Passive Acoustic Monitoring for Marine Mammals and Ambient Noise Near Norfolk Canyon

Report Authors:
Natalie Posdaljian[1], Clara M. Schoenbeck[1], Annamaria DeAngelis[2], Lindsey Transue[2], Lauren M. Baggett[1], Genevieve Davis[2], Kaitlin E. Frasier[1]

[1]Scripps Institution of Oceanography, University of California, San Diego
[2]NOAA NMFS Northeast Fisheries Science Center

May 20, 2026

Suggested Citation

Posdaljian, N., Schoenbeck, C.M., DeAngelis, A.I., Baggett, L.M., Davis, G., Transue, L., Williamson, C., Forsberg, L., Cuatrecasas, R., & Frasier, K.E. (2025). *Passive Acoustic Monitoring for Marine Mammals and Ambient Noise Near Norfolk Canyon*. Scripps Institution of Oceanography, University of California San Diego, and NOAA Northeast Fisheries Science Center. MPL Technical Memorandum #680.

Table of Contents

1 Executive Summary

The Virginia Capes Range Complex, adjacent to Norfolk Canyon off Virginia, encompasses dynamic slope waters that support a diverse community of marine mammals. This report summarizes findings from a long-term passive acoustic monitoring study conducted near Norfolk Canyon from 2014 to 2021 using High-frequency Acoustic Recording Packages (HARPs). The goal of this study is to characterize the spatial and temporal presence of marine mammals and patterns in ambient noise at dynamic slope waters along the U.S. Atlantic coast.

HARPs were deployed across six deployments with the hydrophone depth ranging from 950-1050 m. Acoustic recordings were analyzed for echolocation signals from odontocetes, vocalizations from mysticetes, and low-frequency ambient sound.

Sperm whales and presumed larger-bodied delphinids (UD LF) were the most frequently detected odontocetes at Norfolk Canyon. Presumed smaller-bodied delphinids (UD HF & 47) also showed sustained, high-level presence across all years with effort. Goose-beaked whales were acoustically present throughout the monitoring period at low to moderate levels, with intermittent occurrence across years and seasonal increases in winter and mid-summer. Other beaked whales (Gervais', True's, Blainville's, and Sowerby's) occurred less regularly, *Kogia* spp. were detected at low levels, and Risso's dolphins showed moderate and seasonally variable presence. BWG ("Beaked Whale of the Gulf"), an unidentified beaked whale signal discovered in the Gulf of Mexico, was included in the classifier but was not detected during this study.

Seasonal patterns grouped by similarity were as follows: goose-beaked whales and the Gervais'/True's group showed a primary winter maximum with occasional midsummer increases; Sowerby's and Blainville's beaked whales, along with presumed smaller-bodied delphnids (UD HF & 47), peaked from winter through spring; late-spring through summer increases were characteristic of *Kogia* spp. and Risso's dolphins (with Risso's often rising in March–April and again in July–August); and the strongest summer–early fall presence occurred for presumed larger-bodied delphinids (UD LF) and sperm whales.

Diel patterns were generally weak or inconsistent, though True's beaked whales, Kogia spp., and smaller-bodied delphinids (UD HF & 47) showed nighttime/early-morning activity consistent with diel foraging. Across years, smaller-bodied delphinids (UD HF & 47) declined sharply after 2015 and again after 2019, and Sowerby's beaked whales were lower in 2020–2021.

Mysticete species also showed clear seasonal structure. Most baleen whales were acoustically present from late fall through spring and largely absent in summer. Fin whales exhibited the strongest and most sustained occurrence, with a long seasonal peak from August through March. Sei whales occurred regularly from November through May, with highest activity in March through April. Blue whales showed two seasonal pulses,

a winter–spring window (February–March) and a more sustained late-summer through early-winter presence (August–December). Humpback whales were primarily detected from February through April, with occasional late-fall presence. Minke whales were infrequent overall but showed a weak bimodal pattern with intermittent detections in winter through spring and again in fall. North Atlantic right whales were detected only sporadically across scattered months, consistent with occasional transits through the region rather than regular seasonal use. Together, these species-specific patterns highlight Norfolk Canyon as a seasonally used habitat and migratory corridor for multiple baleen whale species.

Ambient noise analyses revealed persistent peaks in the 30–60 Hz band attributable to commercial shipping, with seasonal enhancements in the 20 Hz band linked to increased fin whale presence. Peaks around 120 and 170 Hz were observed in winter months and likely reflect seasonal minke whale vocal activity. At frequencies above 200 Hz, spectral levels increased due to elevated sea states in the winter and fall.

Although these data provide exceptional temporal resolution at a fixed location off the Virginia Capes, they do not represent the full spatial heterogeneity of the western North Atlantic. As comparative work has shown, species' apparent regional presence varies depending on bathymetric and oceanographic setting (DeAngelis et al. 2025). These findings contribute to the long-term understanding of species distribution and acoustic habitat use in a highly variable oceanographic region and provide a valuable baseline for future studies assessing environmental change and anthropogenic impacts along the U.S. Atlantic slope.

2 Introduction

2.1 Project Background

The U.S. Navy's Virginia Capes Range Complex is situated in the coastal and offshore waters of the western North Atlantic Ocean, adjacent to the coasts of Delaware, Maryland, Virginia, and North Carolina. This area encompasses a varied seafloor landscape, featuring a broad continental shelf with an inner zone of less than 200 meters in water depth, extending to an outer zone that reaches depths of up to 2,000 meters. The region supports a diverse array of marine mammals, including both baleen and toothed whales, which rely on these habitats for foraging, migration, and other life history functions.

From 2014 to 2021, a comprehensive acoustic monitoring effort was conducted within the boundaries of the Virginia Capes Range Complex to study marine mammal presence and ambient noise levels. The objective was to characterize the vocalizations of marine mammal species in the area, identify their seasonal presence patterns, and assess the potential impacts of naval operations on these species. This report presents the findings from the analysis of data collected using six High-frequency Acoustic Recording Packages (HARPs; Wiggins & Hildebrand 2007), which were strategically deployed within the Virginia Capes Range Complex near Norfolk Canyon (Figure 1 & Table 1).

Table 1: Recording effort for Norfolk Canyon deployments.

Deployment	Start Date	End Date	Depth (m)	Recording Duration (Days)
01	2014-06-19	2015-04-05	980	290
02	2016-04-30	2017-06-08	970	404
03	2017-06-30	2018-06-02	950	337
04	2018-06-02	2019-05-18	1050	350
05	2019-05-19	2020-05-08	1050	355
06	2021-06-29	2021-09-19	1050	82

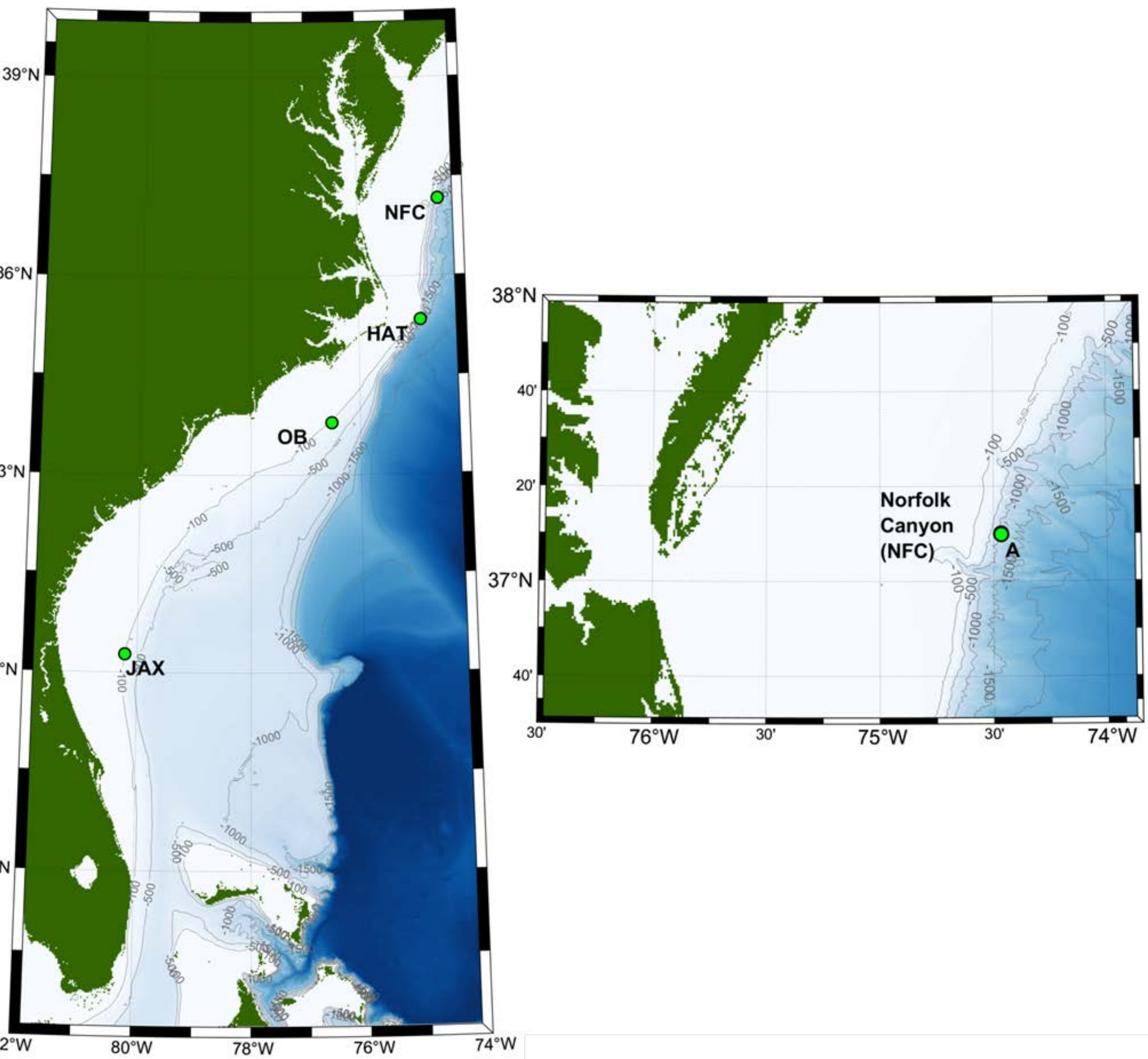

Figure 1: Location of the High-frequency Acoustic Recording Packages (HARPs) at the Norfolk Canyon (NFC) site. Left: Large-scale view of the NFC project location along the U.S. East Coast. Right: Zoomed-in view showing the positions of individual deployments.

3 Data Collection & Quality

High Frequency Acoustic Recording Packages (HARPs) are autonomous underwater acoustic recording devices that, depending on configuration, can record sounds over a bandwidth from 10 Hz to 100 kHz and are capable of approximately one year of continuous recording. The HARPs were deployed in a large mooring configuration with the hydrophone suspended approximately 10 m above the seafloor. Each HARP was 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 & Hildebrand 2007).

The vast majority of the data collected were found to be error free. Deployment 02 experienced limited data loss toward the end of the recording period due to a hard drive malfunction. Intermittent data gaps appeared at the end of deployment 03 due to a data logger malfunction. Recording coverage began as 100% and was 84% by the end of the recording period. We do not believe the intermittent gaps observed in deployments 02 and 03 have significant impact on the resulting data analysis. Deployment 06 had no useable acoustic data after September 14, 2022, likely due to a failure of the hydrophone, hydrophone cable, or ATD board.

4 Data Analysis

The data analysis process is described below for the major classes of odontocete and mysticete vocalizations and low-frequency ambient soundscape at the Norfolk Canyon sites, detailing the detection and characterization methods.

These datasets were analyzed individually as part of the data collection effort. During the span of data collection, both analytical methods and recording devices evolved. Here, we have reanalyzed all of the datasets using the latest and best available methods at the time of writing, to improve comparability. However, some differences between successive deployments remain, particularly due to changes in hydrophone designs aimed at improving and optimizing high frequency recordings. Current machine learning methods greatly improve comparability but may lack robustness to instrument specific acoustic features not well represented in their training data (Roch et al. 2015). We have expended effort to ensure that the data is as comparable as possible over this timeseries, and have aimed for a level of granularity in our results that is relatively robust to these differences.

