Passive Acoustic Monitoring for Marine Mammals Near Norfolk Canyon May 2019 – May 2020

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Cuvier's Beaked Whales (*Ziphius cavirostris*) Photo Credit: Gustavo Cárdenas Hinojosa

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Additional information on previous HARP deployments and availability of all associated reports is available on the project profile page of the U.S. Navy's Marine Species Monitoring Program web portal.

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Author Contributions:

M.A.R. compiled, wrote, and edited the report, conducted explosion and *Kogia* spp. analysis. A.C.R. conducted LFA sonar analysis, MFA sonar analysis, and produced ambient soundscape and MFA metric plots. A.S.B. contributed to beaked whale analysis methods. K.E.F. managed project and contributed to beaked whale analysis. B.J.T. and J.P.H. coordinated field work logistics and deployed and recovered instruments. D.M. processed all recovered data. S.M.W. and K.E.F. contributed to algorithm development. S.B. and J.A.H. developed the project and determined data analysis approaches.

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Executive Summary

A High-Frequency Acoustic Recording Package (HARP) was deployed from May 2019 to May 2020 to detect marine mammal and anthropogenic sounds in the Navy's Virginia Capes Range Complex offshore from Norfolk Canyon (NFC). The HARP was deployed 75 nm offshore in approximately 857 m of water. The HARP recorded sound in the frequency band 10 Hz–100 kHz. Data analysis consisted of analyst scans of long-term spectral averages (LTSAs) and spectrograms, and automated computer algorithm detection when possible. Three frequency bands were analyzed for marine mammal vocalizations and anthropogenic sounds: (1) Low-frequency, between 10–500 Hz, (2) Mid-frequency, between 1,000–5,000 Hz, and (3) High-frequency, between 5–100 kHz.

Ambient sound levels of 80–85 dB re 1 μPa^2 / Hz were observed around 30–60 Hz, predominantly due to basin-wide commercial shipping. Peaks in spectrum levels at 20 Hz from mid-September 2019 to early March 2020 were related to the seasonally increased presence of fin whales. Sound levels at 200–1000 Hz were higher during winter, related to wind and wave noise from higher sea states.

Several known odontocete species were detected. Cuvier's beaked whale detections were found throughout the recording period but were highest in December 2019. Gervais'/ True's beaked whale echolocation clicks were detected throughout the recording period but were highest in June and August 2019 and in February 2020. Sowerby's beaked whale echolocation clicks were detected throughout the recording period but were highest in April 2020. *Kogia* spp. echolocation clicks were found in low numbers throughout the recording period but were highest in September 2019.

Three types of anthropogenic sounds were identified. Low-Frequency Active sonar (LFA) events were detected infrequently with five events occurring in July and December 2019 and in March and April 2020. Mid-Frequency Active sonar (MFA) was detected intermittently throughout the recording period but was highest in September 2019. Explosions were detected intermittently with a total of 275 explosions during the recording period and detections highest in late October 2019.

Project Background

The US Navy's Virginia Capes Range Complex (VACAPES) is located in the coastal and offshore waters of the western North Atlantic Ocean adjacent to Delaware, Maryland, Virginia, and North Carolina. The seafloor features a broad continental shelf, with an inner zone of less than 200 m water depth, and an outer zone extending to water depths of 2000 m. A diverse array of marine mammals is found in this region, including baleen and toothed whales.

In March 2012, an acoustic monitoring effort was initiated within the boundaries of the Virginia Capes Range Complex with funding support from the United States Fleet Forces Command (USFF). The goal of this effort was to characterize the vocalizations of marine mammal species present in the area, to determine their seasonal presence patterns, and to evaluate the potential for impact from naval operations. This report documents the analysis of data recorded by a High-Frequency Acoustic Recording Package (HARP) that was deployed within the Virginia Capes Range Complex near Norfolk Canyon and collected data from May 2019 to May 2020 (Figure 1).

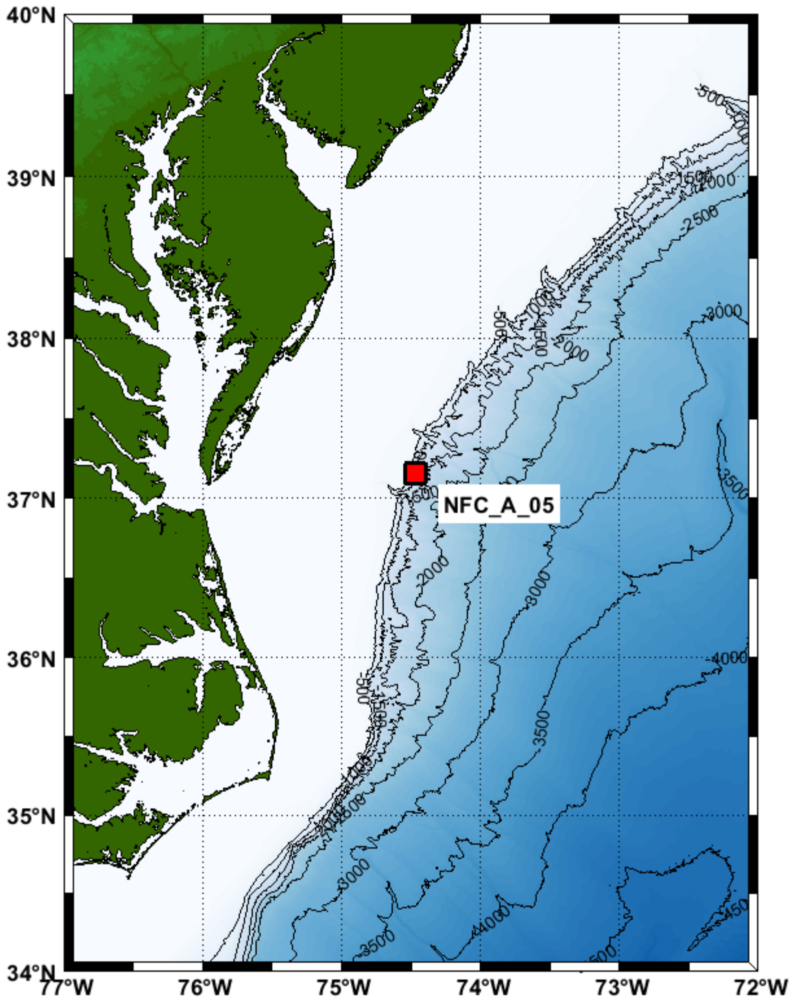

Figure 1. Location of High-Frequency Acoustic Recording Package (HARP) at NFC Site A (37° 09.87 N, 74° 27.95 W, depth 875 m) deployed near Norfolk Canyon from May 2019 to May 2020.

Methods

High-Frequency Acoustic Recording Package (HARP)

HARPs are autonomous underwater acoustic recording packages that can record sounds over a bandwidth from 10 Hz up to 160 kHz and that are capable of approximately 300 days of continuous data storage. The HARP was deployed in a small mooring configuration with the hydrophone suspended approximately 22 m above the seafloor. Each HARP is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations (Wiggins and Hildebrand, 2007).

Data Collected

One HARP recorded data from May 2019 to May 2020 at NFC Site A (37° 09.871', 74° 27.951' W, depth 875 m) and sampled continuously at 200 kHz to provide 100 kHz of effective bandwidth. The instrument recorded 355 days from May 19, 2019 to May 8, 2020, for a total of 8,520 hours of data analyzed. Earlier data collection at the NFC site is documented in previous detailed reports (Rafter *et al.*, 2020; Rafter *et al.*, 2019; Rafter *et al*., 2018; Debich *et al*., 2016).

Data Analysis

To visualize the acoustic data, frequency spectra were calculated for all data using a time average of 5 seconds and 100 Hz frequency bins for high-frequency, 10 Hz for mid-frequency, and 1 Hz for low-frequency. These data, called Long-Term Spectral Averages (LTSAs), were then examined as a means to detect marine mammal and anthropogenic sounds. Data were analyzed by visually scanning LTSAs in source-specific frequency bands and, when appropriate, using automatic detection algorithms (described below). During visual analysis, when a sound of interest was identified in the LTSA but its origin was unclear, the waveform or spectrogram was examined to further classify the sounds to species or source. Signal classification was carried out by comparison to known species-specific spectral and temporal characteristics.

Recording over a broad frequency range of 10 Hz–100 kHz allows detection of baleen whales (mysticetes), toothed whales (odontocete), and anthropogenic sounds. The presence of acoustic signals from multiple marine mammal species and anthropogenic noise was evaluated in these data. To document the data analysis process, we describe the major classes of marine mammal calls and anthropogenic sound in this band in the Norfolk Canyon region, and the procedures used to detect them. For effective analysis, the data were divided into three frequency bands: (1) Low-frequency, 10–1,000 Hz, (2) Mid-frequency, 1,000–5,000 Hz, and (3) High-frequency, 5–100 kHz.

Each band was analyzed for the sounds of an appropriate subset of species or sources. Low-Frequency Active (LFA) sonar less than 500 Hz was classified as low-frequency. Explosions, Low-Frequency Active (LFA) sonar greater than 500 Hz, and Mid-Frequency Active (MFA) sonar sounds were classified as mid-frequency. The remaining odontocete and sonar sounds were considered high-frequency. Analysis of low-frequency recordings required decimation of the original recordings by a factor of 100. For the analysis of the mid-frequency recordings, the original recordings were decimated by a factor of 20.

We summarize acoustic data collected at the NFC Site A from May 2019 to May 2020. We discuss seasonal occurrence and relative abundance of calls for different species and anthropogenic sounds that were consistently identified in the acoustic data.

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.*, 2006a; Wiggins *et al.*, 2016), wind causes increased sound pressure levels from 200 Hz to 20 kHz (Knudsen *et al.*, 1948). In the absence of wind, ambient sound pressure levels are low and difficult to measure at frequencies above ~10 kHz. Therefore, to analyze the ambient soundscape, the recordings 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.

High-Frequency Marine Mammals

Marine mammal species with sounds in the high-frequency range and possibly found in the Virginia Capes Range Complex include bottlenose dolphins (*Tursiops truncatus*), short-finned pilot whales (*Globicephala macrorhynchus*), long-finned pilot whales (*Globicephala melas*), short-beaked common dolphins (*Delphinus delphis*), Atlantic spotted dolphins (*Stenella frontalis*), pantropical spotted dolphins (*Stenella frontalis*), spinner dolphins (*Stenella longirostris*), striped dolphins (*Stenella coeruleoalba*), Clymene dolphins (*Stenella clymene*), rough-toothed dolphins (*Steno bredanensis*), Risso's dolphins (*Grampus griseus*), Fraser's dolphins (*Lagenodelphis hosei*), pygmy killer whales (*Feresa attenuata*), melon-headed whales (*Peponocephala electra*), sperm whales (*Physeter macrocephalus*), dwarf sperm whales (*Kogia sima*), pygmy sperm whales (*Kogia breviceps*), Cuvier's beaked whales (*Ziphius cavirostris*), Gervais' beaked whales (*Mesoplodon europaeus*), Blainville's beaked whales (*Mesoplodon densirostris*), True's beaked whales (*Mesoplodon mirus*) and Sowerby's beaked whales (*Mesoplodon bidens*).

High-Frequency Call Types

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 the spectrogram (Figure 2).

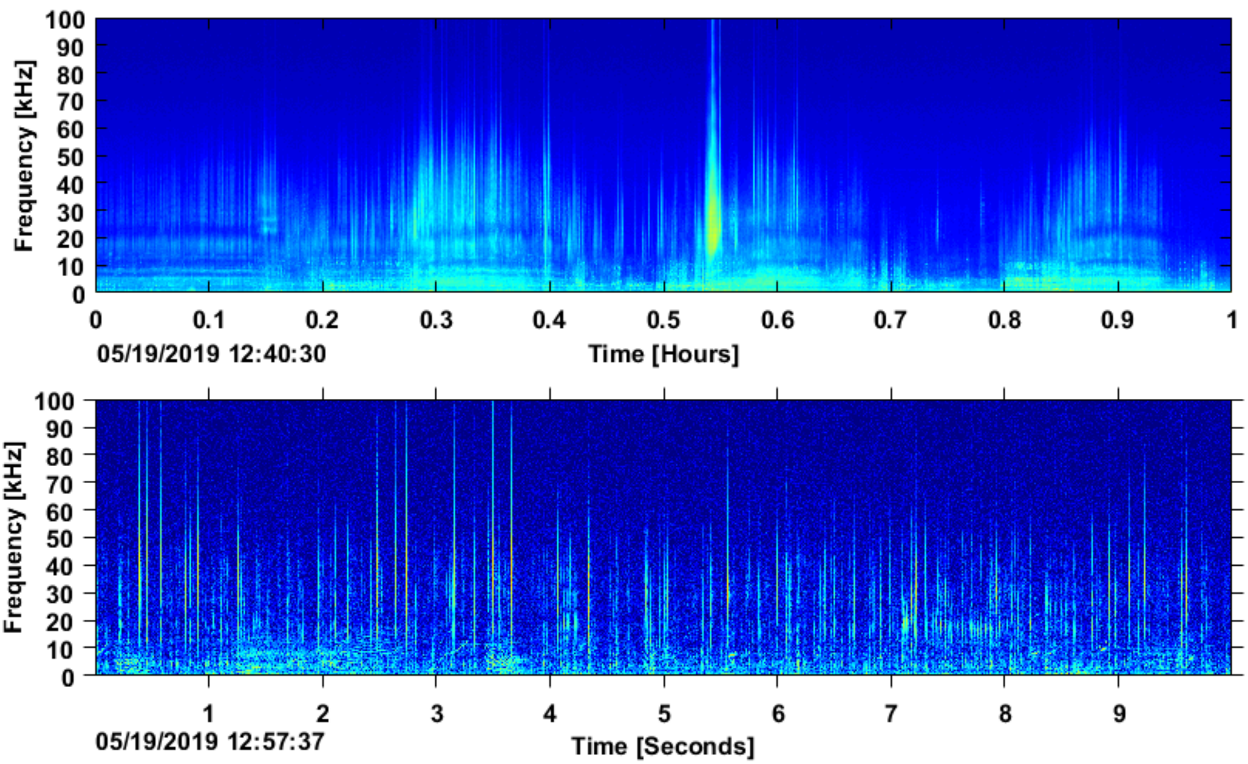

Figure 2. LTSA (top) and spectrogram (bottom) demonstrating odontocete signal types.

