) of broadband ship sounds between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Higher axes for sites OC and BC due to a higher amount of broadband ship detections compared to the rest of the sites.*



Figure 116. Weekly presence (black bars) of broadband ship sounds between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for site WC due to a higher amount of broadband ship detections compared to the rest of the sites.*



Figure 117. Broadband ship sounds in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 118. Broadband ship sounds in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Explosions

- Explosions were detected at all eight sites throughout the recording period and were highest at site NC (Figure 119; Figure 120). The total number of explosions detected at each site are as follows:
 - o 8 at HZ
 - 47 at OC
 - 632 at NC
 - 149 at BC
 - $\circ \quad 210 \text{ at WC}$
 - \circ 45 at GS
 - 11 at BP
 - 44 at BS
- There was no clear diel pattern for explosion detections (Figure 121; Figure 122).



Figure 119. Weekly presence (black bars) of explosions between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Different axes due to the variable amounts of explosion detections at these sites.*



Figure 120. Weekly presence (black bars) of explosions between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change at site WC due to the higher number of explosion detections compared to the other sites.*



Figure 121. Explosion detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 122. Explosion detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Airguns

- Airguns were detected at all eight sites. The number of airgun detections varied widely across all sites, but tended to be higher at the more southern sites (Figure 123; Figure 124). The highest peak occurred in June at site BS, followed by July at site GS (Figure 124).
- There was no clear diel pattern for airgun detections at any site (Figure 125; Figure 126).



Figure 123. Weekly presence (black bars) of airguns between June 2017 and June 2018 at sites HZ, OC, NC, and BC. Effort markings are described in Figure 47. *Note: Different axes due to the variable amounts of airgun detections at these sites*.



Figure 124. Weekly presence (black bars) of airguns between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Different axes due to the variable amounts of airgun detections at these sites*.



Figure 125. Airgun detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 126. Airgun detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

Echosounders

- Echosounders were detected intermittently at all eight sites (Figure 127; Figure 128).
- Site HZ had the highest number of detections, with a peak in August 2017, while sites BC, WC, and GS had peaks during the fall (Figure 127; Figure 128).
- There was no diel pattern for echosounder detections (Figure 129; Figure 130).



Figure 127. Weekly presence (black bars) of echosounders between June 2017 and June 2018 at sites HZ, NC, OC, and BC. Effort markings are described in Figure 47. *Note: Axis change for sites HZ and BC due to a higher amount of echosounder detections compared to the rest of the sites*.



Figure 128. Weekly presence (black bars) of echosounders between June 2017 and June 2018 at sites WC, GS, BP, and BS. Effort markings are described in Figure 47. *Note: Axis change for sites WC and GS due to a higher amount of echosounder detections compared to the rest of the sites*.


Figure 129. Echosounder detections in five-minute bins (blue bars) at sites HZ, OC, NC, and BC. Effort markings are described in Figure 49.



Figure 130. Echosounder detections in five-minute bins (blue bars) at sites WC, GS, BP, and BS. Effort markings are described in Figure 49.

References

- Amundsen, L., and Landro, M. (2010). *Marine Seismic Sources, Part 1 Air-guns for no experts* (Geo ExPro).
- Au, W. L. (1993). The sonar of dolphins (Springer Verlag Inc., New York, NY).
- Barger, J. E., and Hamblen, W. R. (**1980**). "The air gun impulsive underwater transducer," The Journal of the Acoustical Society of America **68**, 1038-1045.
- 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. (2013). "Species-specific beaked whale echolocation signals," Journal of the Acoustical Society of America 134, 2293-2301.
- Baumann-Pickering, S., Simonis, A. E., Roch, M. A., McDonald, M. A., Solsona Berga, A., Oleson, E. M., Wiggins, S. M., Brownell, J., Robert, L., and Hildebrand, J. A. (2014). "Spatiotemporal patterns of beaked whale echolocation signals in the North Pacific," PLOS One, e86072.
- Blackman, D. K., De Groot-Hedlin, C., Harben, P., Sauter, A., and Orcutt, J. A. (2004). "Testing low/very low frequency acoustic sources for basin-wide propagation in the Indian Ocean," The Journal of the Acoustical Society of America 116, 2057-2066.
- 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," Journal of the Acoustical Society of America **134**, 3905-3912.
- Clarke, E., Feyrer, L. J., Moors-Murphy, H., and Stanistreet, J. (2019). "Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*) and Sowerby's beaked whales (*Mesoplodon bidens*) off eastern Canada," Journal of the Acoustical Society of America 146, 307-315.
- DeAngelis, A. I., Stanistreet, J., Baumann-Pickering, S., and Cholewiak, D. A. (**2018**). "A description of echolocation clicks recorded in the presence of True's beaked whale (Mesoplodon mirus)," Journal of the Acoustical Society of America **144**, 2691-2700.
- Fraiser, K. E. (**2015**). "Density estimation of delphinids using passive acoustics: A case study in the Gulf of Mexico," (University of California San Diego, Scripps Institution of Oceanography, La Jolla, CA, USA), p. 321.
- Fraiser, K. E., Roch, M. A., Soldevilla, M. S., Wiggins, S. M., Garrison, L. P., and Hildebrand, J. A. (2017). "Automated classification of dolphin echolocation click types from the Gulf of Mexico," PLOS Computational Biology 13, e1005823.
- 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," The Journal of the Acoustical Society of America **125**, 3428.
- Goold, J. C., and Jones, S. E. (**1995**). "Time and frequency domain characteristics of sperm whale clicks," Journal of the Acoustical Society of America **98**, 1279-1291.
- Hildebrand, J. A. (2009). "Anthropogenic and natural sources of ambient noise in the ocean," Marine Ecology Progress Series 395, 5-20.
- Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., and Tyack, P. L. (2004). "Beaked whales echolocate on prey," Proceedings of the Royal Society B: Biological Sciences 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," Journal of Experimental Biology **209**, 5038-5050.
- Knudsen, V. O., Alford, R. S., and Emling, J. W. (**1948**). "Underwater ambient nosie," Journal of Marine Research **7**, 410-429.