Analyses here describe temporal patterns at the Norfolk Canyon site, not spatial gradients across the western North Atlantic. Comparisons to other studies that include the Norfolk Canyon study area are provided for context rather than extrapolation beyond the study area. Species presence and temporal patterns can differ even at nearby locations with varying bathymetry, distance from the slope, and Gulf Stream proximity (DeAngelis et al. 2025).

4.1 Odontocete Analyses

Odontocete sounds can be categorized as echolocation clicks, burst pulses, or whistles. Echolocation clicks are broadband impulses with peak energy between 1 and 150 kHz, dependent upon the species. Buzzes or burst pulses are rapidly repeated clicks that have a creak, squeal, screech, or buzz-like sound quality; they are often 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 a long-term spectral average (LTSA) as well as the spectrogram. Analyses in this report focus only on echolocation clicks as a proxy for odontocete presence because they are currently the most promising call type for species classification in the region.

List of odontocete species analyzed:

- Goose-beaked whale (*Ziphius cavirostris*)
- Gervais' beaked whale (*Mesoplodon europaeus*)
- True's beaked whale (*Mesoplodon mirus*)
- Blainville's beaked whale (*Mesoplodon densirostris*)
- Sowerby's beaked whale (*Mesoplodon bidens*)
- Beaked Whale of the Gulf (BWG)
- Sperm whale (*Physeter macrocephalus*)
- *Kogia* spp.
- Risso's dolphin (*Grampus griseus*)
- Unidentified delphinids – smaller-bodied delphinids (UD HF & 47)
- Unidentified delphinids – larger-bodied delphinids (UD LF)

4.1.1 Beaked Whale Click Classification

Potential beaked whale echolocation clicks were detected automatically using a generic pulse detector, publicly available in the SPICE Detector remora package in Triton (Frasier 2021). Detection parameters included a fifth-order Butterworth filter with a high passband between 5 and 100 kHz and a minimum received sound pressure level (SPL) of 118 dB peak-to-peak re $1\mu Pa^2$.

For deployments NFC 02-04 and 06, following the generic pulse detector, an unsupervised clustering method, accessible in the Cluster-Tool remora package (Frasier 2021), was applied. Detections were clustered within successive 5-min windows and dominant click types were identified in each window using spectral features, inter-click intervals, and waveform envelopes. A minimum for 10 clicks per cluster bin was set to include ephemeral beaked whale encounters (Solsona-Berga et al. 2024). For deployments 01 and 05, a targeted species classification method was applied prior to the unsupervised clustering (Solsona-Berga et al. 2024). A hard negative filter based on commonly used rules for identifying beaked whale click characteristics (peak and center frequency, click duration, sweep rate) was applied to exclude non-beaked whale-like clicks prior to clustering (Solsona-Berga et al. 2024). From there, the same unsupervised clustering method was applied. A deep neural network was trained to classify these signal types with an overall accuracy of 97.7% on a balanced test set (Solsona-Berga et al. 2024). A trained analyst then manually verified the neural network labels for all deployments, using DetEdit, an open-source software for visualizing events within large acoustic datasets (Solsona-Berga et al. 2020).

4.1.2 Sperm Whale Click Detection

Sperm whale echolocation clicks were detected using the multi-step approach described in Solsona-Berga et al. 2020 (appendix). These clicks have multiple pulses (Backus & Schevill 1966), 2–9 ms apart, depending upon the size of the animal (Norris & Harvey 1972). As a result, the detector had a lockout for clicks separated by less than 30 ms to avoid multiple detections of a single click. Band-pass filtering the data (5–95 kHz) minimized the effects of low-frequency noise from vessels, weather, or instrument self-noise on detections, but allowed for detection of the echolocation clicks of toothed whales. The Power Spectral Density (PSD) of detected signals was calculated with the Pwelch method using 4 ms of the waveform and a 512-point Hann window with 50% overlap (Welch 1967). Instrument specific full-system transfer functions were applied to account for the hydrophone sensor response, signal conditioning electronics, and analog-to-digital conversion. To provide a consistent detection threshold, only clicks exceeding peak-to-peak (pp) sound pressure level (RL) of at least 125 dBpp re 1 µPa were analyzed. This threshold was chosen to eliminate noise signals and the echolocation clicks of other odontocetes, while retaining sperm whale clicks.

Sperm whale echolocation clicks can be confused with the impulsive signals from ship propeller cavitation. An automated classifier developed by Solsona-Berga et al. 2020 (appendix) was used to exclude periods of ship passages. The classifier identified potential ship passages from long-term spectral averages (LTSA), which are long duration spectrograms (Wiggins & Hildebrand 2007). Further averaging was calculated as Average Power Spectral Densities (APSD) per 2-hour blocks over low (1–5 kHz), medium (5–10 kHz), and high (10–50 kHz) frequency bands with 100 Hz bins and 50% overlap. Using received sound levels, transient ship passage signals were separated from odontocete echolocation clicks and weather events. A trained analyst manually reviewed identified ship passages using the MATLAB-based custom software program Triton (Wiggins & Hildebrand 2007). Ship passage times were removed from further analysis and considered time periods with no effort.

Instrument self-noise and the echolocation clicks of other odontocetes were also removed to reduce the number of false positive detections. A classifier using spectral click shape was implemented, taking advantage of a sperm whale click’s distinct low-frequency spectral shape to remove dissimilar clicks by delphinid and beaked whales, which typically have higher frequencies (Solsona-Berga et al. 2020). The remaining acoustic encounters containing putative sperm whale echolocation clicks were manually reviewed with DetEdit, a custom, MATLAB-based graphical user interface (GUI) software program used to view, evaluate, and edit automatic detections (Solsona-Berga et al. 2020).

4.1.3 *Kogia* Spp., Risso's Dolphin, and Unidentified Delphinid Click Classification

Odontocete echolocation clicks were detected automatically using an energy detector with a minimum received level threshold of 120 dBpp re: 1 μPa ((Roch et al. 2011; Frasier et al. 2016)). To classify detected clicks to putative taxonomic groups, dominant click types and false positive categories at these sites were identified using automated unsupervised clustering methods (Frasier 2021). Detections were clustered within successive 5-min windows, and dominant click types were identified in each window using spectral features, inter-click intervals (ICI), and waveform envelopes. Regular clicks were the focus of this analysis; therefore, clicks with an ICI less than 0.001 s were excluded to limit the inclusion of buzz clicks. An automated clustering algorithm was then used to identify recurrent types based on spectral features, ICI, and waveform distributions at each site (Frasier et al. 2017). Common click types were manually aggregated across all western North Atlantic sites to form classifier training and testing datasets for 13 signal types, including nine odontocete signal classes and four sources of false positives.

Click types were attributed to a specific species when acoustically identifiable (e.g., *Kogia* spp. and Risso's dolphin) or assigned to unidentified categories when species-level identification was not possible (e.g., delphinids). A deep neural network was trained to classify these signal types, achieving at least 93% classification accuracy on a balanced test set. This trained network was then used to classify all 5-min windows across all sites.

Only five odontocete signal categories are presented in this report: *Kogia* spp., Risso's dolphin, unidentified presumed smaller-bodied delphinids (UD HF & 47), which were combined due to their similar acoustic characteristics), and unidentified presummed larger-bodied delphinids (UD LF). The classifier achieved high accuracy on an independent test set, with 100% accuracy for *Kogia* spp., 97.3% for Risso's dolphins, 93.2% for the combined smaller-bodied delphinid classes, and 97.6% for larger-bodied delphinids (UD LF). Some misclassification occurred among acoustically similar delphinid classes, reflecting overlapping click characteristics; however, cross-class confusion was generally low, and overall model performance was consistent with the spectro-temporal distinctiveness of each class.

Classifications for *Kogia* spp. and larger-bodied delphinids (UD LF) were filtered using a 95% confidence threshold and a minimum of 100 clicks per 5-min bin to ensure high-confidence detections. For Risso's dolphins and smaller-bodied delphinid classes (UD HF & 47), no confidence threshold was applied in order to retain consistent detection coverage across the full monitoring period, while still applying the 100-click minimum to reduce false positives.

4.2 Odontocete Species Call Descriptions

Several odontocetes are resident to the Western Atlantic Cape Hatteras region. A description of the identifying features of each species' call types follows. For all odontocete species (except sperm whales), the following figures are presented:

- Average spectrum of an acoustic signal type with associated variance
- Histogram of average ICIs for an acoustic signal type
- Envelope of the signal waveform
- Long-term average spectrogram (LTSA) of an acoustic encounter over 1-hour
- Standard spectrogram of acoustic signals over 5 seconds

4.2.1 Goose-Beaked Whale

Beaked whales can be identified acoustically by their echolocation signals (Baumann-Pickering et al. 2014). These signals are frequency-modulated (FM) upsweep 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, goose, and Gervais' beaked whales.

Goose-beaked whale's echolocation signals are polycyclic, with a characteristic FM pulse upsweep, peak frequency around 40 kHz (Figures 2 & 3), and uniform inter-click interval (ICI) of about 0.5 s (Johnson et al. 2004; Zimmer et al. 2005). An additional feature that helps with the identification of goose-beaked whale FM pulses is that they have three characteristic spectral peaks around 17, 23, and 70 kHz.

Previous studies have shown that goose-beaked whales are among the most frequently detected beaked whales in the western North Atlantic, with high acoustic presence along the shelf break and slope from Cape Hatteras north through the Mid-Atlantic (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025). They are less frequently detected south of Cape Hatteras, while detections at Hatteras and farther north occur year-round, with increased prevalence in winter and spring (Haver et al. 2025; Stanistreet et al. 2022; Cohen et al. 2023).

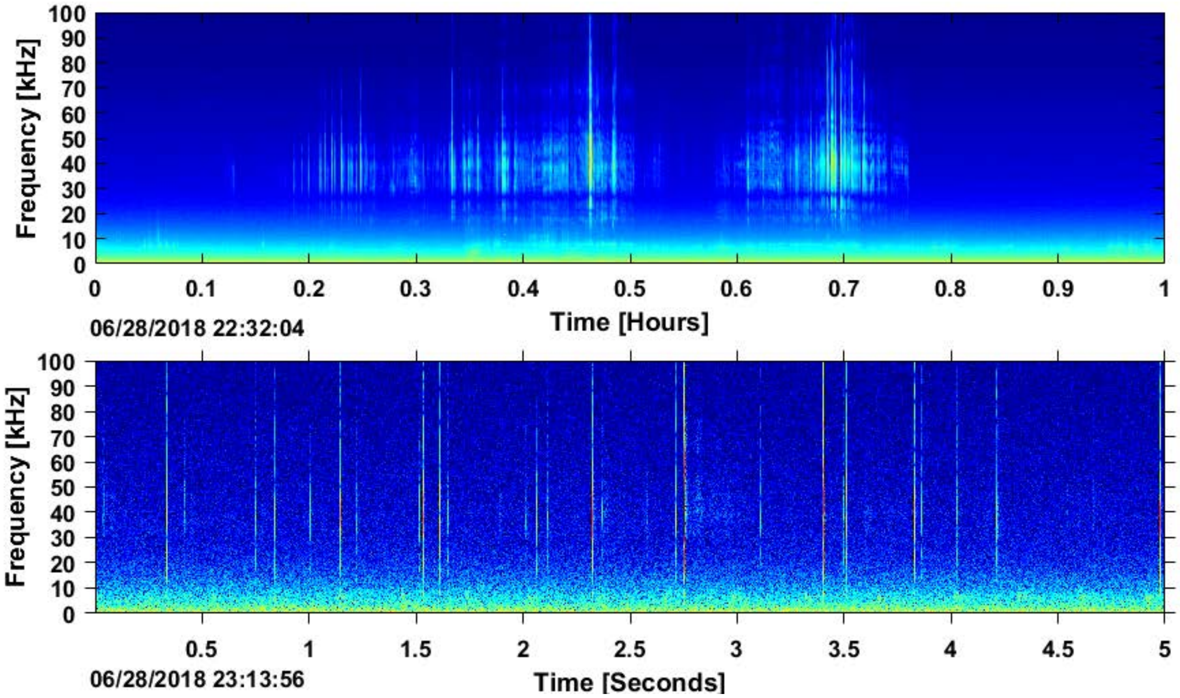

Figure 2: Goose-beaked whale signal in LTSA (top) and spectrogram (bottom).