Beaked Whales

Beaked whales can be identified acoustically by their echolocation signals (Baumann-Pickering *et al.*, 2014). 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 potentially occur in this region, namely Gervais', Blainville's, Cuvier's, True's, and Sowerby's beaked whales.

Beaked whale FM pulses were detected and classified with an automated method. This automated effort was used for all identifiable beaked whale signals found in the Cape Hatteras Complex. A large library of manually-identified beaked whale acoustic encounters identified in previous HARP deployments was used to train a deep neural network to identify 7 species of beaked whale. Echolocation clicks from these encounters were grouped and averaged in 5-minute bins retaining features including mean spectra, inter-pulse interval distribution and mean waveform envelope (Frasier 2021). To apply the trained classifier to the present dataset, all echolocation clicks were detected automatically using an energy detector with a minimum peak-to-peak received level threshold of 118 dB re: 1 µPa (Frasier *et al.*, 2015), and an expert system discriminated between delphinid clicks and beaked whale FM pulses (Simone *et al.*, 2013). The remaining clicks consistent with beaked whales were clustered within successive 5-minute time bins and similar clicks within each bin were combined into one or more bin-level averages. These 5-minute bins were then reviewed by the classifier and assigned a probable label. An analyst reviewed and verified all labels using detEdit, an interactive interface (Solsona Berga *et al.*, 2020).

Blainville's Beaked Whale

Blainville's beaked whale echolocation signals are, like most beaked whales' signals, polycyclic, with a characteristic frequency-modulated upsweep, peak frequency around 34 kHz and uniform inter-pulse interval (IPI) of about 280 ms (Johnson *et al*., 2004; Baumann-Pickering *et al*., 2013). Blainville's FM pulses are also distinguishable in the spectral domain by their sharp energy onset around 25 kHz with only a small energy peak at around 22 kHz (Figure 3). Blainville's beaked whales were not identified at NFC Site A during the recording period.

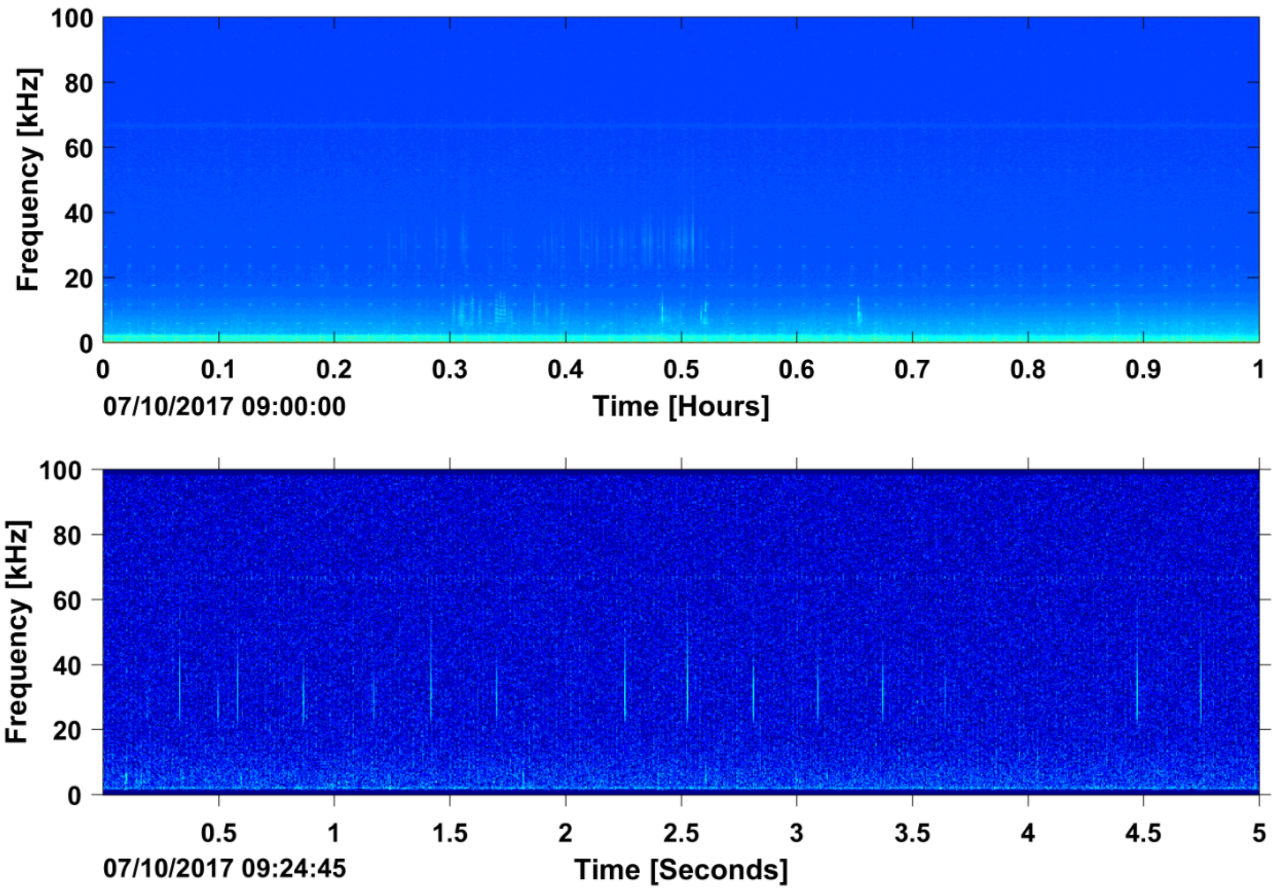

Figure 3. Blainville's beaked whale echolocation clicks in the LTSA (top) and spectrogram (bottom) recorded at NFC Site A, July 2017.

Cuvier's Beaked Whales

Cuvier's echolocation signals are polycyclic, with a characteristic FM pulse upsweep, peak frequency around 40 kHz (Figure 4), 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.

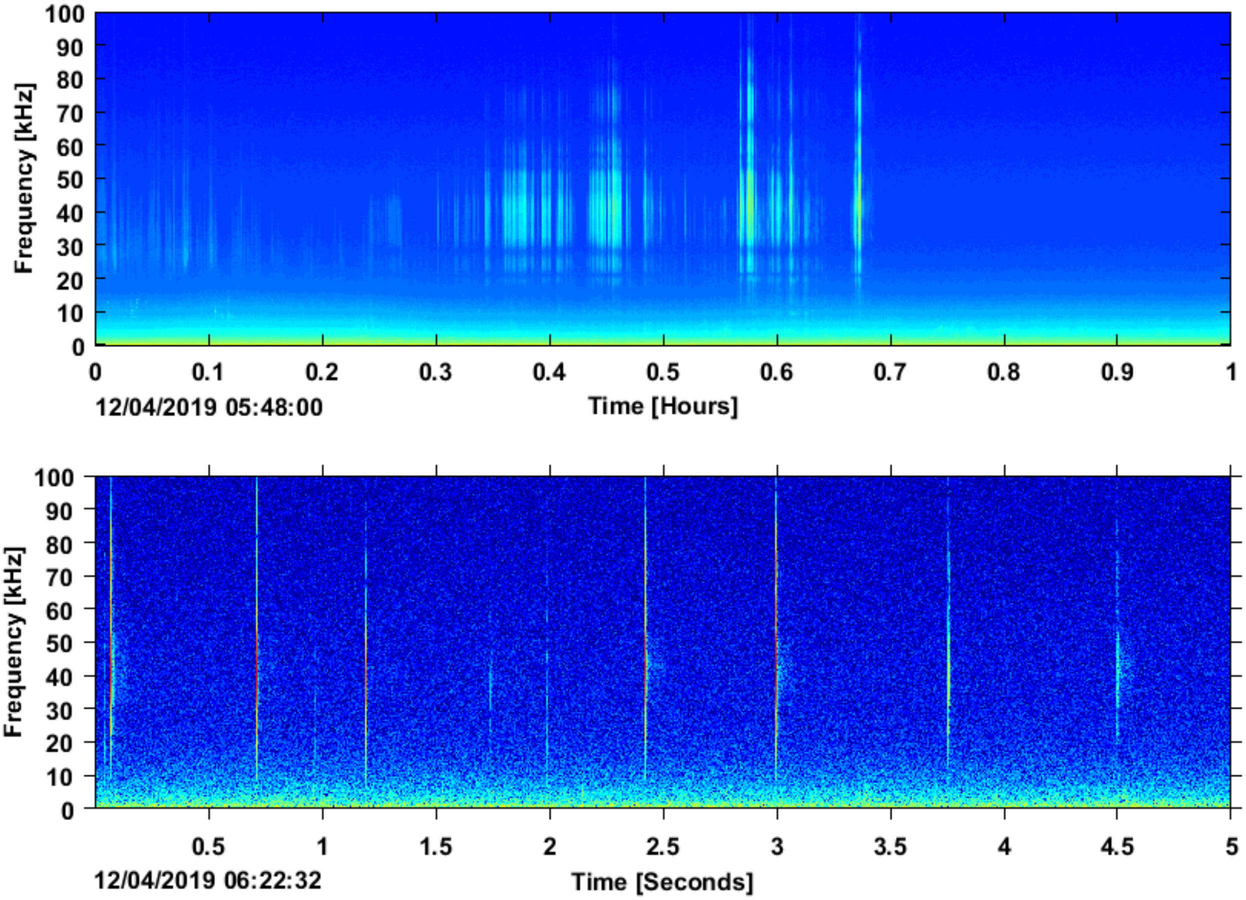

Figure 4. Cuvier's beaked whale signals in LTSA (top) and spectrogram (bottom) recorded at NFC Site A, December 2019.

Gervais' Beaked Whales

Gervais' beaked whale signals 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 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. Similarly, Gervais' beaked whale FM pulses sweep up in frequency (Figure 5). The IPI for Gervais' beaked whale signals is typically around 275 ms (Baumann-Pickering *et al*., 2013).

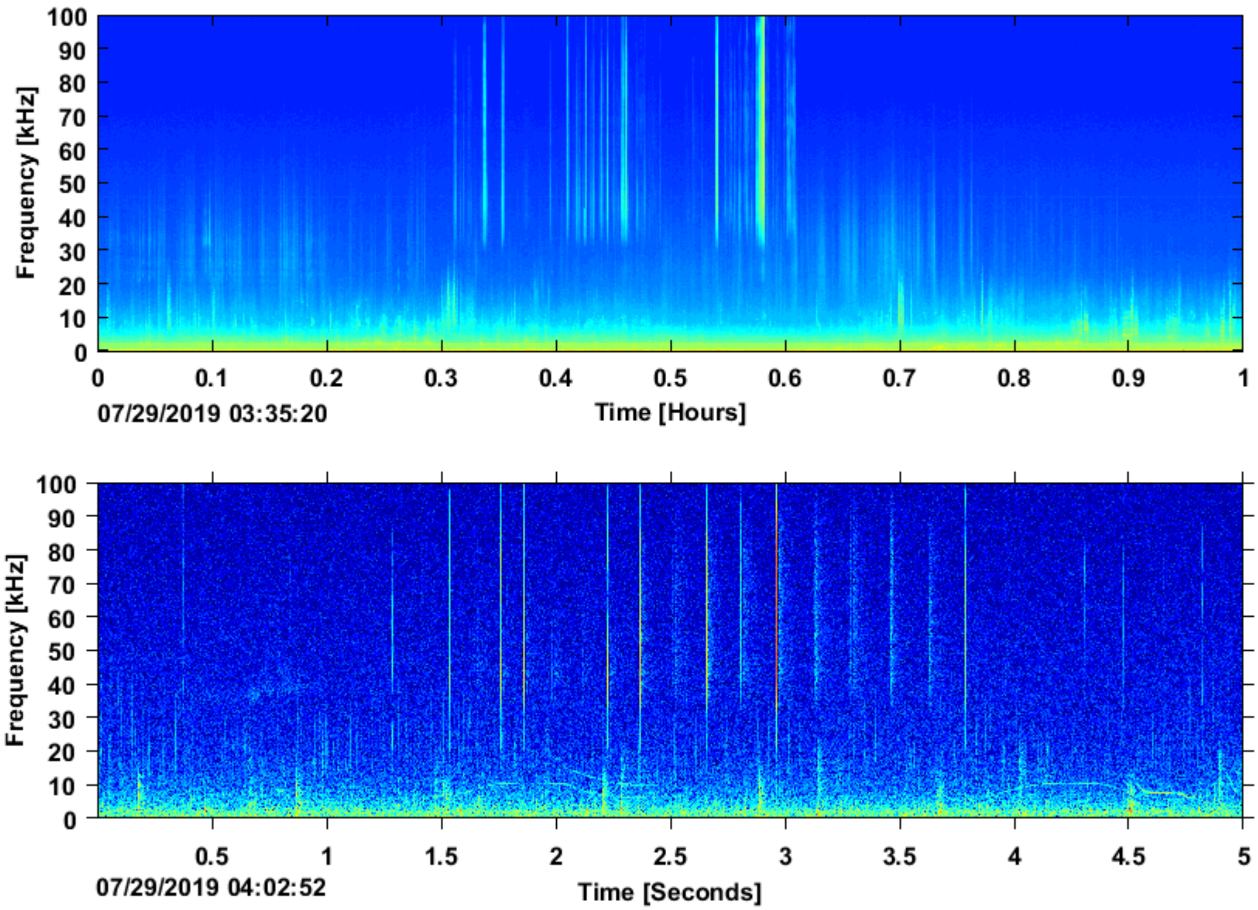

Figure 5. Gervais' beaked whale signals in LTSA (top) and spectrogram (bottom) recorded at NFC Site A, July 2019.