- Madsen, P. T., Payne, R., Kristiansen, N. U., Wahlberg, M., and Møhl , B. (**2002a**). "Sperm whale sound production studied with ultrasound time/depth-recording tags," Journal of Experimental Biology **205**, 1899.
- Madsen, P. T., Wahlberg, M., and Møhl, B. (**2002b**). "Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: implications for echolocation and communication," Behavioral Ecology and Sociobiology **53**.
- McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. (2006). "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California," The Journal of the Acoustical Society of America 120, 711-718.
- McKenna, M. F., Ross, D., Wiggins, S. M., and Hildebrand, J. A. (2012). "Underwater radiated noise from modern commercial ships," Journal of the Acoustical Society of America 131, 92-103.
- Møhl, B., Wahlberg, M., and Madsen, P. T. (**2003**). "The monopulsed nature of sperm whale clicks," Journal of the Acoustical Society of America **114**, 1143-1154.
- Rafter, M. A., Frasier, K. E., Thayre, B. J., Ziegenhorn, M. A., Cohen, R., O'Neill, E., Wiggins, S. M., Baumann-Pickering, S., Hildebrand, J. A., Cholewiak, D. M., and Van Parijs, S. M. (2018). "Passive Acoustic Monitoring for Marine Mammals in the Western Atlantic April 2016 June 2017," (Final Report. Marine Physical Laboratory Technical Memorandum 632.), p. 126.
- Roch, M. A., Klinch, 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," Journal of the Acoustical Society of America 129, 467-475.
- Širović, A., Hildebrand, J. A., Wiggins, S. M., McDonald, M. A., Moore, S. E., and Thiele, D. (2004). "Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula," Deep Sea Research II 51, 2327-2344.
- Soldevilla, M. S., Baumann-Pickering, S., Cholewiak, D., Hodge, L. E. W., Oleson, E. M., and Rankin, S. (2017). "Geographic variation in Risso's dolphin echolocation click spectra," The Journal of the Acoustical Society of America 142, 599-617.
- Varga, L. M., Frasier, K. E., Trickey, J. S., Debich, A. J., Hildebrand, J. A., Thayre, B. J., Rafter, M., Brewer, A. M., Wiggins, S. M., Baumann-Pickering, S., Cholewiak, D. M., and Van Parijs, S. M. (2017). "Passive Acoustic Monitoring for Marine Mammals in the Western Atlantic April 2015 - March 2016," (Final Report. Marine Physical Laboratory Technical Memorandum 615.), p. 70.
- Watkins, W. A., and Schevill, W. E. (**1977**). "Sperm whale codas," Journal of the Acoustical Society of America **62**, 1485-1490.
- Watwood, S., Miller, P. J. O., Johnson, M., Madsen, P. T., and Tyack, P. L. (2006). "Deep-diving behaviour of sperm whales (*Physeter macrocephalus*)," Journal of Animal Ecology 75, 814-825.
- Wenz, G. M. (**1962**). "Acoustic ambient noise in the ocean: Spectra and sources," Journal of the Acoustical Society of America **34**, 1936-1956.
- Wiggins, S. M., Hall, J. M., Thayre, B. J., and Hildebrand, J. A. (2016). "Gulf of Mexico lowfrequency ocean soundscape impacted by airguns," Journal of the Acoustical Society of America 140, 176-183.
- Wiggins, S. M., and Hildebrand, J. A. (2007). "High-frequency acoustic recording package (HARP) for broadband, long-term marine mammal monitoring," in *International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables and Related Technologies 2007* (Institute of Electrical and Electronics Engineers, Tokyo, Japan), pp. 551-557.

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*)," Journal of the Acoustical Society of America 117, 3919-3927.