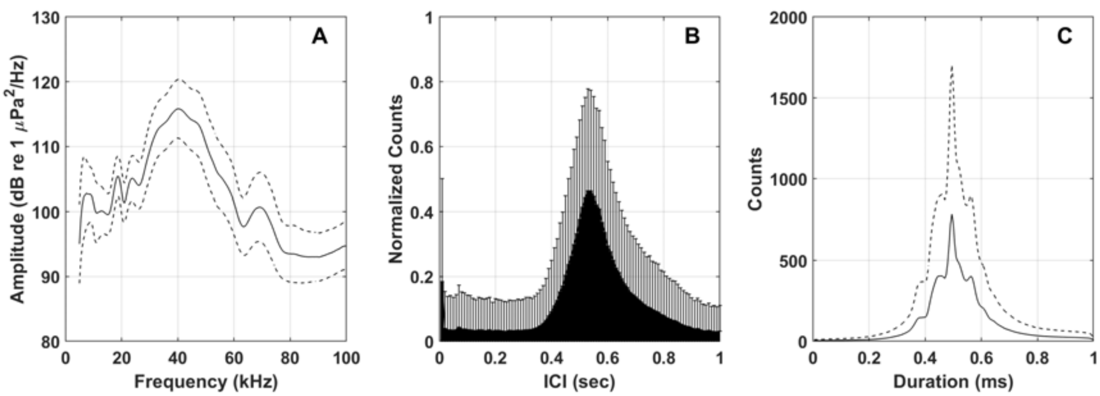

Figure 3: Left: Mean frequency spectrum of goose-beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.5 s; Right: Mean waveform envelope (solid line) and standard deviation (dashed line) of representative clicks.

4.2.2 Gervais' Beaked Whale

Gervais' beaked whale echolocation 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) (Figures 4 & 5). While Gervais' beaked whale signals are similar to those of True's and Blainville's beaked whales, the Gervais' beaked whale FM pulses have a slightly longer ICI (near 0.3 s compared to 0.2 s) than True's and are at a slightly higher frequency than Blainville's. Similar to all beaked whales, Gervais' beaked whale FM pulses sweep up in frequency. The ICI for Gervais' beaked whale signals is typically around 0.28 s (Baumann-Pickering et al. 2013; Gillespie et al. 2009).

Previous studies have shown that Gervais' beaked whales are concentrated from Cape Hatteras southward along the western North Atlantic slope (1000m contour), with limited presence north of Hatteras (Cohen et al. 2022; Haver et al. 2025; Cohen et al. 2023; DeAngelis et al. 2025). They occur year-round in these southern regions, with increased detections from late summer through winter (Stanistreet et al. 2022; Cohen et al. 2023). These patterns indicate that Cape Hatteras and waters to the south represent important foraging hotspots for this species within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023). Broad-scale surveys further show that Gervais' presence is closely tied to warm, low-chlorophyll Gulf Stream waters, distinguishing them from True's beaked whales, which occur more often in cooler slope and abyssal habitats (DeAngelis et al. 2025).

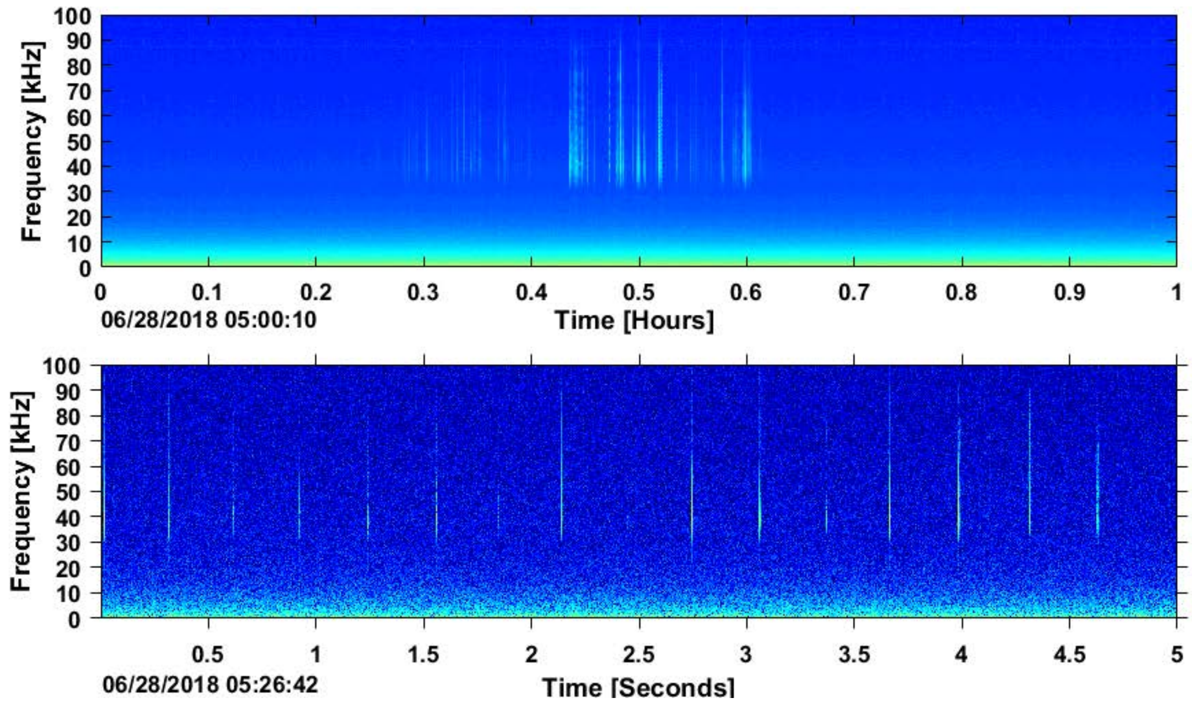

Figure 4: Gervais' beaked whale signal in LTSA (top) and spectrogram (bottom).

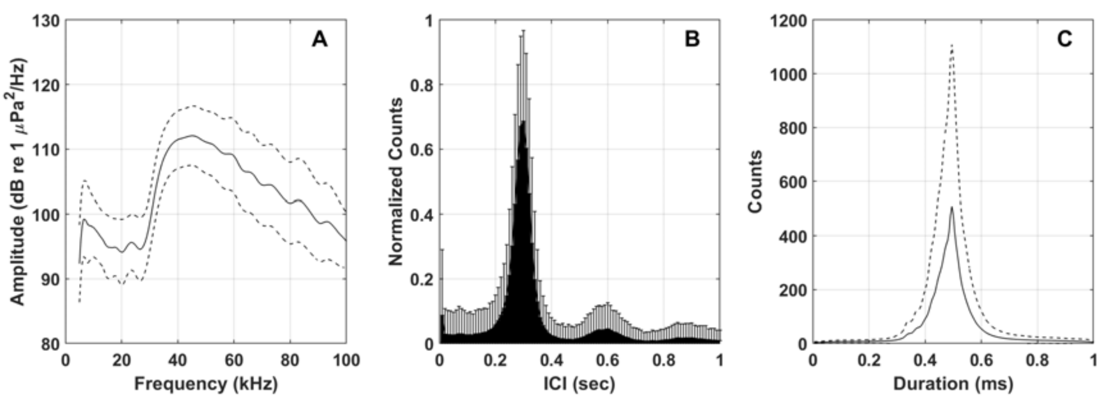

Figure 5: Left: Mean frequency spectrum of Gervais' beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.3 s. Smaller peaks can occur at multiples of the main peak, and represent cases where a subset of clicks in a click train have been missed by the detector or classifier; Right: Mean waveform envelope of representative clicks.

4.2.3 True's Beaked Whale

True's beaked whale echolocation signals are FM upsweep pulses, with a peak frequency around 46 kHz and an inter-pulse interval of about 0.18 s. The spectral features of True's beaked whale FM pulses closely resemble those produced by Gervais' beaked whales (DeAngelis et al. 2018) (Figures 6 & 7).

Previous studies have shown that True's beaked whales are primarily associated with deep slope and canyon habitats along the western North Atlantic slope (1000 m contour), with presence concentrated from Cape Hatteras north through the mid-Atlantic canyons (Stanistreet et al. 2022; Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025). They are infrequently reported south of Cape Hatteras, and acoustic detections indicate year-round presence with increased prevalence from winter through summer at northern sites (Stanistreet et al. 2022; Cohen et al. 2022; Cohen et al. 2023). Broad-scale surveys further indicate that True's detections are more frequent in cooler slope and abyssal habitats, distinguishing them from Gervais' beaked whales that are more closely tied to Gulf Stream waters (DeAngelis et al. 2025). These patterns suggest that slope waters north of Cape Hatteras, including the canyon regions, represent important foraging hotspots for this species within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023).

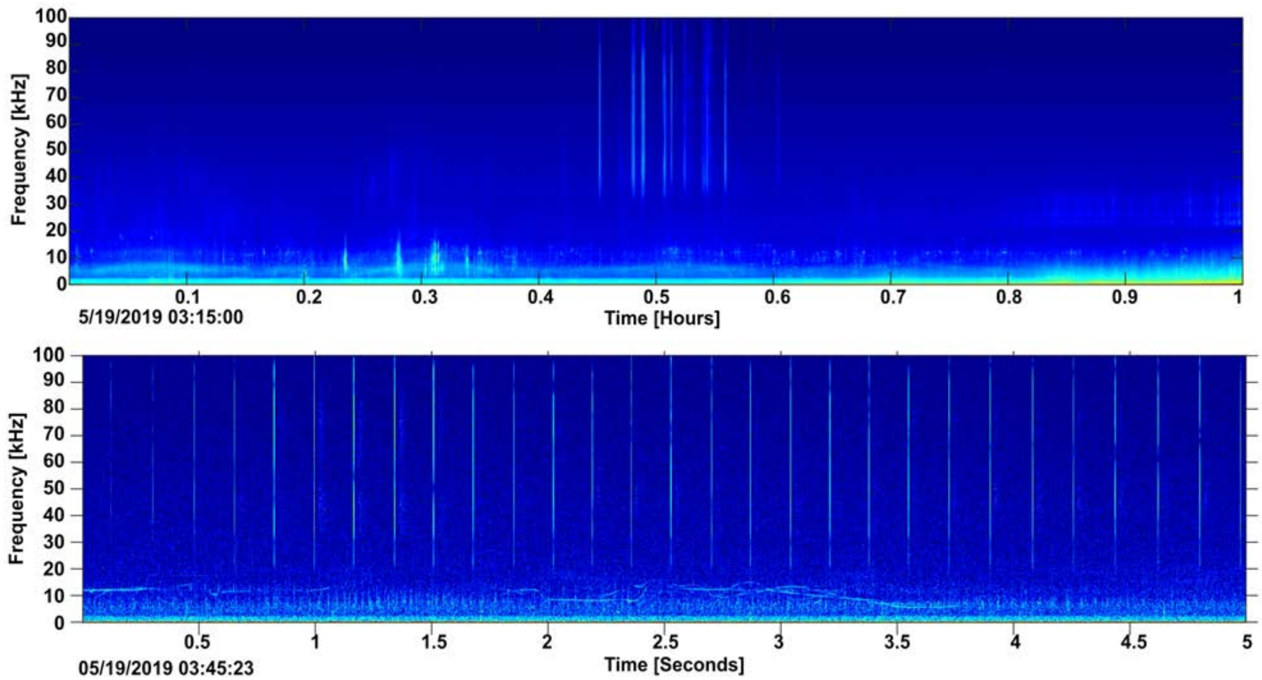

Figure 6: True's beaked whale signal in LTSA (top) and spectrogram (bottom).