True’s Beaked Whale

True’s beaked whale echolocation signals are FM upsweep pulses, with peak frequency around 46 kHz and an inter-pulse interval of about 180 ms (Figure 6). 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).

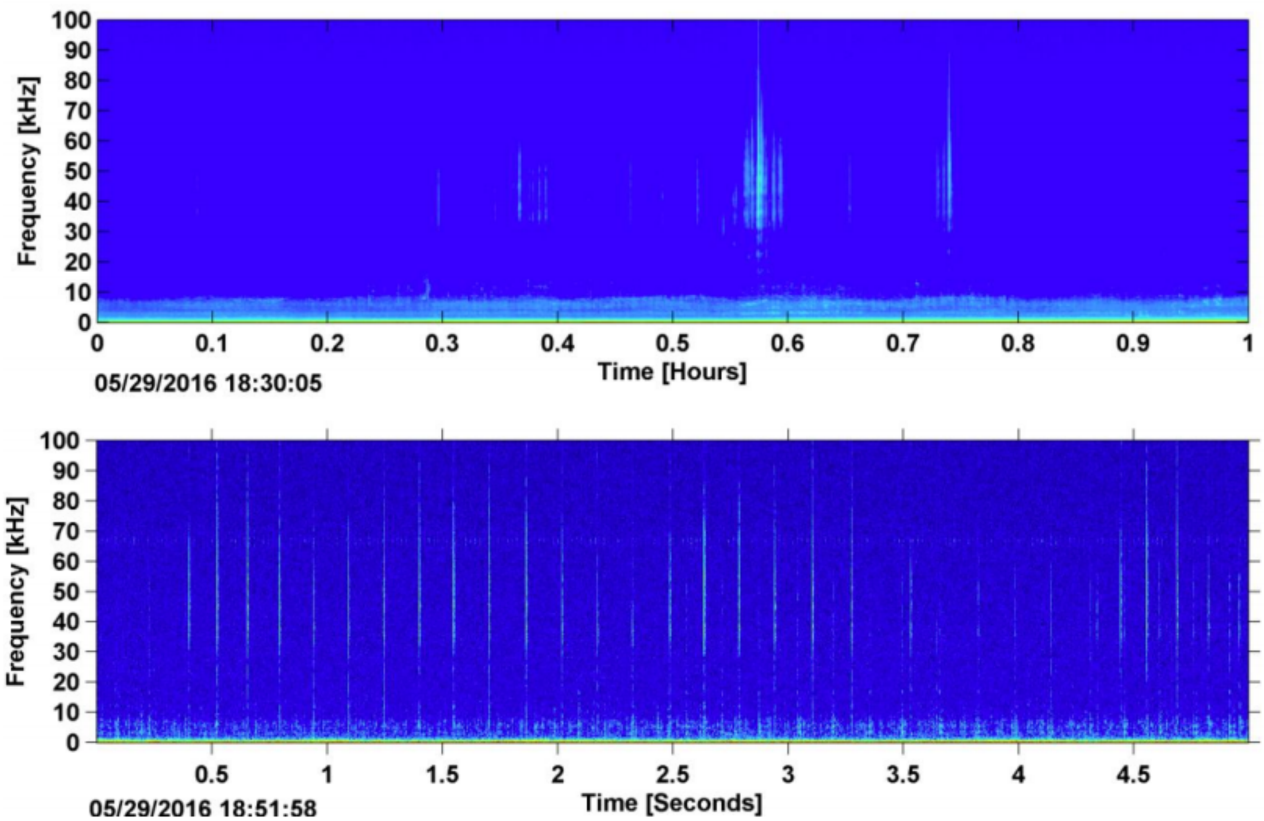

Figure 6. True’s beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded in the Western Atlantic at Nantucket Canyon, May 2016.

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 7). 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).

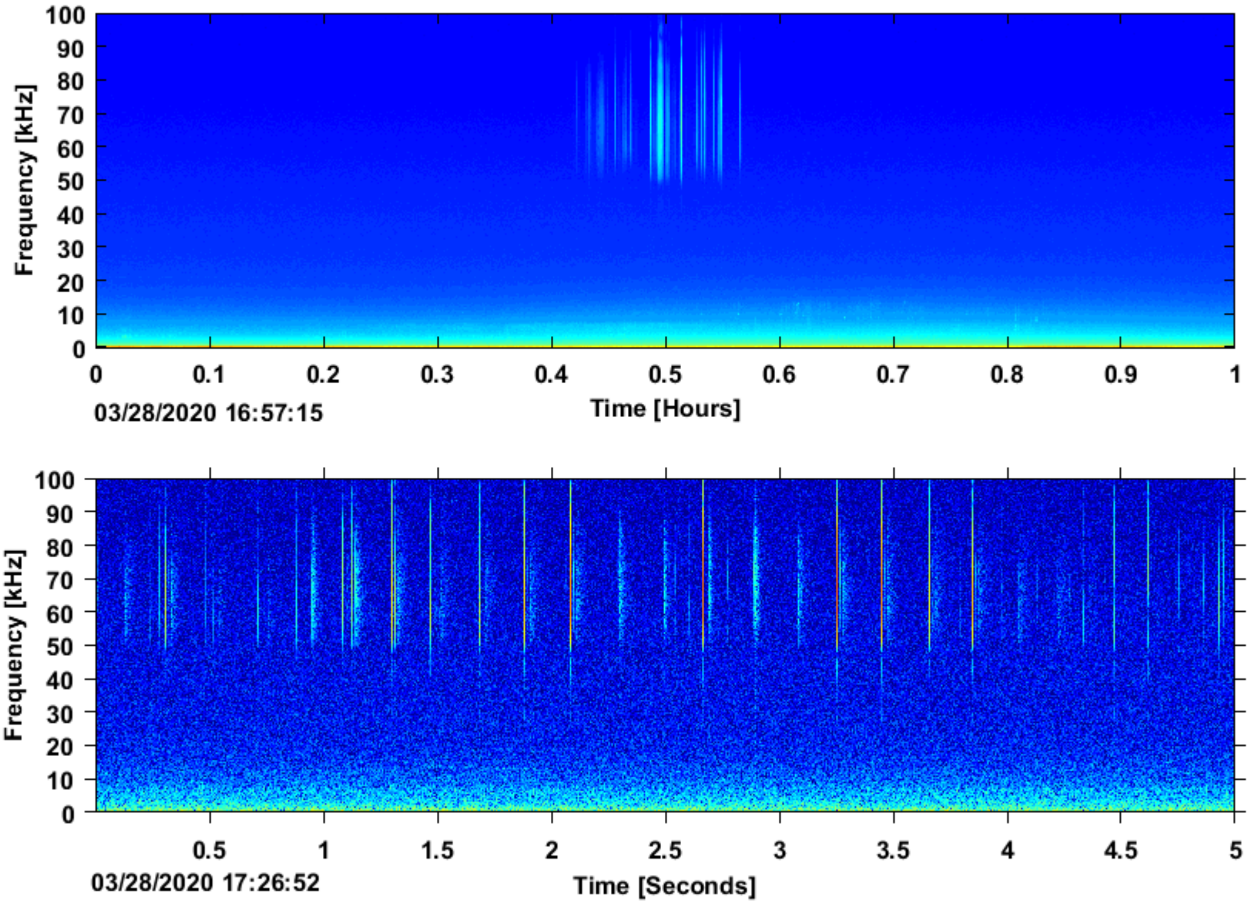

Figure 7. Sowerby's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at NFC Site A, March 2020.

Kogia spp.

Dwarf and pygmy sperm whales emit echolocation signals that have peak energy at frequencies near 130 kHz (Au, 1993). While this is above the frequency band recorded by the HARP, the lower portion of the *Kogia* energy spectrum is within the 100 kHz HARP bandwidth (Figure 8). 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. *Kogia* echolocation clicks were analyzed using a multi-step detector. The first step was to identify clicks with energy in the 70-100 kHz band that simultaneously lacked energy in lower frequency bands. An expert system then classified these clicks based on spectral characteristics, and finally an analyst verified all echolocation click bouts manually.

Kogia spp. echolocation clicks were detected automatically using an energy detector with a minimum peak-to-peak received level threshold of 120 dB re: 1 µPa (Frasier *et al.*, 2015). Dominant click types at this site were identified automatically by dividing detections into successive five-minute windows and determining the dominant click type(s) in each window. An automated clustering algorithm was then used to identify recurrent click types as well as false positives across all windows (Frasier *et al.*, 2017). Detections were automatically labeled by a classifier based on the automatically identified categories. All classifications were then verified by an analyst who reviewed LTSAs and mean spectra for each detected bout. A bout was defined as a period of clicking separated before and after by at least 15 minutes without clicking.

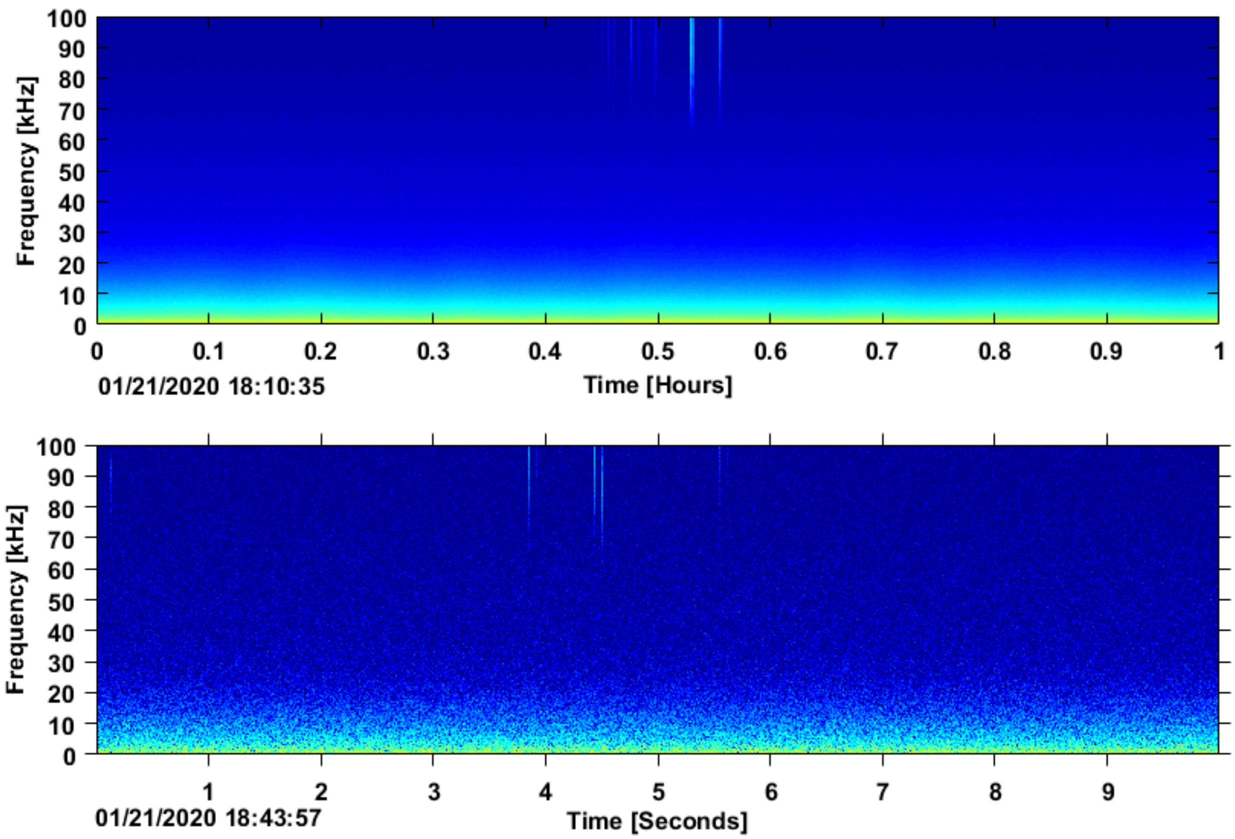

Figure 8. *Kogia* spp. echolocation clicks in LTSA (top) and spectrogram (bottom) from HARP recorded at NFC Site A, January 2020.