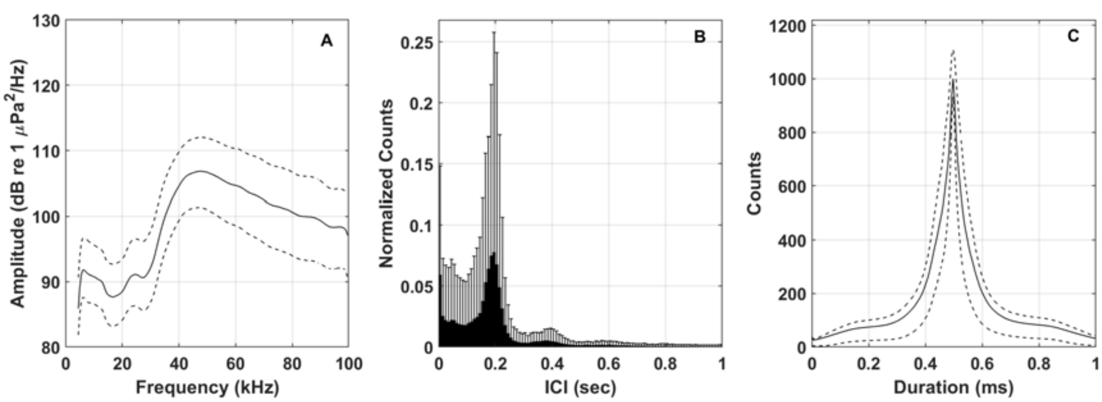

Figure 7: Left: Mean frequency spectrum of True's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.18 s; Right: Mean waveform envelope of representative clicks.

4.2.4 Blainville's Beaked Whale

Blainville's beaked whale echolocation signals are, like most beaked whales' signals, polycyclic with a characteristic frequency-modulated upsweep, and are identifiable by a peak frequency around 34 kHz and uniform ICI of about 0.28 s (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 (Figures 8 & 9).

Previous studies have shown that Blainville's beaked whales are rarely encountered in the western North Atlantic slope (1000 m contour), with only occasional detections along the slope and shelf break of the U.S. EEZ (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025). When present, they are generally restricted to southern regions near and south of Cape Hatteras, and detections occur sporadically throughout the year without clear seasonality (Stanistreet et al. 2022; Cohen et al. 2023). Broad-scale surveys further indicate that Blainville's detections are primarily associated with Gulf Stream waters, distinguishing them from goose-beaked whales, which are more broadly distributed across slope habitats (DeAngelis et al. 2025). These patterns suggest that Blainville's beaked whales are uncommon in the region, with only limited use of Cape Hatteras and southern mid-Atlantic waters as foraging habitat (Haver et al. 2025; Cohen et al. 2023; DeAngelis et al. 2025).

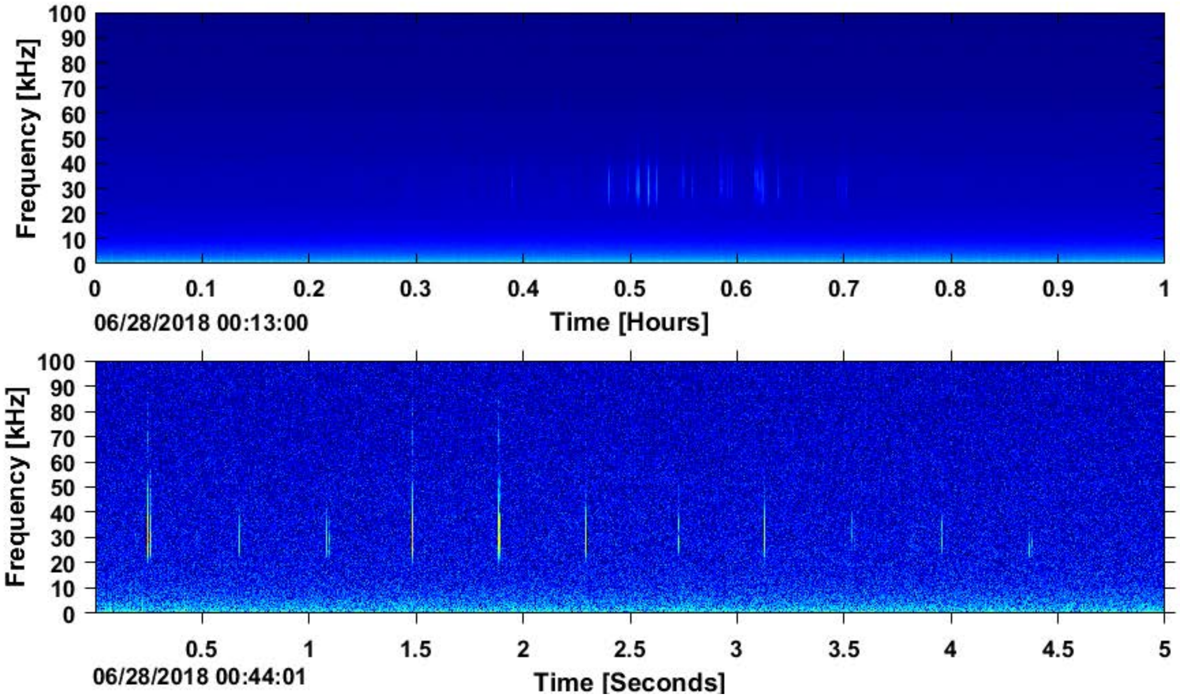

Figure 8: Blainville's beaked whale signal in LTSA (top) and spectrogram (bottom).

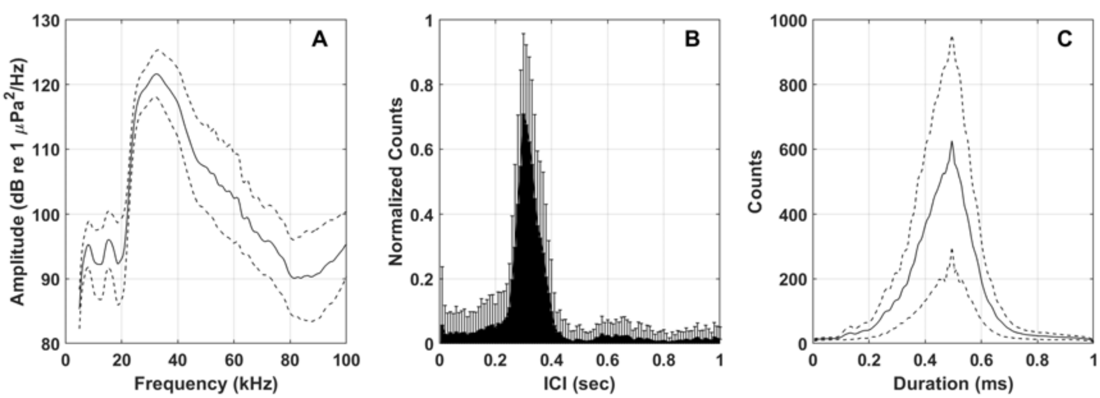

Figure 9: Left: Mean frequency spectrum of Blainville's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.3 s; Right: Mean waveform envelope of representative clicks.

4.2.5 Sowerby’s Beaked Whale

Sowerby’s beaked whale echolocation signals have energy concentrated in the 50-95 kHz band, with a peak at 67 kHz. 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 0.15 s (Clarke et al. 2019) (Figures 10 & 11).

Previous studies have shown that Sowerby’s beaked whales are found primarily in the northern portion of the western North Atlantic slope (1000 m contour), with detections concentrated north of Norfolk Canyon and limited presence farther south (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025). They occur year-round in these northern slope and canyon habitats, with detections peaking from summer through winter (Stanistreet et al. 2022; Cohen et al. 2023). Broad-scale surveys further show that Sowerby’s detections are closely tied to the shelf-break front and continental slope waters, underscoring their predominance in more northerly habitats (DeAngelis et al. 2025). These patterns indicate that regions north of Norfolk Canyon represent the main foraging hotspots for this species within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023; DeAngelis et al. 2025).

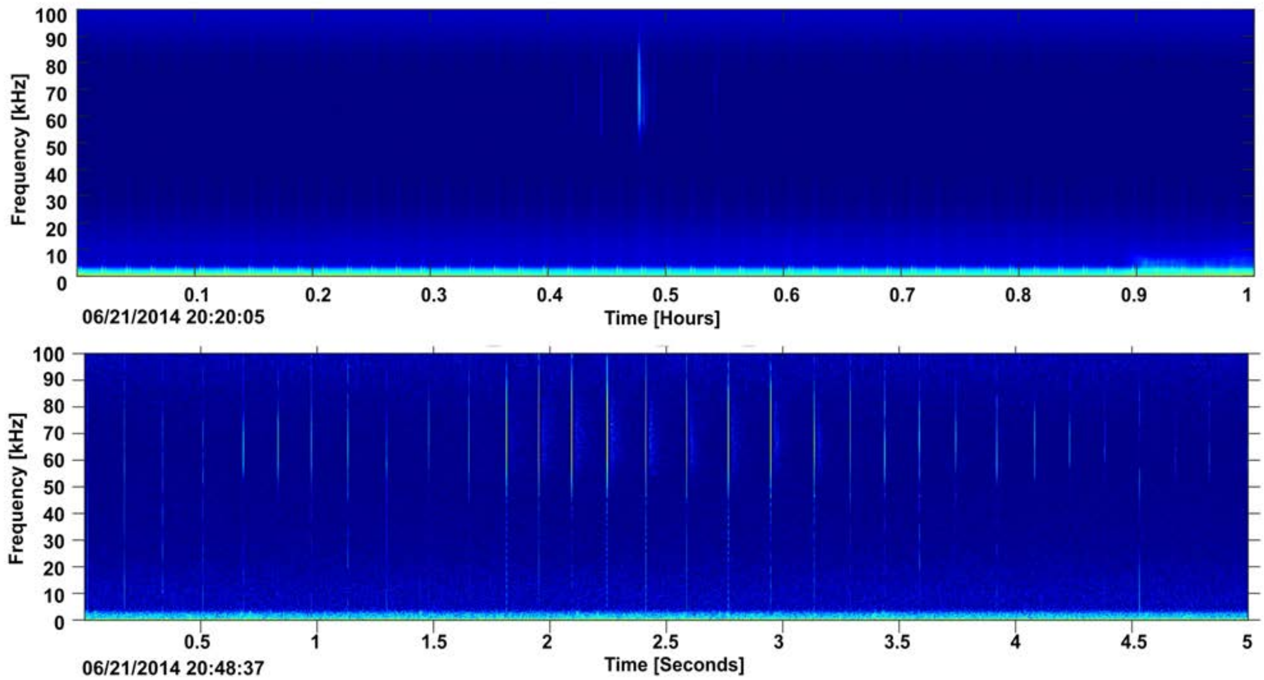

Figure 10: Sowerby's beaked whale signal in LTSA (top) and spectrogram (bottom).

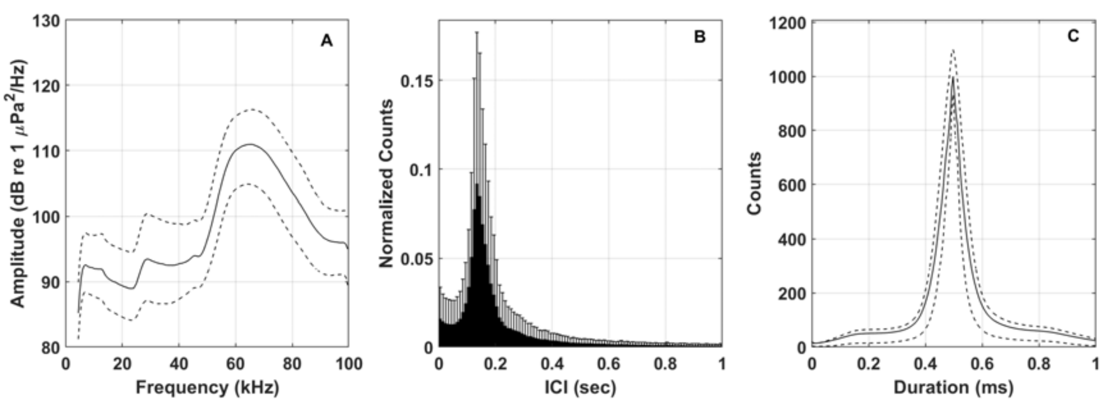

Figure 11: Left: Mean frequency spectrum of Sowerby's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.15 s; Right: Mean waveform envelope of representative clicks.

4.2.6 BWG

BWG ("Beaked Whale Gulf") is a signal believed to be produced by a beaked whale but currently of an unidentified species. BWG echolocation signals are FM upsweep pulses, with a peak frequency around 47 kHz and an inter-pulse interval of about 133 ms (Baumann-Pickering et al. 2013). BWG pulses have a longer click duration and are greater bandwidth than other beaked whale species in this area (Hildebrand et al. 2015) (Figures 12 & 13). Although BWG was included in the neural network classifier, no encounters were detected during the analysis period, though classifier performance for BWG-like signals is lower than for other beaked whale species due to limited training and test sample sizes, which may reduce detection reliability.

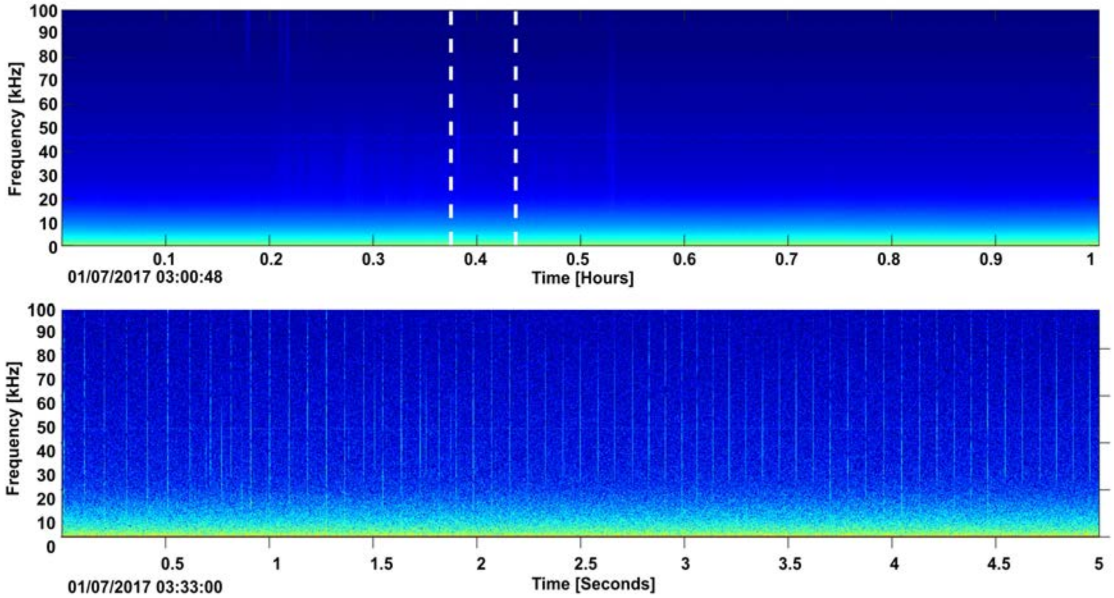

Figure 12: BWG signal in LTSA (top) and spectrogram (bottom).

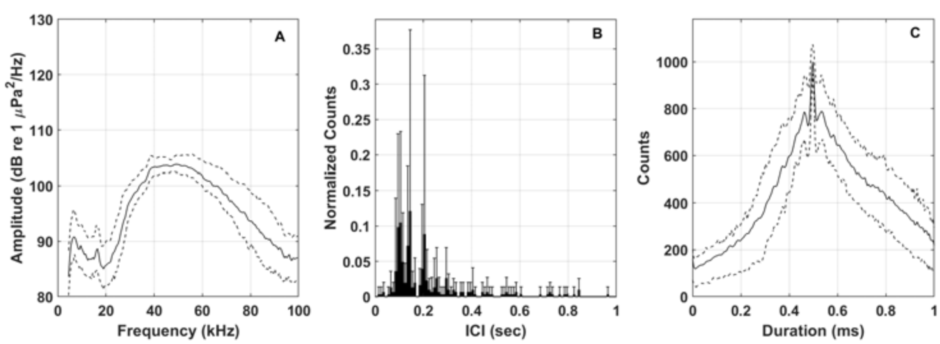

Figure 13: Left: Mean frequency spectrum of BWG echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.18 s; Right: Mean waveform envelope of representative clicks.

4.2.7 Sperm Whales

Sperm whale clicks contain energy from 1-20 kHz, with the majority of energy between 10-15 kHz (Møhl et al. 2003) (Figure 14). With predominantly lower frequency energy, their echolocation clicks are highly distinguishable from those of other odontocetes. Regular clicks, observed during foraging dives, demonstrate an ICI from 0.25-2 s (Goold & Jones 1995) (Madsen et al. 2002). 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). Effort was not expended to denote whether sperm whale detections were codas, creaks, regular or slow clicks, or to associate clicks with demographic groups (e.g. males vs. females, (Solsona-Berga et al. 2022)).

Previous studies have shown that sperm whales are distributed along the western North Atlantic slope (1000 m contour), with detections from the southeastern U.S. through Cape Hatteras and northward into New England waters (Stanistreet et al. 2018). They are present year-round, though occurrence is lower in the southern regions, with increased prevalence off Cape Hatteras in winter and farther north during spring and summer (Stanistreet et al. 2018). These patterns indicate that Cape Hatteras and slope habitats to the north represent important foraging areas for this species within the U.S. EEZ (Stanistreet et al. 2018).

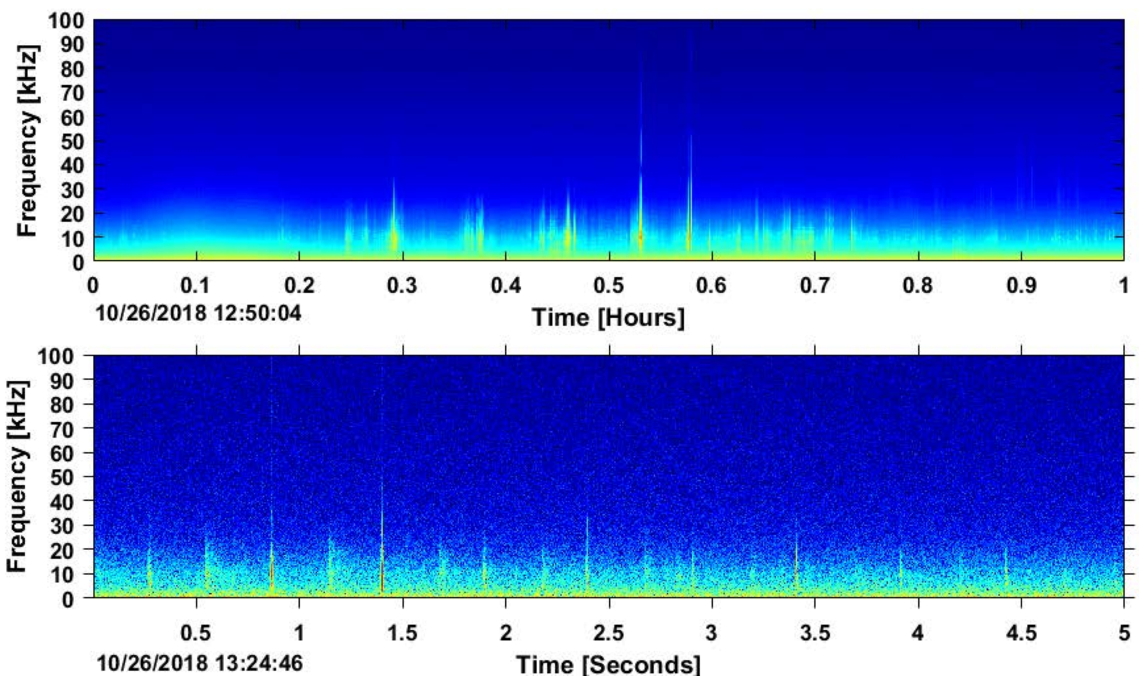

Figure 14: Sperm whale signals in LTSA (top) and spectrogram (bottom).

4.2.8 *Kogia* spp.

Dwarf and pygmy sperm whales emit echolocation signals which have peak energy at frequencies near 130 kHz (Au 1993). Their clicks can readily be distinguished from other species in the Western Atlantic, but not from each other. While the peak frequency of these clicks is above the upper frequency band recorded by the HARP 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 (Figures 15 & 16). Typical modal ICIs for *Kogia* spp. are near 0.1 s.

Previous studies have shown that Kogia spp. are broadly distributed along the western North Atlantic slope (1000 m contour), with acoustic detections from the southeastern U.S. through Cape Hatteras and into the mid-Atlantic (Haver et al. 2025; Cohen et al. 2022). They are present year-round, but detections are generally more common in southern regions, including Cape Hatteras and southward, than in northern slope waters (Cohen et al. 2023). These patterns suggest that Cape Hatteras and adjacent southern slope habitats represent important foraging hotspots for Kogia spp. within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023).

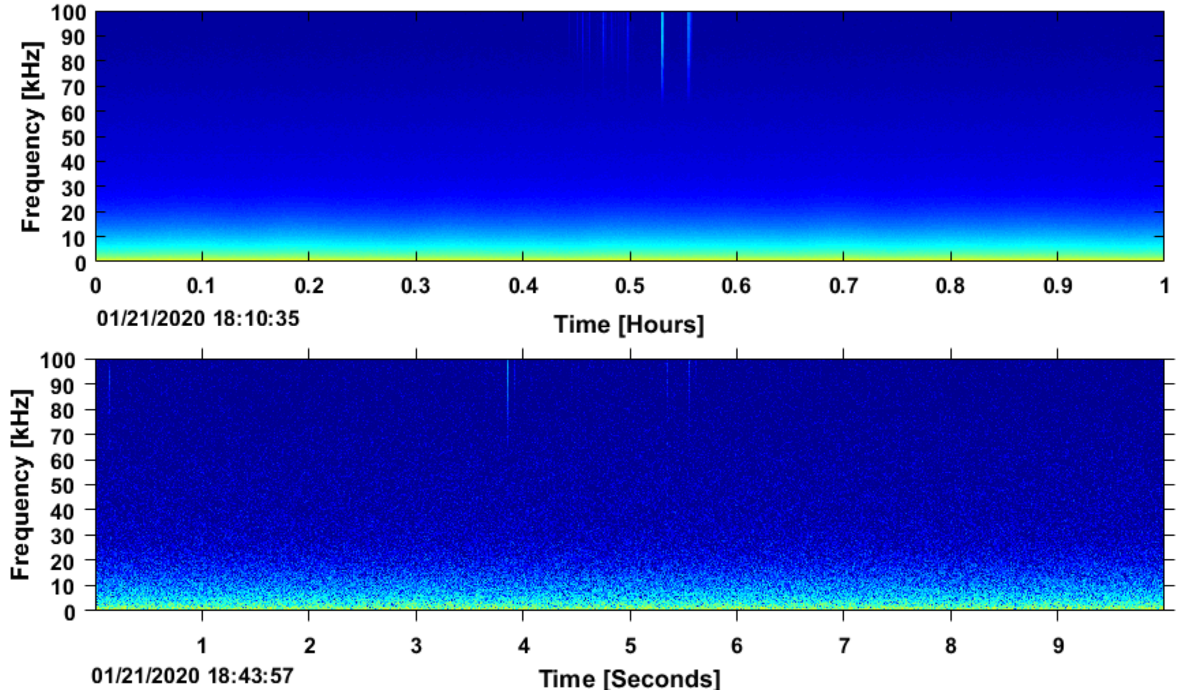

Figure 15: ***Kogia*** **spp. signals in LTSA (top) and spectrogram (bottom).**

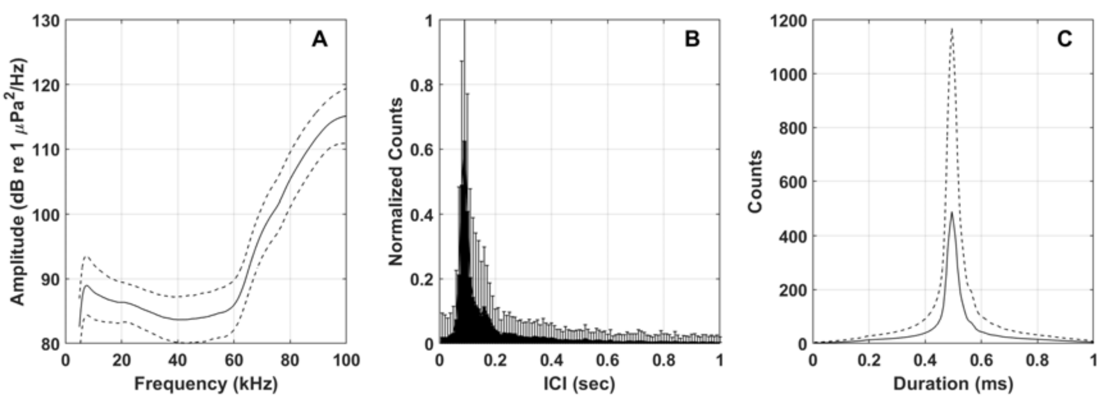

Figure 16: Left: Mean frequency spectrum of ***Kogia*** **spp. echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.1 s; Right: Mean waveform envelope of representative clicks.**

4.2.9 Risso's Dolphins

Risso's dolphin clicks (Figures 17 & 18) have frequency peaks at approximately 22, 26, and 33 kHz. These clicks have a modal ICI of approximately 0.15 seconds. 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 in the Gulf of Mexico are similar to what has been found elsewhere.