Anthropogenic Sounds

Several anthropogenic sounds including Low-Frequency Active (LFA) sonar, Mid-Frequency Active (MFA) sonar, and explosions were monitored for this report. The LTSA search parameters used to manually detect LFA are given in Table 1. MFA sonar and explosions were analyzed by using automated detectors, described below.

Table 1. Anthropogenic sound data manual effort analysis parameters.

Sound Type	LTSA Search Parameters	
	Plot Length (Hour)	Display Frequency Range (Hz)
LFA Sonar	1	10–1,000

Low-Frequency Active Sonar

Low-Frequency Active (LFA) sonar includes military sonar between 100 and 500 Hz and other sonar systems up to 1 kHz. Effort was expended for LFA sonar less than 500 Hz and between 500 Hz and 1 kHz (Figure 9).

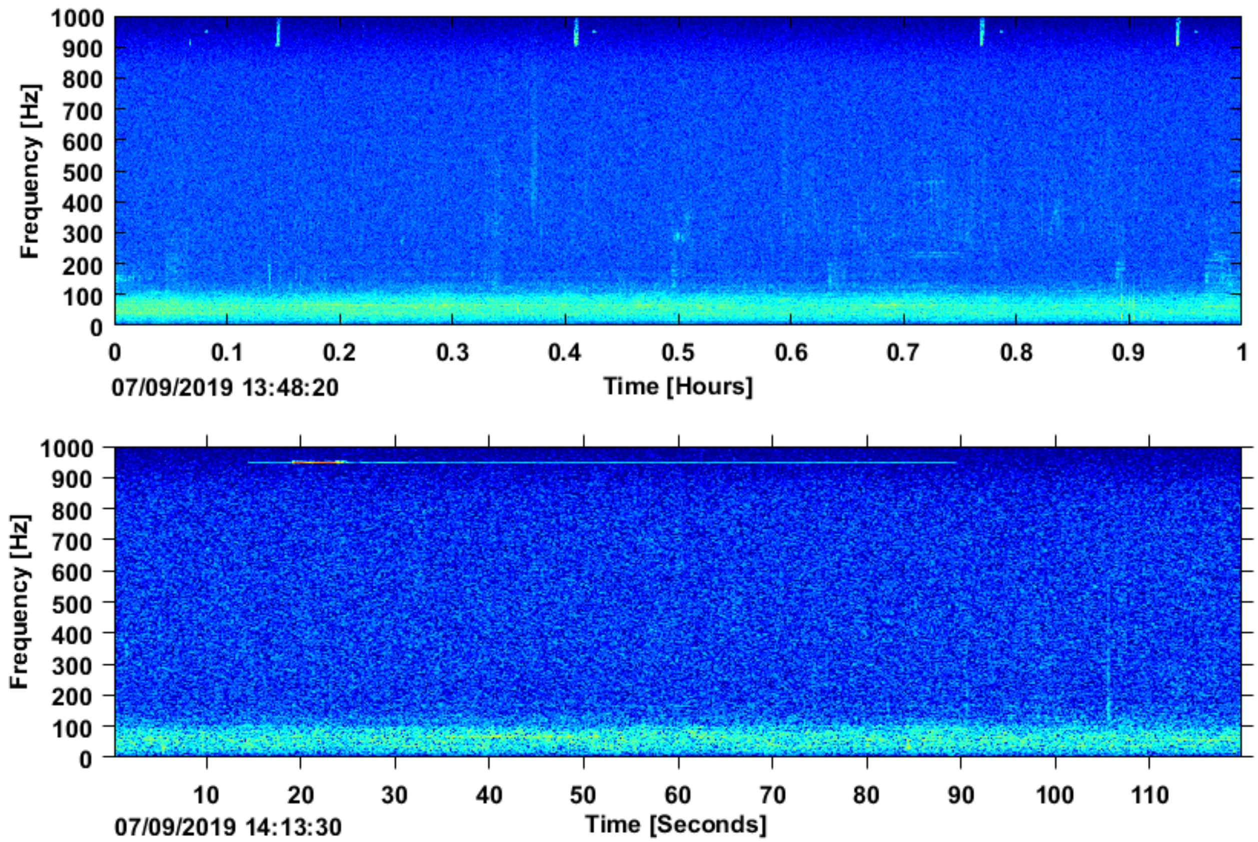

Figure 9. Low-Frequency Active (LFA) sonar in Hz in the LTSA (top) and spectrogram (bottom) recorded at NFC Site A, July 2019.

Mid-Frequency Active Sonar

Sounds from MFA sonar vary in frequency (1–10 kHz) and are composed of pulses of both frequency modulated (FM) sweeps and continuous wave (CW) tones grouped in packets with durations ranging from less than 1 s to greater than 5 s. Packets can be composed of single or multiple pulses and are transmitted repetitively as wave trains with inter-packet-intervals typically greater than 20 s (Figure 10). In Norfolk Canyon, the most common MFA sonar packet signals are between 2 and 5 kHz and are known more generally as '3.5 kHz' sonar.

MFA sonar was detected using a modified version of the Silbido detection system (Roch *et al.*, 2011a) originally designed for characterizing toothed whale whistles. The algorithm identifies peaks in time-frequency distributions (e.g. spectrogram) and determines which peaks should be linked into a graph structure based on heuristic rules that include examining the trajectory of existing peaks, tracking intersections between time-frequency trajectories, and allowing for brief signal dropouts or 21 interfering signals. Detection graphs are then examined to identify individual tonal contours looking at trajectories from both sides of time-frequency intersection points. For MFA detection, parameters were adjusted to detect tonal contours at or above 2 kHz in data decimated to a 10 kHz sample rate with time-frequency peaks with signal to noise ratios of 5 dB or above and contour durations of at least 200 ms with a frequency resolution of 100 Hz. The detector frequently triggered on noise produced by instrument disk writes that occurred at 75 s intervals.

Over periods of several months, these disk write detections dominated the number of detections and could be eliminated using an outlier detection test. Histograms of the detection start times modulo the disk write period were constructed and outliers were discarded. This removed some valid detections that occurred during disk writes, but as the disk writes and sonar signals are uncorrelated this is expected to only have a minor impact on analysis. As the detector did not distinguish between sonar and non-anthropogenic tonal signals within the operating band (e.g. humpback whales), human analysts examined detection output and accepted or rejected contiguous sets of detections. Start and end time of these cleaned sonar events were then created to be used in further processing.

These start and end times were used to read segments of waveforms upon which a 2.4 to 4.5 kHz bandpass filter and a simple time series energy detector was applied to detect and measure various packet parameters after correcting for the instrument calibrated transfer function (Wiggins, 2015). For each packet, maximum peak-to-peak (pp) received level (RL), sound exposure level (SEL), root-mean-square (RMS) RL, date/time of packet occurrence, and packet RMS duration (for RLpp – 10 dB) were measured and saved.

Various filters were applied to the detections to limit the MFA sonar detection range to ~20 km for off-axis signals from an AN/SQS 53C source, which resulted in a received level detection threshold of 130 dB pp re 1 µPa (Wiggins, 2015). Instrument maximum received level was ~164 dB pp re 1 µPa, above which waveform clipping occurred. Packets were grouped into wave trains separated by more than 1 hour. Packet received levels were plotted along with the number of packets and cumulative SEL (CSEL) in each wave train over the study period. Wave train duration and total packet duration were also calculated. Wave train duration is the difference between the first and last packet detections in an event. The total packet duration of for a wave train is the sum of the individual packet (i.e., group of pings) durations, which is measured as the period of the waveform that is 0 to 10 dB less than the maximum peak-to-peak received level of the ping group.

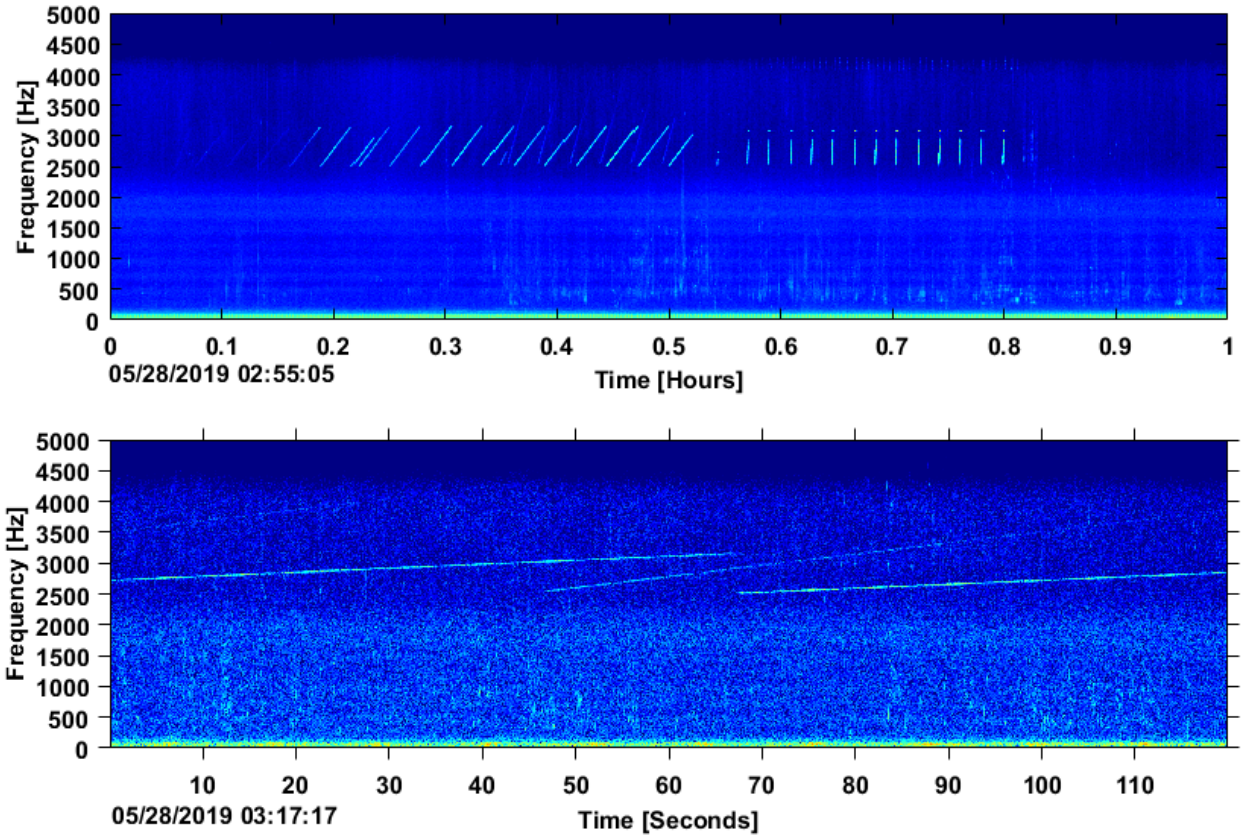

Figure 10. Mid-Frequency Active (MFA) sonar in LTSA (top) and spectrogram (bottom) recorded at NFC Site A, May 2019.

Explosions

Effort was directed toward finding explosive sounds in the data including military explosions, shows 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 sharp onset reverberant decay (Figure 11). Explosions were detected automatically using a matched filter detector on data decimated to a 10 kHz sampling rate. The time series was filtered with a 10th order Butterworth bandpass filter between 200 and 2,000 Hz. Cross correlation was computed between 75 seconds of the envelope of the filtered time series 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 explosion detections. A floating threshold was calculated by taking the median cross correlation value over the current 75 seconds of data to account for detecting explosions within noise, such as shipping. A cross correlation threshold above the median was set. When the correlation coefficient reached above threshold, the time series was inspected more closely. Consecutive explosions were required to have a minimum time distance of 2 seconds to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end above threshold was determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and rms received levels (RL) were computed over the potential explosion period and a time series of the length of the explosion template before and after the explosion. The potential explosion was classified as false detection and deleted if 1) the dB difference pp and rms between signal and time after the detection was less than 4 dB or 1.5 dB, respectively; 2) the dB difference pp and rms between signal and time before signal was less than 3 dB or 1 dB, respectively; and 3) the detection was shorter than 0.03 and longer than 0.55 seconds 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. Explosions were automatically detected and then manually verified to remove false positives associated with airgun activity and fish sounds.