Previous studies have shown that Risso's dolphins are commonly distributed along the western North Atlantic slope (1000 m contour) and shelf break, with frequent occurrence from Cape Hatteras north through the mid-Atlantic (Baumgartner & Mussoline 2011; Haver et al. 2025). They are present year-round, though detections tend to be higher in warmer months, particularly summer and fall, when they are most often associated with the slope waters of the mid-Atlantic region (Baumgartner & Mussoline 2011; Cohen et al. 2023). These patterns indicate that Cape Hatteras and mid-Atlantic slope habitats represent important foraging areas for this species within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023).

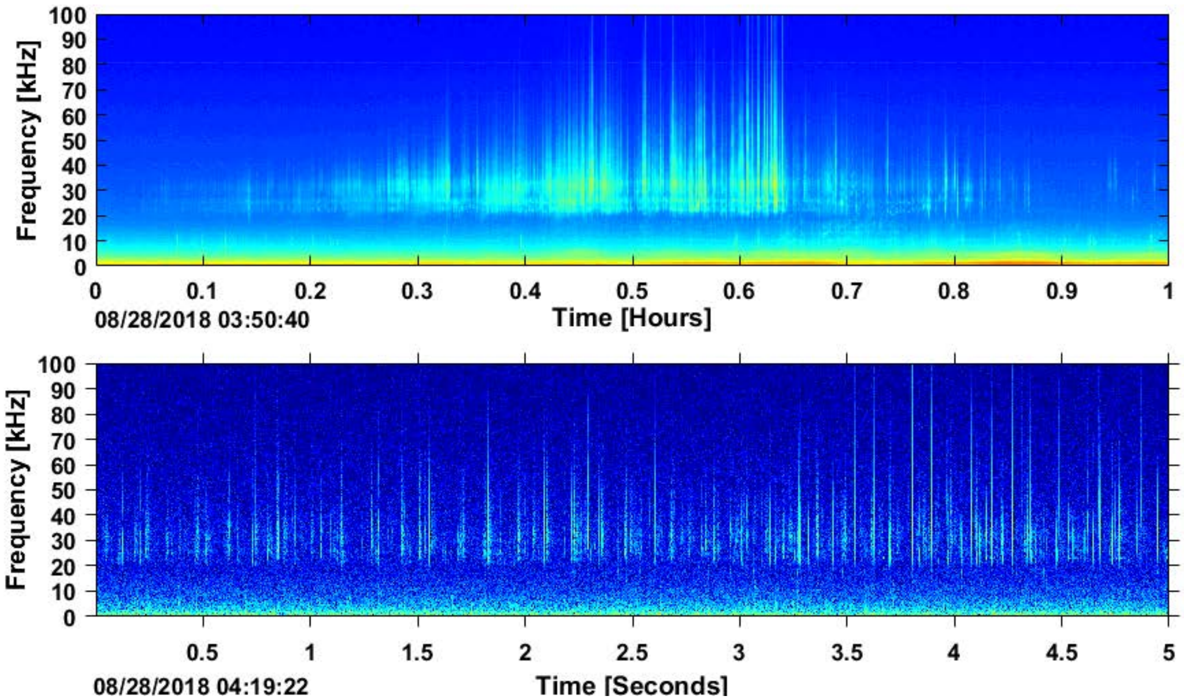

Figure 17: Risso's dolphins signals in LTSA (top) and spectrogram (bottom).

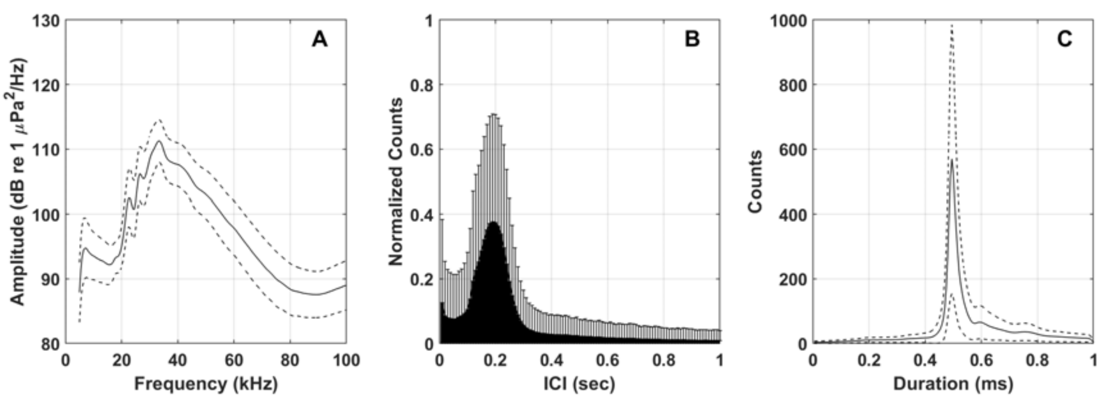

Figure 18: Left: Mean frequency spectrum of Risso's dolphins echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.2 s; Right: Mean waveform envelope of representative clicks.

4.2.10 Unidentified Dolphins – Presumed Smaller-Bodied Delphinids (UD HF)

High-frequency unidentified dolphin clicks (UD HF) were among the dominant click types identified by the unsupervised clustering algorithm. These clicks are acoustically distinctive but have not been conclusively associated with a single species. This grouping likely represents a suite of smaller-bodied delphinids known to occur in the mid-Atlantic, with dominant contributions at Norfolk Canyon most likely from short-beaked common dolphins (*Delphinus delphis*) and offshore bottlenose dolphins (*Tursiops truncatus*), based on regional spatiotemporal patterns reported for this site and nearby monitoring locations (Cohen et al. 2022). Cooler-water species such as Atlantic white-sided (*Lagenorhynchus acutus*) and white-beaked dolphins (*Lagenorhynchus albirostris*) may also contribute seasonally. While delphinids in the genus *Stenella* (e.g., Atlantic spotted, pantropical spotted, spinner, Clymene, and striped dolphins) are acoustically plausible contributors, these species are expected to be less prevalent at this site given their more southerly and tropical distributions.

UD HF clicks are characterized by peak frequencies primarily between 30 and 45 kHz (Figures 19 & 20). The inter-click interval (ICI) distribution exhibits two distinct modes, with a dominant peak near 0.065 s and a secondary peak near 0.1 s. The shorter ICI is consistent with click rates reported for *Stenella* species, while the longer ICI is more typical of offshore bottlenose dolphins. Further refinement of this category is anticipated, with future analyses likely to resolve this grouping into multiple click types and reduce classification confusion among acoustically similar delphinid signals.

Presumed smaller-bodied delphinids represented by the UD HF click type (hereafter referred to as smaller-bodied delphinids), occur year-round throughout the northwestern Atlantic, with higher prevalence along slope and canyon habitats off Cape Hatteras and in the mid-Atlantic (Haver et al. 2025; Cohen et al. 2023). Seasonal variation has been observed, with detections increasing during spring and summer in these regions (Cohen et al. 2023).

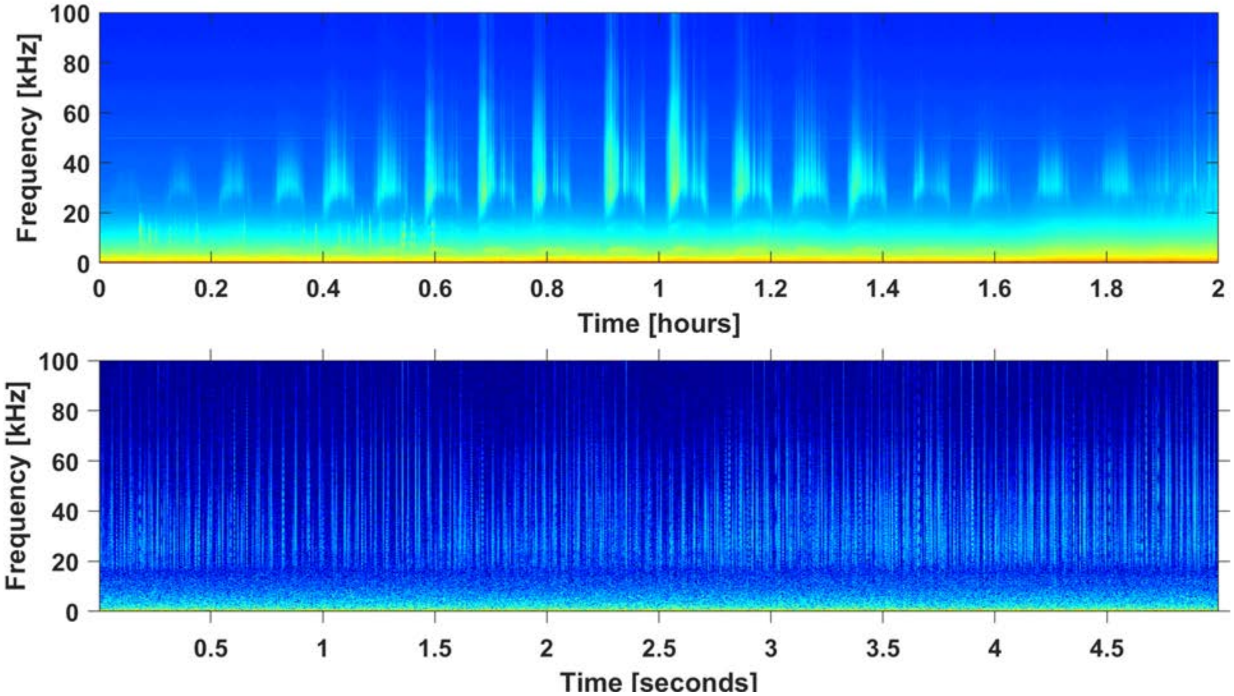

Figure 19: Unidentified dolphin high-frequency (UD HF) echolocation signals in LTSA (top) and spectrogram (bottom).

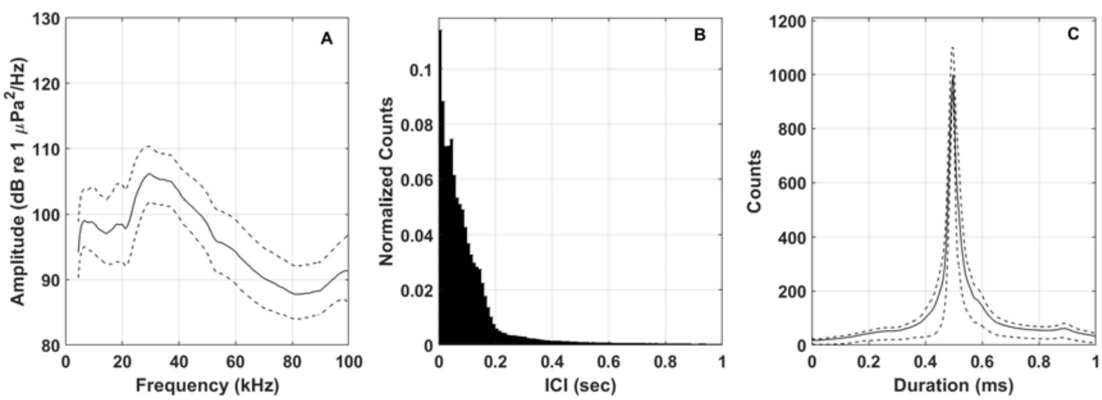

Figure 20: Left: Mean frequency spectrum of unidentified dolphin mid-frequency (UD HF) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.065 s and 0.1 s; Right: Mean waveform envelope of representative clicks.