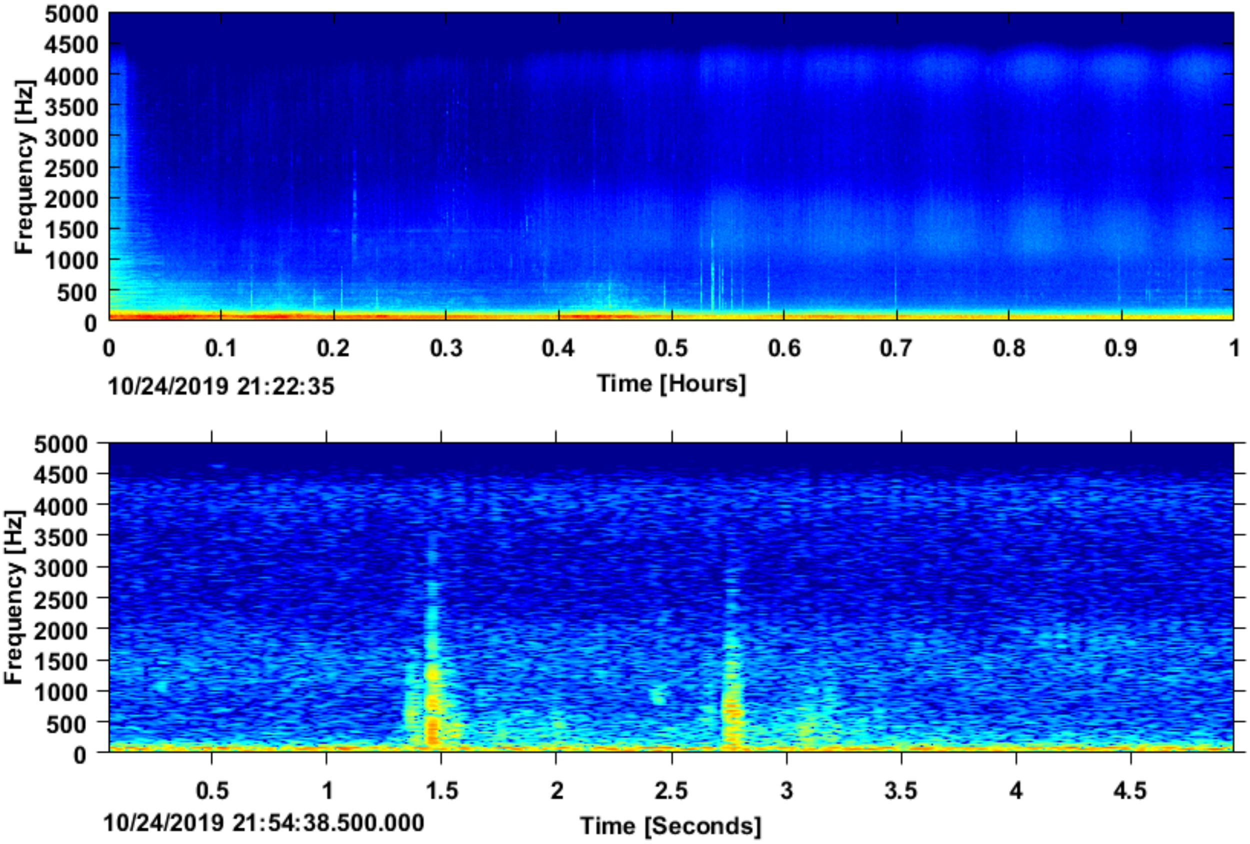

Figure 11. Explosions in LTSA (top) and spectrogram (bottom) recorded at NFC Site A, October 2019.

Results

The results of acoustic data analysis at NFC Site A from May 2019 to 2020 are summarized, and the seasonal occurrence and relative abundance of marine mammal acoustic signals and anthropogenic sounds are documented.

Ambient Soundscape

To provide a means for evaluating seasonal spectral variability, daily-averaged spectra were processed into monthly averages (Figure 12) and plotted so that months could be compared. Incomplete days have been removed from the analysis, incomplete months were not. Partial months include an asterisk (*) in the color legend (Figure 12). Long-term spectrograms were generated using daily-averaged spectra (Figure 13).

- The increased spectrum levels centered around 45 Hz are a result of commercial shipping activity (Figure 12).
- From mid-September 2019 to early March 2020, the peak in spectrum levels at 20 Hz is related to the seasonal increase in fin whale 20 Hz calls (Figure 13).
- Sound levels at 200–1000 Hz are higher during winter, related to wind and wave noise associated with higher sea states (Figure 13).

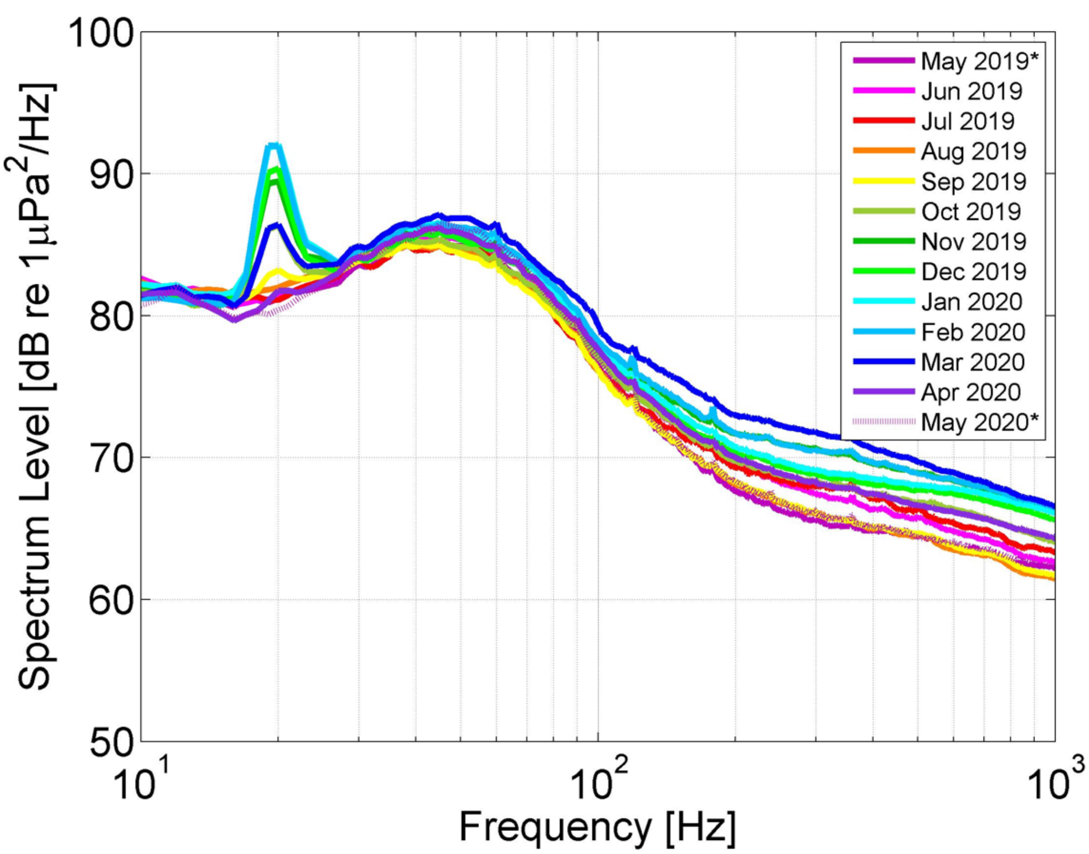

Figure 12. Monthly averages of ambient soundscape at NFC Site A from May 2019 to 2020. Legend gives color coding by month. Months with an asterisk are partial recording periods.

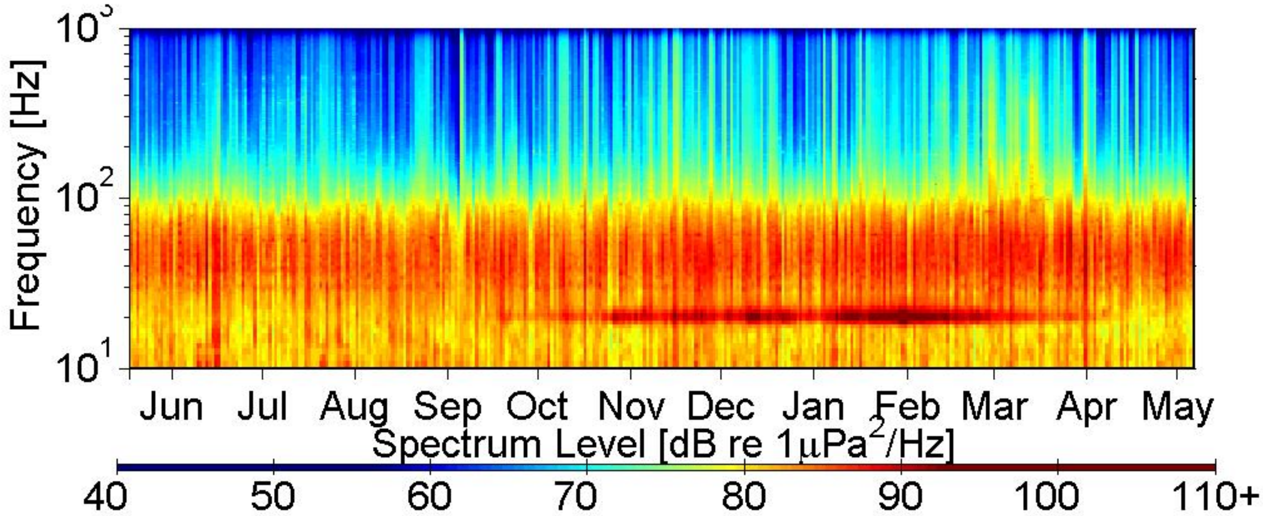

Figure 13. Long-term spectrograms using daily-averaged spectra for NFC Site A from May 2019 to 2020.

Odontocetes

Clicks from Cuvier's beaked whale, Gervais'/ True's beaked whale, Sowerby's beaked whale, and *Kogia* spp. were detected. No Blainville's beaked whales were detected. Further details of each species' presence from May 2019 to 2020 are given below.

Cuvier's Beaked Whale

- Cuvier's beaked whale echolocation clicks were detected throughout the recording period but were highest in December 2019 (Figure 14).
- There was no diel pattern in detections of Cuvier's beaked whale echolocation clicks (Figure 15).

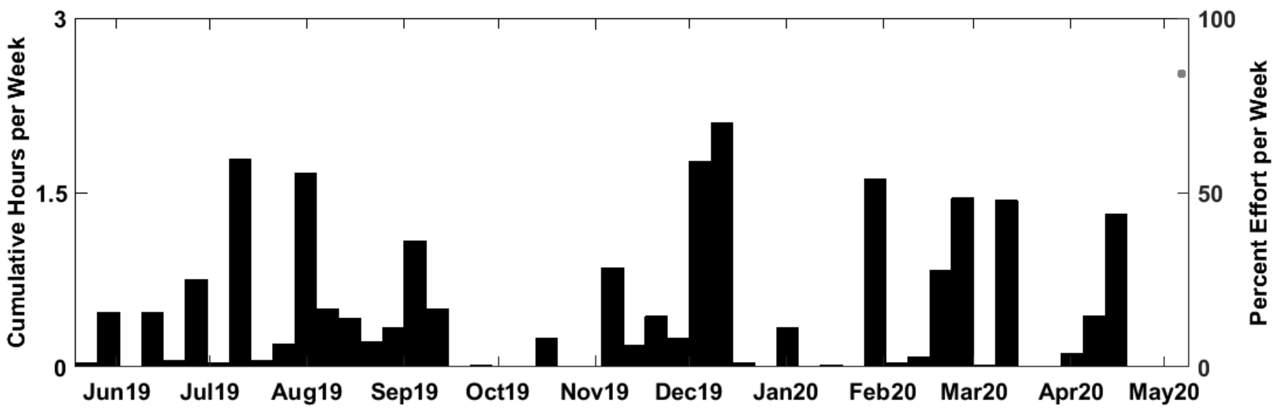

Figure 14. Weekly presence of Cuvier's beaked whale echolocation clicks from May 2019 to 2020 at NFC Site A. Gray dots represent percent of effort per week in weeks with less than 100% recording effort. Where gray dots are absent, full recording effort occurred for the entire week. X-axis labels refer to month and year of recording.

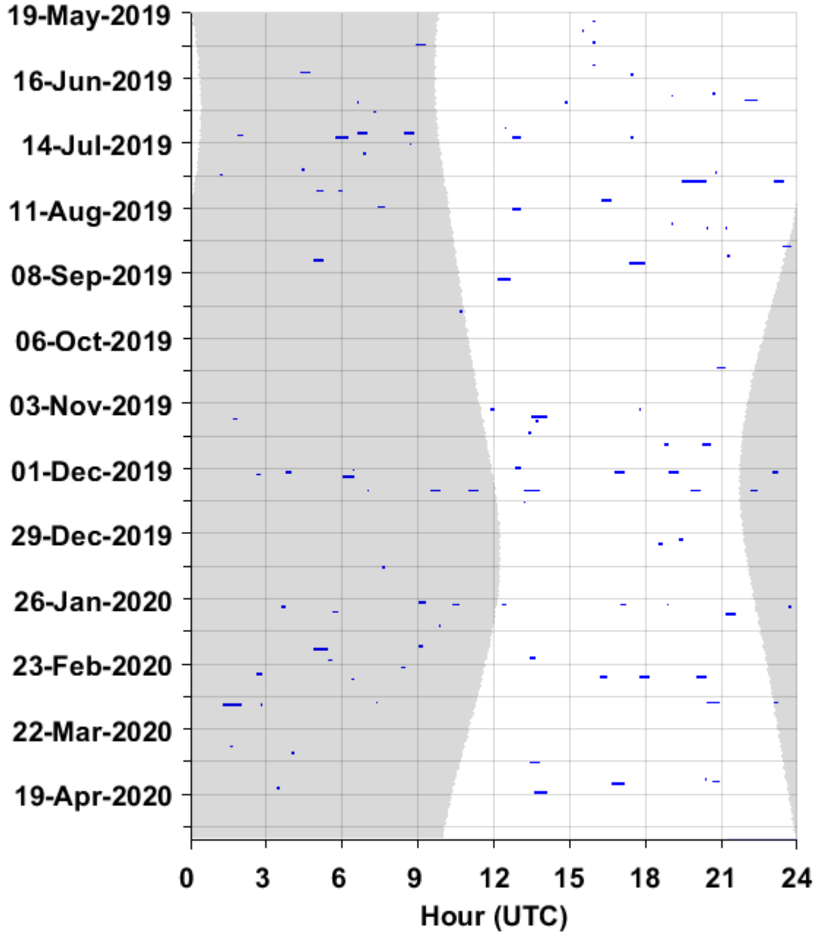

Figure 15. Cuvier's beaked whale echolocation clicks in five-minute bins from May 2019 to 2020 at NFC Site A. Gray vertical shading denotes nighttime.