4.2.11 Unidentified Dolphins – Presumed Smaller-Bodied Delphinids (UD47)

A second, acoustically distinct unidentified dolphin click type characterized by multiple low-frequency spectral peaks and a broader band of higher-frequency energy (UD47) was among the dominant click types identified by the unsupervised clustering algorithm. This click type was classified separately due to its unique and recognizable spectral features and has not been conclusively linked to a specific species. UD47 clicks exhibit small spectral peaks near 13 and 19 kHz, with a broader region of elevated energy between approximately 30 and 50 kHz (Figures 21 & 22). The inter-click interval distribution for this click type shows a modal peak near 0.1 s, consistent with click rates reported for smaller-bodied delphinids and similar to those observed for the UD HF click type.

Species represented by the UD47 click type are widely distributed along the western North Atlantic shelf break and slope, particularly near the 1000 m isobath (Cohen et al. 2022; Haver et al. 2025). Detections occur year-round across the U.S. Exclusive Economic Zone, with relatively higher prevalence off Cape Hatteras and into the mid-Atlantic slope waters (Haver et al. 2025; Cohen et al. 2023). Seasonal increases have been reported during summer and fall, consistent with broader patterns of delphinid occurrence in the region (Cohen et al. 2023). These observations suggest that mid-Atlantic slope habitats represent important foraging areas for smaller-bodied delphinids producing UD47 clicks (Haver et al. 2025; Cohen et al. 2023).

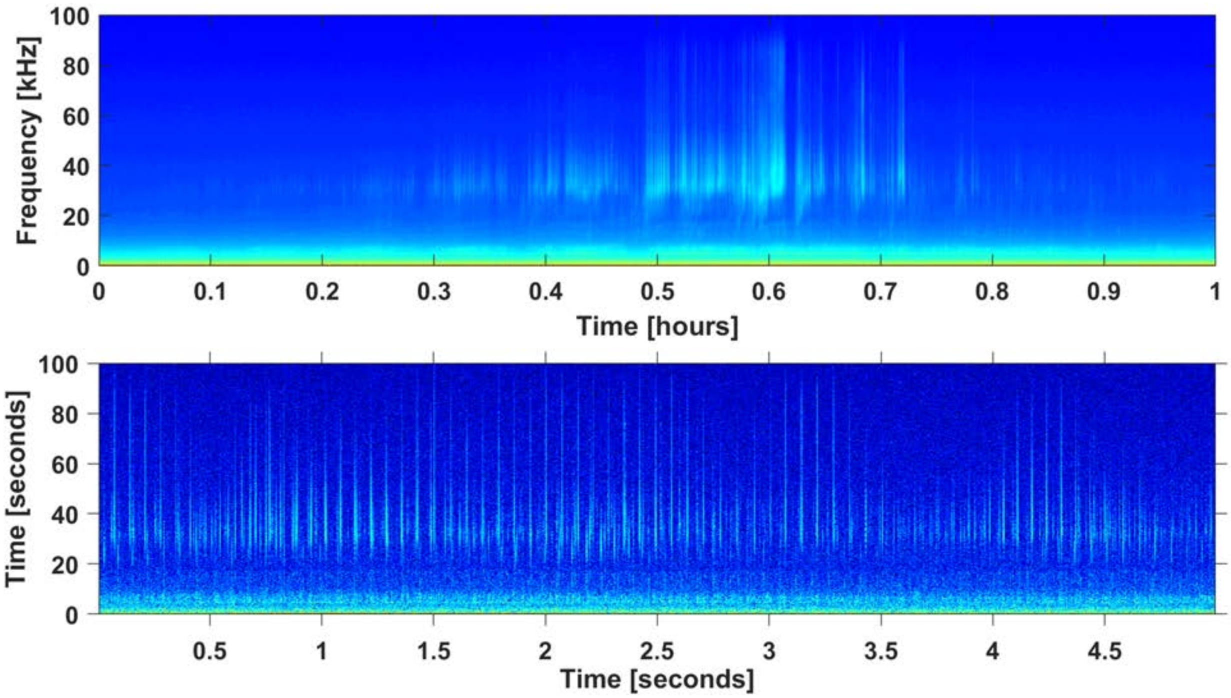

Figure 21: Unidentified dolphin 47 (UD47) echolocation signals in LTSA (top) and spectrogram (bottom).

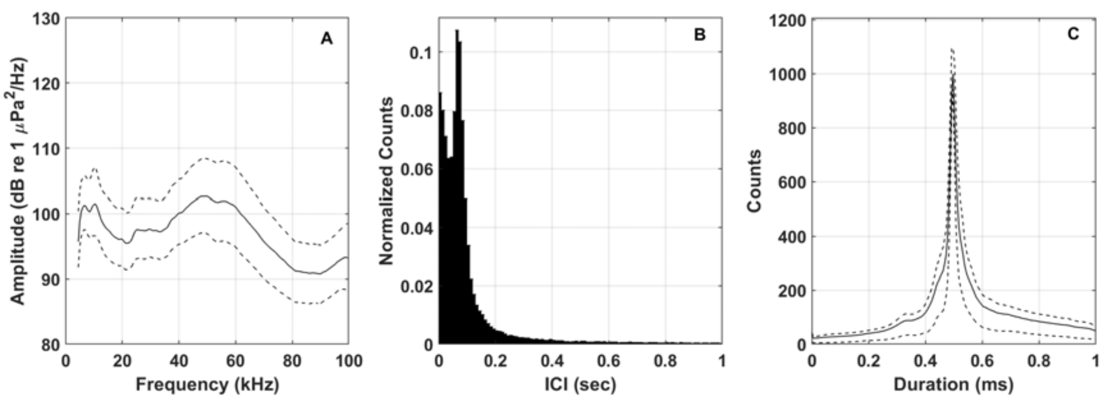

Figure 22: Left: Mean frequency spectrum of unidentified dolphin 47 (UD47) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.1 s; Right: Mean waveform envelope of representative clicks.

4.2.12 Unidentified Dolphins – Presumed Larger-Bodied Delphinids (UD LF)

A low-frequency unidentified dolphin click category (UD LF) was another dominant click type identified by the unsupervised clustering algorithm. This category likely represents several larger-bodied delphinid species, listed in order of expected abundance, including short-finned pilot whales (*Globicephala macrorhynchus*; Cohen et al. 2022), long-finned pilot whales (*Globicephala melas*), melon-headed whales (*Peponocephala electra*), false killer whales (*Pseudorca crassidens*), and killer whales (*Orcinus orca*; Leu et al. 2022). UD LF clicks are characterized by peak frequencies below 30 kHz and a variable modal inter-click interval near 0.2 s (Figures 23 & 24). This is a diverse category, and ongoing analyses are expected to further resolve this grouping into multiple subtypes that may be attributable to individual species.

Presumed larger-bodied delphinids producing UD LF clicks (hereafter referred to as larger-bodied delphinids) are consistently detected along the western North Atlantic slope, particularly near the 1000 m isobath (Cohen et al. 2022). These signals occur year-round within the U.S. Exclusive Economic Zone, with concentrations along the slope near Cape Hatteras and extending into the mid-Atlantic region (Haver et al. 2025; Cohen et al. 2023). Seasonal variation has been reported, with detections generally increasing during winter near Cape Hatteras and during fall in more northern regions (Cohen et al. 2023). These patterns indicate that the mid-Atlantic slope represent important foraging areas for larger-bodied delphinids producing UD LF clicks (Cohen et al. 2023).

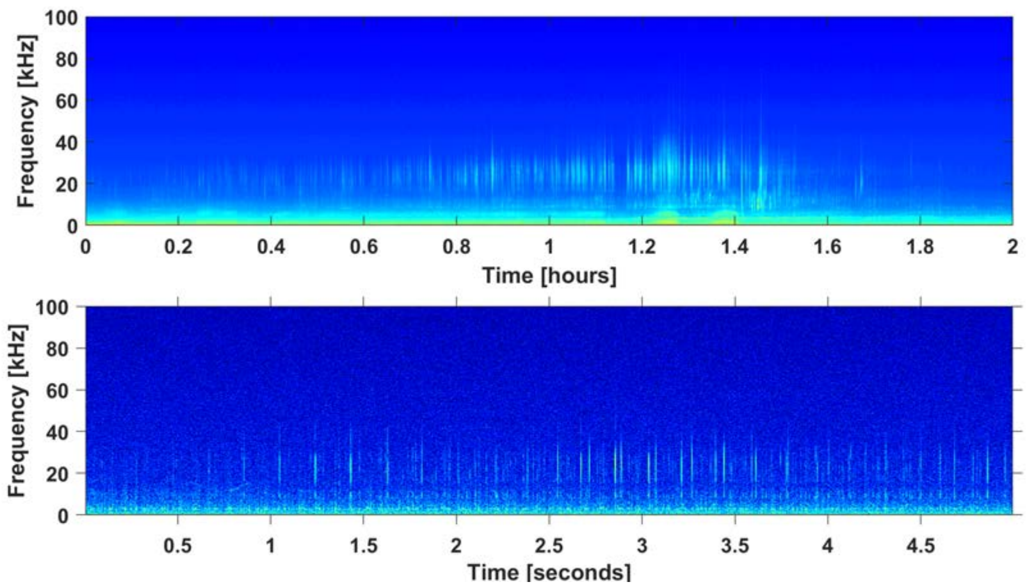

Figure 23: Unidentified dolphin low-frequency (UD LF) echolocation signals in LTSA (top) and spectrogram (bottom).

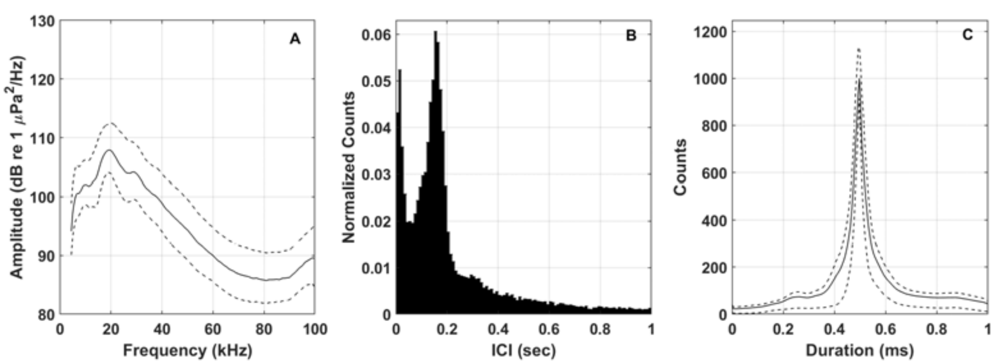

Figure 24: Left: Mean frequency spectrum unidentified dolphin low-frequency (UD LF) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.2 s; Right: Mean waveform envelope of representative clicks.

4.3 Mysticete Whale Analyses and Species Call Description

All mysticete species in this analysis, with the exception of minke whales, were detected using the Low Frequency Detection and Classification System (LFDCS; Baumgartner & Mussoline 2011). Minke whales were analyzed separately using a combination of manual logging and a custom detector, described below.

LFDCS creates conditioned spectrograms using a short-time Fourier transform with a data frame of 512 samples and 75% overlap, resulting in a time step of 64 ms and frequency resolution of 3.9 Hz. After tracing contour lines, or "pitch tracks," through tonal sounds, the program uses multivariate discriminant function analysis to classify the pitch tracks into species-specific call types based on a call library. Each detection is assigned a Mahalanobis distance (MD), which measures the deviation of a sound's pitch track from the assigned call type (Baumgartner & Mussoline 2011). A lower MD indicates a closer match to the assigned call type. For a well-developed call type in the LFDCS (i.e., the seven attributes used in the discriminant function analysis are multivariate normal), 75% of pitch tracks for the call type will have an MD of 3.0 or less (Baumgartner et al. 2013). Setting an MD threshold is necessary to minimize false detection rates, but in doing so, some true detections may be missed. The MD threshold of 3.0 was chosen for all call types detected and classified in the North Atlantic right whale, humpback, sei, and fin whale call library. However, for blue whales, false detection rates were lower than for any of the other species, and thus an MD threshold of 5.0 was originally chosen to reduce the probability of missing true detections; this threshold has since been increased to 6.0 for the current analysis.