Gervais' Beaked Whale / True's Beaked Whale

- Gervais'/ True's beaked whale echolocation clicks were detected throughout the recording period but were highest in June and August 2019 and in February 2020 (Figure 16).
- There was no discernible diel pattern for Gervais'/ True's beaked whale clicks (Figure 17).
- Because the FM pulse types produced by Gervais' and True's beaked whales are highly similar and acoustic discrimination between them remains challenging (DeAngelis *et al*. 2018), it was not possible to classify detections of this signal type to the species level.

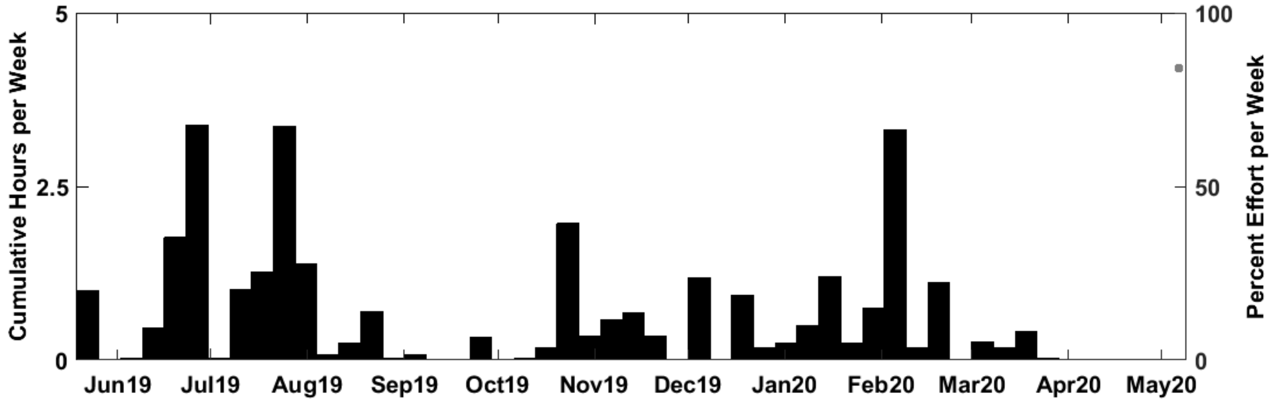

Figure 16. Weekly presence of Gervais' / True's beaked whale echolocation clicks from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

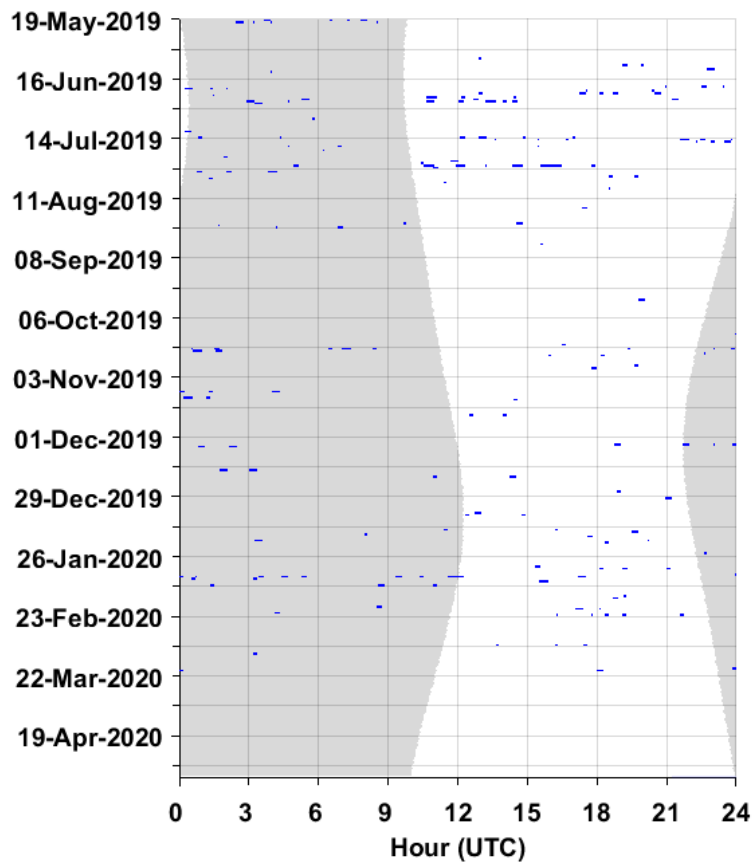

Figure 17. Gervais' / True's beaked whale echolocation clicks in five-minute bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

Sowerby's Beaked Whale

- Sowerby's beaked whale echolocation clicks were detected throughout the recording period but were highest in April 2020 (Figure 18).
- There was no discernible diel pattern for Sowerby's beaked whale clicks (Figure 19).

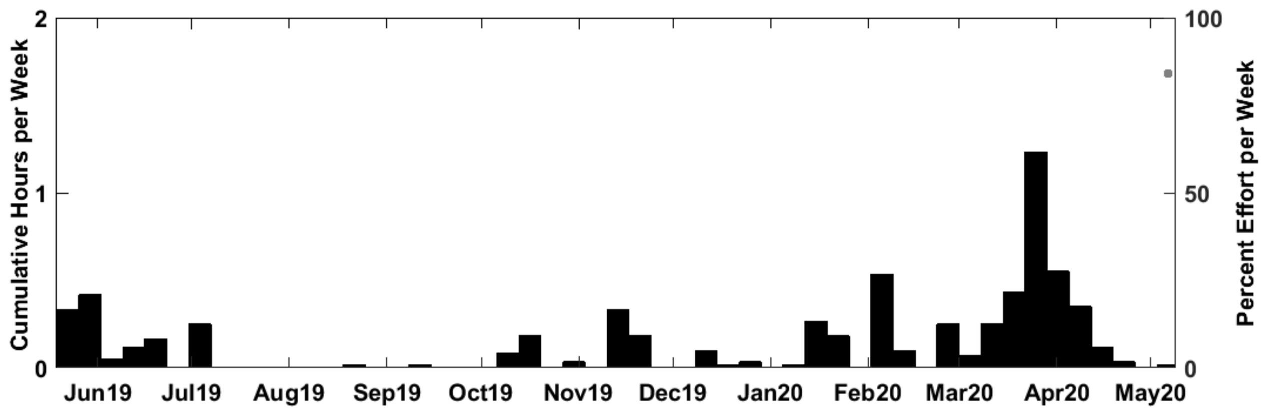

Figure 18. Weekly presence of Sowerby's beaked whale echolocation clicks from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

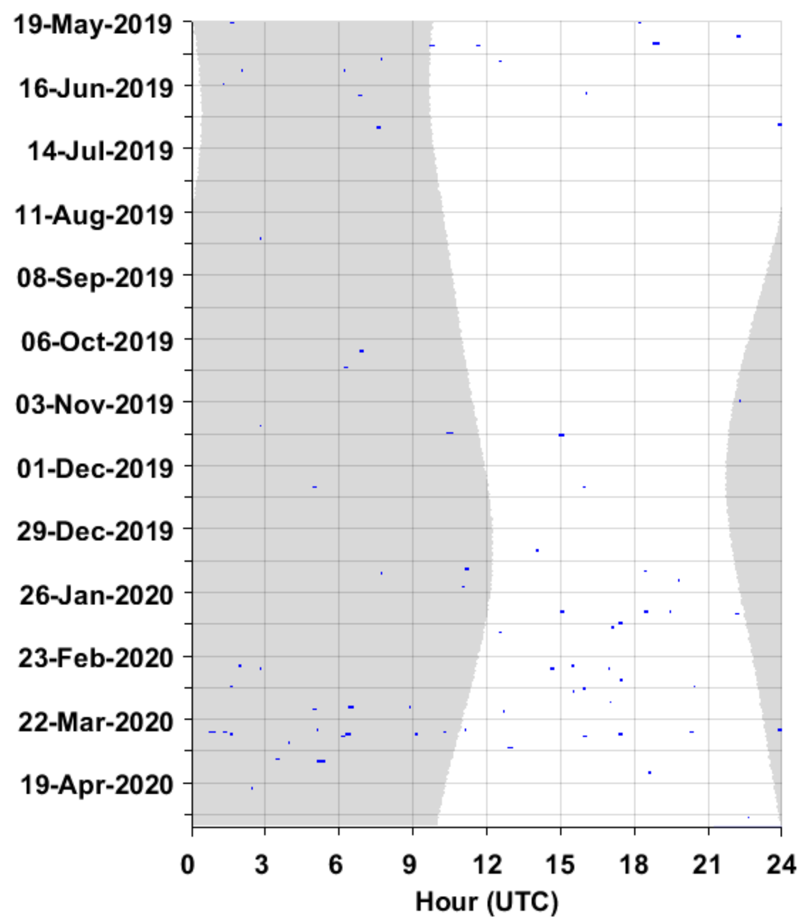

Figure 19. Sowerby's beaked whale echolocation clicks in five-minute bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

***Kogia* spp.**

- *Kogia* spp. echolocation clicks were detected intermittently throughout the detection period with highest number of detections occurring in September 2019 (Figure 20).
- There was no discernible diel pattern for *Kogia* spp. echolocation clicks (Figure 21).

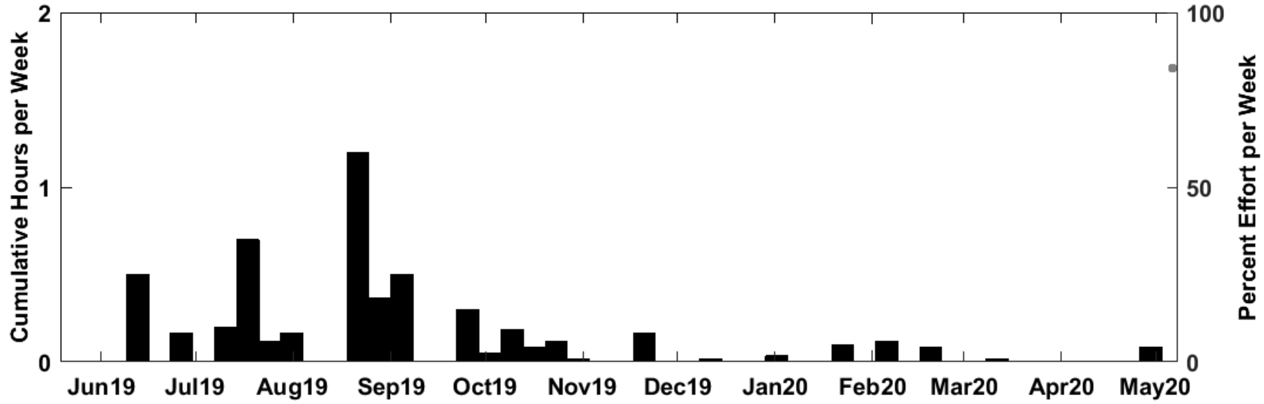

Figure 20. Weekly presence of *Kogia* spp. clicks from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

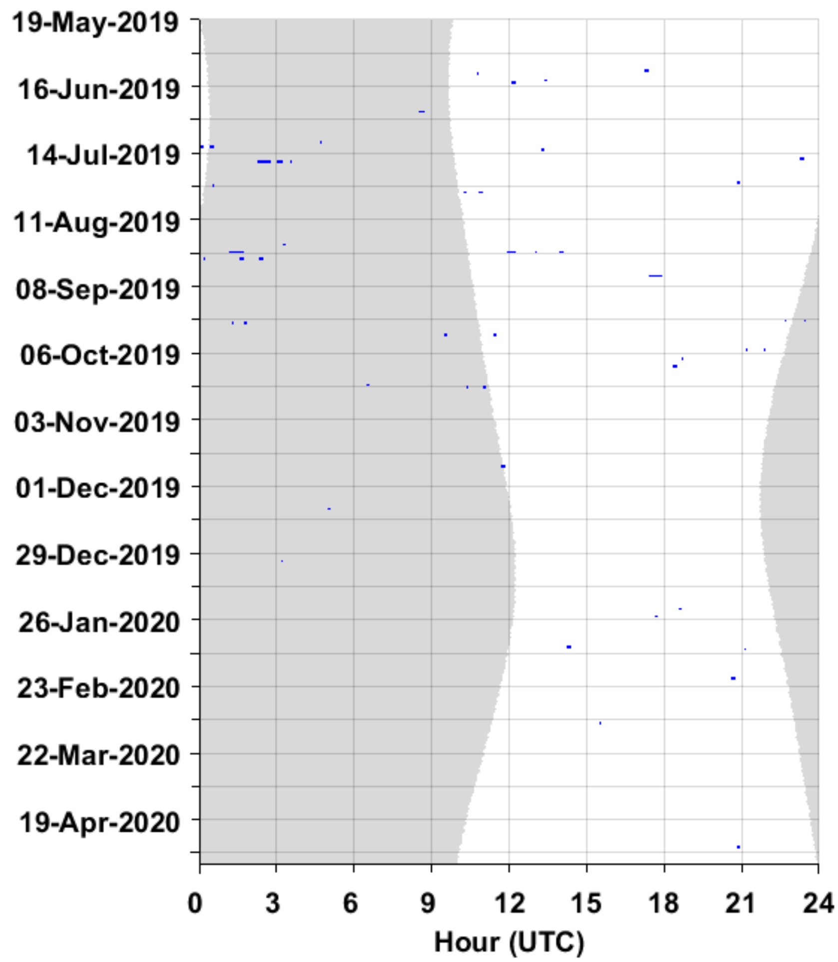

Figure 21. *Kogia* spp. clicks in five-minute bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

Anthropogenic Sounds

Three types of anthropogenic sounds were detected from May 2019 to 2020.

LFA Sonar

- LFA sonar greater than 500 Hz was detected in July and December 2019 and in March and April 2020 (Figure 22).
- There were not enough encounters of LFA to determine a diel pattern during the recording period (Figure 23).
- There were no detections of LFA less than 500 Hz during the recording period.

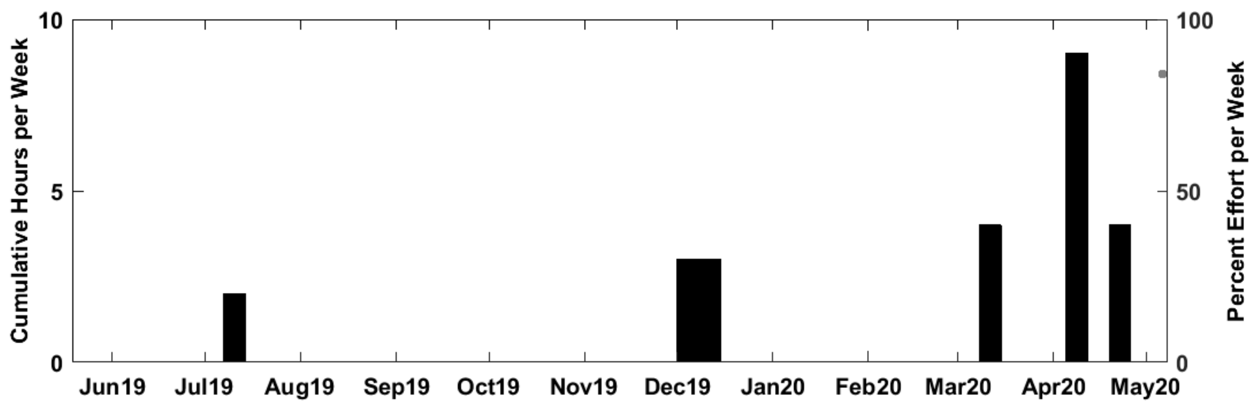

Figure 22. Weekly presence of LFA sonar from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

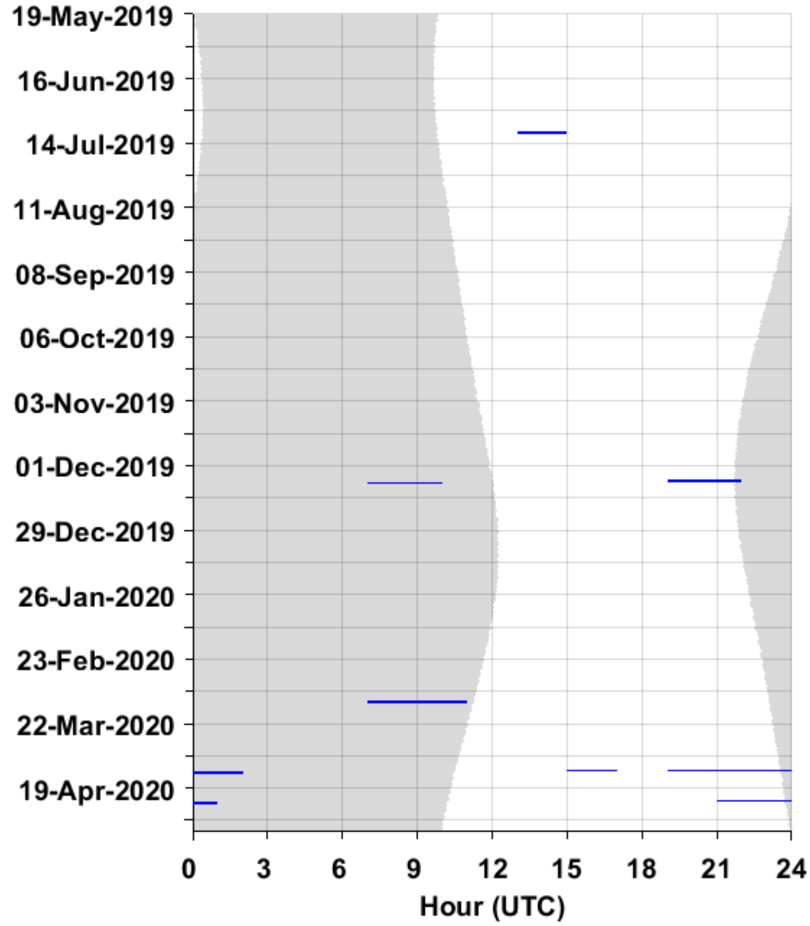

Figure 23. LFA sonar in one-hour bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

MFA Sonar

- MFA sonar less than 5 kHz were detected intermittently throughout the recording period but were highest in September 2019 (Figure 24).
- There was no discernible diel pattern for MFA sonar less than 5 kHz during the recording period (Figure 25).
- The MFA events with the highest number of packets (>50) were detected in December 2019 and cumulative sound exposure levels (CSEL) were highest (~160 dB re 1 μPa^2 s) were during MFA events in March 2020 (Figure 26).

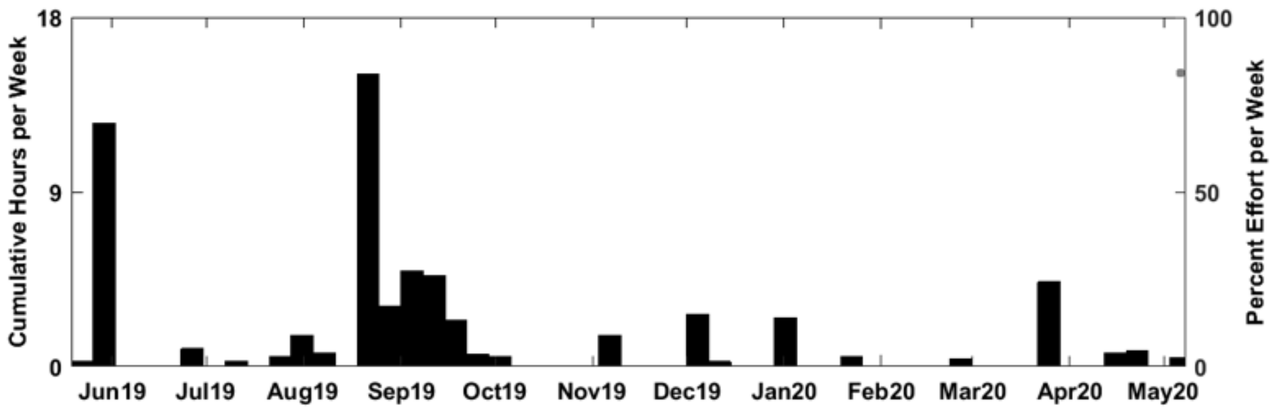

Figure 24. Weekly presence of MFA sonar less than 5 kHz from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

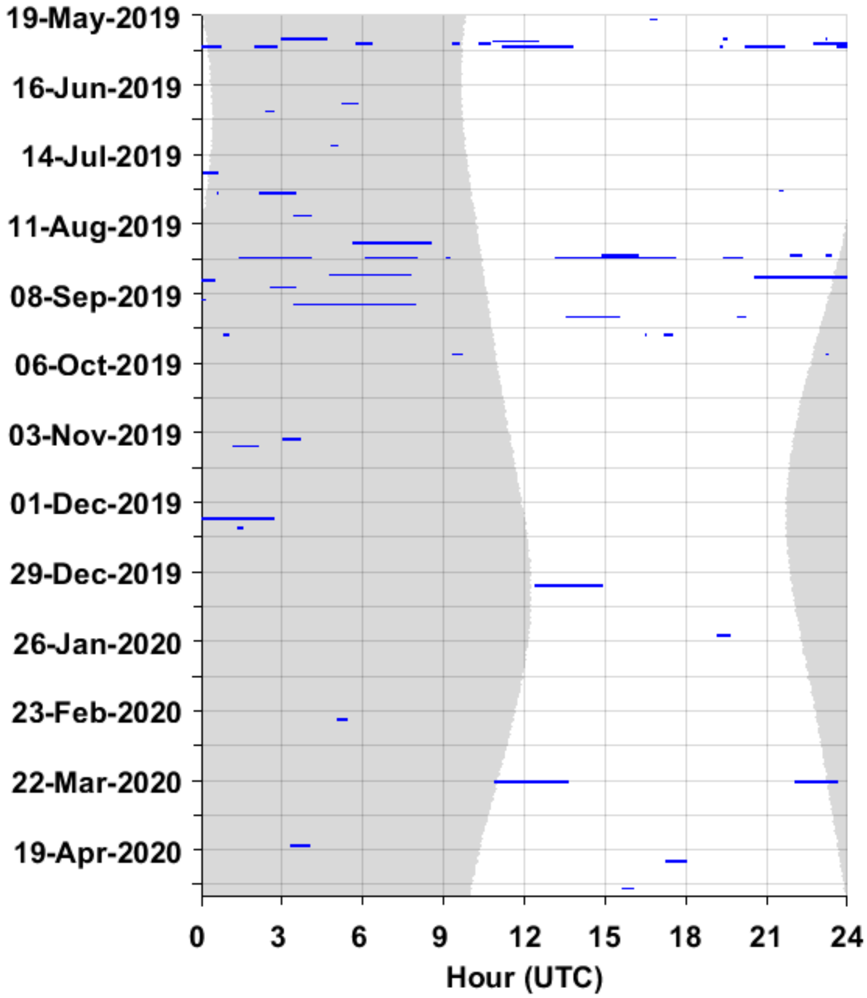

Figure 25. MFA sonar less than 5 kHz in five-minute bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

Table 2. MFA sonar automatic detector results, with wave trains and packets detected by energy detector for this recording period.

Site:	Period Analyzed Day (Years)	Number of Wave Trains	Wave Trains per Year	Number of Packets	Packets per Year	Total Wave Train Duration (h)	Total Packet Duration (s)	Max CSEL (dB re 1 µPa^2 s)
NFC_A_05	356 (0.98)	9	9.2	326	332.7	9.45	716.3	159.5

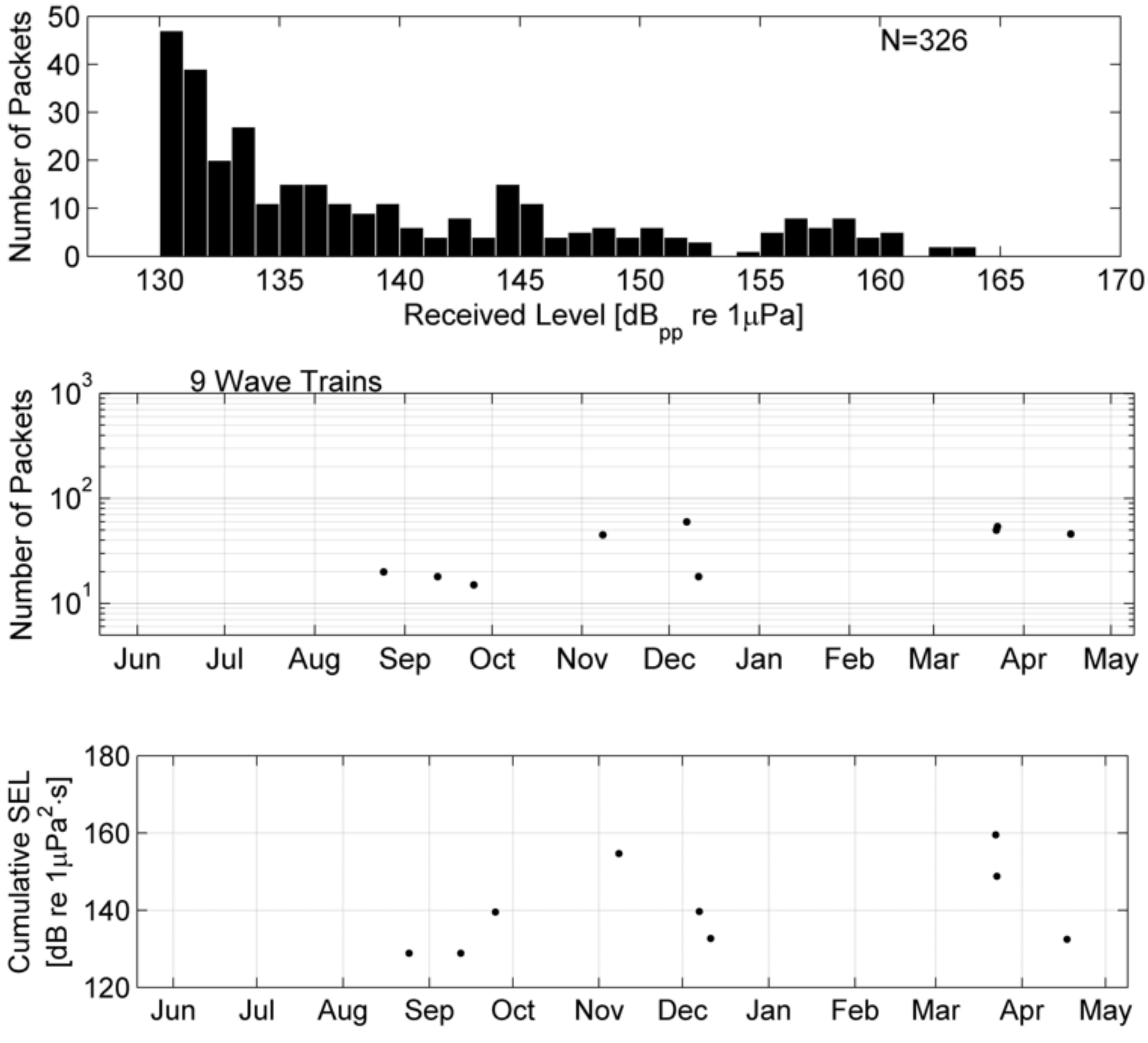

Figure 26. Top: Distribution of received levels (RL) of detected MFA packets. Center: Number of MFA packets detected in each wave train exceeding the minimum RL threshold (130 dBpp re 1µPa). Bottom: Cumulative sound exposure levels (CSEL) associated with each wave train.

Explosions

- 275 explosions were detected during this recording period. Detections were highest in late October 2019 (Figure 27). Manual analysis was conducted to ensure that explosions were not missed by the automated detector.
- There was no discernible diel pattern for explosions during the recording period (Figure 28).

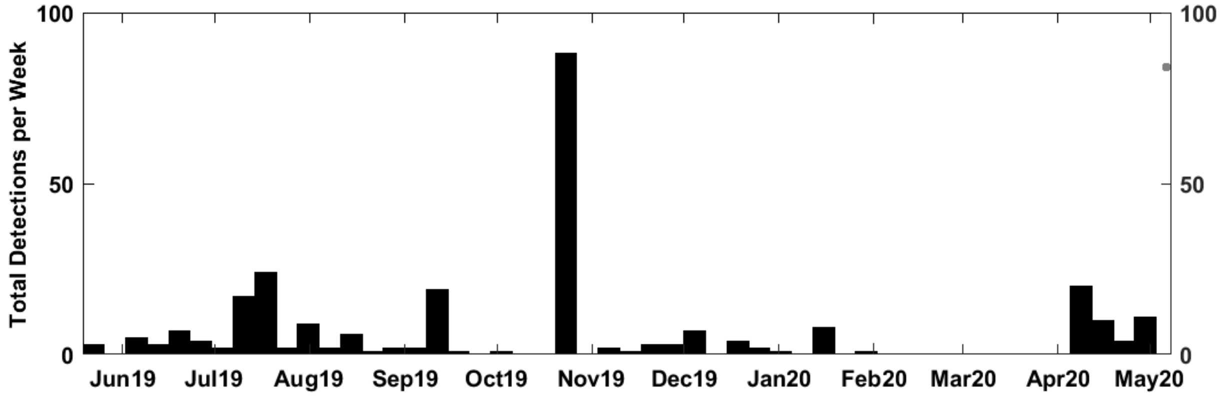

Figure 27. Weekly presence of explosions detected from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 14.

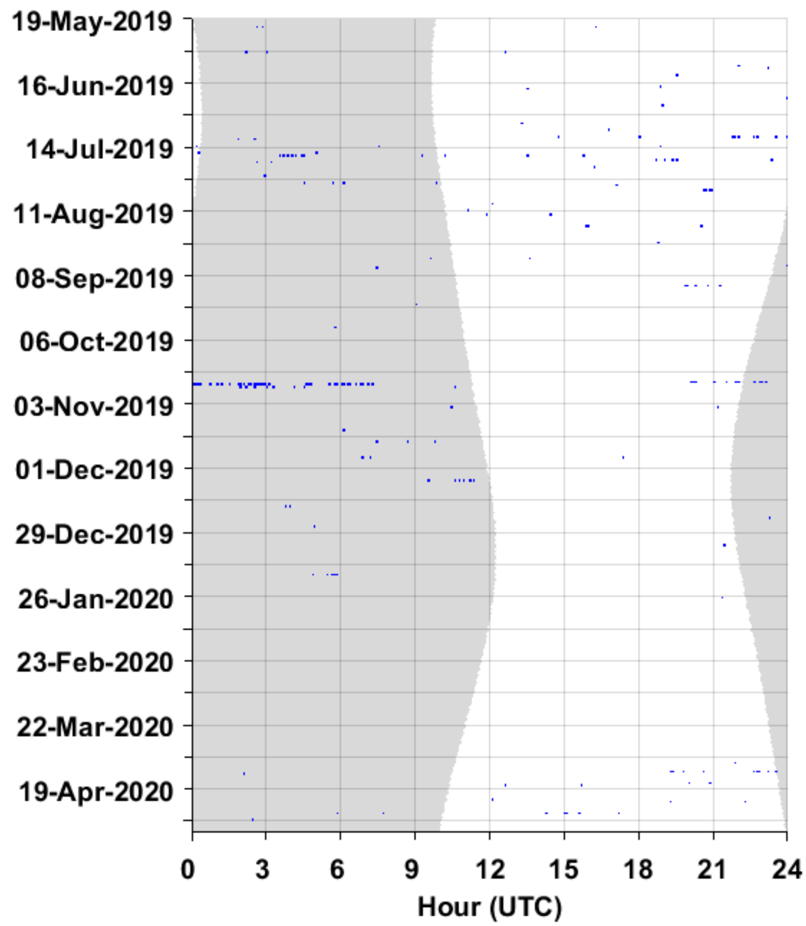

Figure 28. Explosions in five-minute bins from May 2019 to 2020 at NFC Site A. Effort markings are described in Figure 15.

References

Au, W. W. L. (1993). *The Sonar of Dolphins* (Springer).

Baumann-Pickering, S., McDonald, M. A., Simonis, A. E., Berga, A. S., 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," The Journal of the Acoustical Society of America 134, 2293-2301.

Baumann-Pickering, S., Roch, M. A., Brownell Jr, R. L., Simonis, A. E., McDonald, M. A., Solsona-Berga, A., Oleson, E. M., Wiggins, S. M., and Hildebrand, J. A. (2014). "Spatio-Temporal Patterns of Beaked Whale Echolocation Signals in the North Pacific," PLOS ONE 9, e86072.

Cholewiak, D., Baumann-Pickering, S., and Parijs, S. V. (2013). "Description of sounds associated with Sowerby's beaked whales (Mesoplodon bidens) in the western North Atlantic Ocean," The Journal of the Acoustical Society of America 134, 3905-3912.

Clarke, E., Feyrer, L.J., Moors-Murphy, H., Stanistreet, J. (2019). Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*) and Sowerby's beaked whales (*Mesoplodon bidens*) off eastern Canada. The Journal of the Acoustical Society of America. 146. 307-315. 10.1121/1.5111336.

DeAngelis, A. I., Stanistreet, J., Baumann-Pickering, S., and Cholewiak, D. A description of echolocation clicks recorded in the presence of True's beaked whale (*Mesoplodon mirus*). JASA, 2018.

Debich, A. J., Baumann-Pickering, S., Širović, A., Hildebrand, J. A., Brewer, A. M., Frasier, K. E., Gresalfi, R. T., Herbert, S. T., Johnson, S.C., Rice, A.C., Varga, L. M., Wiggins, S. M., Hodge, L. E. W., Stanistreet, J. E., Read. A. J. (2016). Passive Acoustic Monitoring for Marine Mammals in the Virginia Capes Range Complex October 2012 – April 2015. Final Report. Marine Physical Laboratory Technical Memorandum 559. September 2016. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-10-D-3011 - Task Order Number 051 – issued to HDR, Inc.

Frasier, K. E. (2015). Density estimation of delphinids using passive acoustics: A case study in the Gulf of Mexico. Doctoral dissertation, University of California San Diego, Scripps Institution of Oceanography, La Jolla, CA, USA. 321 pp.

Frasier, K. E. (2021). A machine learning pipeline for classification of cetacean echolocation clicks in large underwater acoustic datasets. *PLOS Computational Biology*, *17*(12), e1009613.

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, 3428-3433.

Johnson, M., Madsen, P. T., Zimmer, W. M. X., de Soto, N. A., and Tyack, P. L. (2004). "Beaked whales echolocate on prey," Proceedings of the Royal Society B: Biological Sciences 271, S383-S386.

Knudsen, V. O., Alford, R. S., and Emling, J. W. (1948). Underwater ambient noise. Journal of Marine Research. 7, 410-429.

McDonald, M. A., Messnick, S. L., and Hildebrand, J. A. (2006). "Biogeographic characterisation of blue whale song worldwide: using song to identify populations," Journal of Cetacean Research and Management 8, 55-65.

Rafter, M.A., Frasier, K.E., Trickey, J.S., Rice, A.C., Hildebrand, J.A., Thayre, B.J.,Wiggins, S.M., Širović, A, Baumann-Pickering, S. (2018). Passive Acoustic Monitoring for Marine Mammals at Norfolk Canyon April 2016 – June 2017. Final Report. Marine Physical Laboratory Technical Memorandum 629. July 2018. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-15-D-8006 Subcontract #383-8476 (MSA2015-1176 Task Order 003) issued to HDR, Inc.

Rafter, M.A., Frasier, K.E., Trickey, J.S., Rice, A.C., Reagan, E., Wiggins, S.M., Hildebrand, J.A., Baumann-Pickering, S. (2019). Passive Acoustic Monitoring for Marine Mammals at Norfolk Canyon June 2017 – June 2018. Final Report. Marine Physical Laboratory Technical Memorandum 634. February 2019. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-15-D-8006 Subcontract #383-8476 (MSA2015-1176 Task Order 003) issued to HDR, Inc.

Rafter. M.A., Trickey, J.S., Rice, A.C., Merrifield, M., Thayre, B.J., O'Neill, E., Wiggins, S.M., Baumann-Pickering, S., Frasier K.E., Hildebrand, J.A. Passive Acoustic Monitoring for Marine Mammals Near Norfolk Canyon June 2018 – May 2019. Final Report. Marine Physical Laboratory Technical Memorandum 648. June 2020. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-15-D-8006 Subcontract #383- 8476 (MSA2015-1176 Task Order 003) issued to HDR, Inc.

Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S., and Hildebrand, J. A. (2011). "Classification of echolocation clicks from odontocetes in the Southern California Bight," The Journal of the Acoustical Society of America 129, 467-475.

Širović, A., Bassett, H. R., Johnson, S. C., Wiggins, S. M., and Hildebrand, J. A. (2014). "Bryde's whale calls recorded in the Gulf of Mexico," Marine Mammal Science 30, 399-409.

Soldevilla, M. S., Henderson, E. E., Campbell, G. S., Wiggins, S. M., Hildebrand, J. A., and Roch, M. A. (2008). "Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks," The Journal of the Acoustical Society of America 124, 609-624.

Solsona-Berga, A., Frasier, K. E., Baumann-Pickering, S., Wiggins, S. M., & Hildebrand, J. A. (2020). DetEdit: A graphical user interface for annotating and editing events detected in long-term acoustic monitoring data. *PLoS computational biology*, *16*(1), e1007598.

Wenz, G. M., (1962). "Acoustic Ambient Noise in the Ocean: Spectra and Sources," Journal of the Acoustical Society of America, Vol. 34, No. 12, 1962, pp. 1936-1956.

Wiggins, S. M., and Hildebrand, J. A. (2007). "High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring.," (IEEE, Tokyo, Japan, International Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies), pp. 551-557.

Wiggins, S. M. (2015). "Methods for quantifying mid-frequency active sonar in the SOCAL Range Complex," MPL TM-533. Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, CA, p. 14.

Wiggins, S.M. and J. A. Hildebrand. (2016). Long-Term Monitoring of Cetaceans Using Autonomous Acoustic Recording Packages In Listening in the Ocean, edited by WWL Au and MO Lammers, Springer, New York. pp 35-59.

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