All vocalizations were classified based on a user-developed call library (expanded from Davis et al. 2017; Table S1). The library used for the 2 kHz sampled data included three of the target species, North Atlantic right, humpback, and sei whales. Due to the low-frequency characteristics of fin and blue whale vocalizations, an additional call library was created for these two species that matched the decimated 120 Hz sampled data.

All LFDCS detections were manually reviewed by trained acoustic analysts to determine daily presence of each of the five mysticetes species. A true detection was defined as a pitch track that correctly classified a call or song unit to the species that produced it (Bonnell et al. 2016). Given the variability of each species' vocalizations, the specific methodology to determine daily acoustic presence varied by species, as described below.

Although mysticetes are known to produce a broad repertoire of calls, only specific, consistently detectable call types were targeted for analysis and are described below.

4.3.1 Blue Whales

Daily presence for blue whales was confirmed if three song phrases were visible, including at least one true detection. Given the low false detection rate for this species, the MD threshold was increased from 5.0 to 6.0 in the current analysis to reduce the likelihood of missing true detections (Davis et al. 2020).

Blue whales in the western North Atlantic produce a well-characterized paired call known as the A-B call (Figure 25). The A call is a tonal signal at 18-19 Hz lasting approximately 8 seconds. It is often followed by a B call, which is a downsweep from 18 to 15 Hz and lasts around 11 seconds. This A-B sequence is typical of North Atlantic blue whale vocal behavior and is used in studies to monitor seasonal occurrence and distribution (Mellinger & Clark 2003).

Blue whales are infrequently observed within the U.S. EEZ compared to Canadian waters, but acoustic monitoring confirms their presence in offshore regions. They have been detected in the New York Bight (Muirhead et al. 2018), Mid-Atlantic Ridge (Nieukirk et al. 2004), and around the New England Seamounts (Lesage et al. 2017), as well as farther south near Cape Hatteras and Blake's Plateau (Davis et al. 2020). These detections are generally low in number, suggesting that U.S. waters function more as a migratory corridor and occasional foraging area rather than a primary feeding ground. Seasonal occurrence indicates that blue whales are mostly absent in summer, when they concentrate in northern feeding habitats, but they are detected in winter and during transitional periods, reflecting movement through the mid-Atlantic and southeastern shelf regions (Davis et al. 2020).

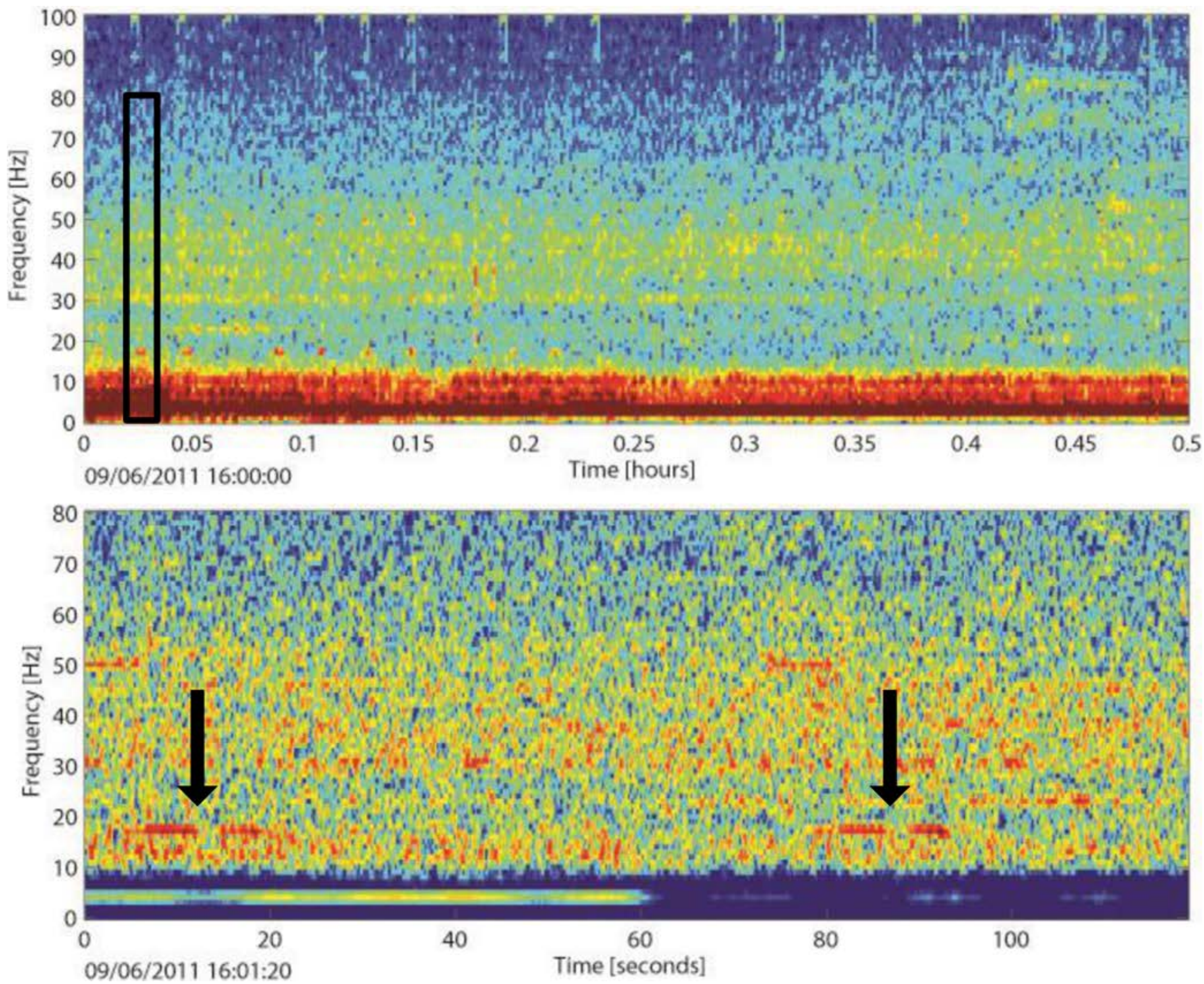

Figure 25: North Atlantic blue whale calls in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by black arrows.

4.3.2 Fin Whales

To confirm true fin whale presence across the full dataset, all hours with at least 29 detections were first identified based on a previous manual logistic regression analysis. Those hours were then manually reviewed, and fin whales were considered present for that day if a true detection was found within a regular interpulse interval pattern of at least three other 20 Hz pulses (Davis et al. 2020).

Fin whales produce a short, low-frequency call known as the 20 Hz pulse, which is a frequency-modulated downsweep from approximately 30 to 15 Hz and lasts around 1 second (Figure 26). These pulses are often produced at regular intervals in the form of song, particularly by males during the breeding season (Thompson et al. 1992), or irregularly as counter-calls among traveling animals (McDonald et al. 1995). The 20 Hz call is one of the most commonly detected fin whale vocalizations worldwide and is highly suitable for passive acoustic monitoring (Watkins 1981).

Fin whales are among the most frequently detected mysticetes in the U.S. EEZ of the western North Atlantic. They occur year-round from the Gulf of Maine to Cape Hatteras, with consistent acoustic detections in Massachusetts Bay, the New York Bight, and farther south near Cape Hatteras and Blake's Plateau (Morano et al. 2012; Muirhead et al. 2018; Davis et al. 2020). Offshore detections extend their seasonal range to Bermuda and the Mid-Atlantic Ridge from fall through spring (Clark & Gagnon 2004; Nieukirk et al. 2004). The Gulf of Maine and southern New England serve as important feeding areas, while mid-Atlantic and southeastern U.S. waters provide overwintering habitat and a migratory corridor linking northern feeding grounds with more southerly habitats (Davis et al. 2020; Clapham & Mead 1999; Kennedy et al. 2014). Although neonatal strandings suggest possible calving in mid-Atlantic latitudes (Hain et al. 1992), calving grounds have not been confirmed.

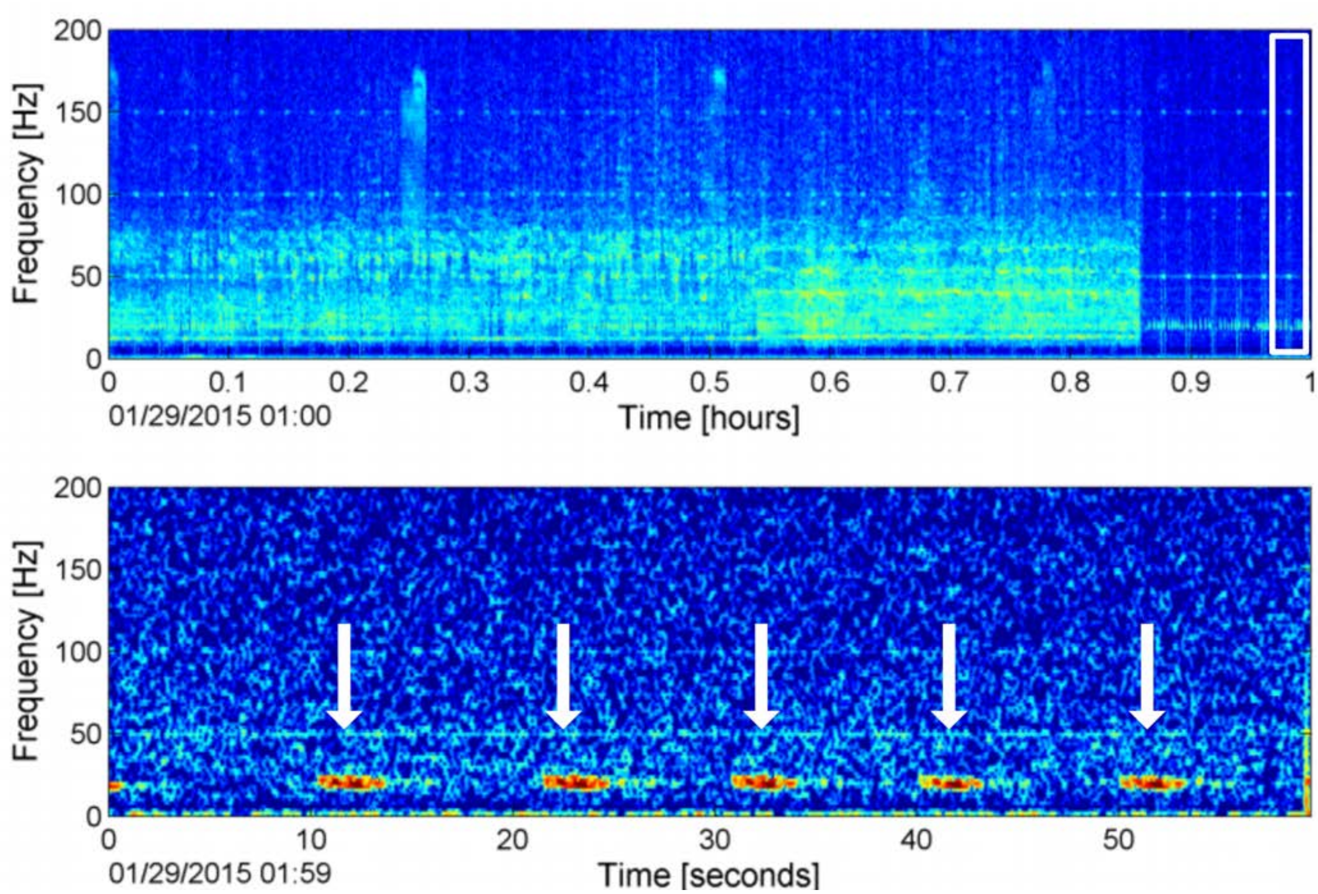

Figure 26: Fin whale 20 Hz calls in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

4.3.3 Sei Whales

Sei whales were considered present if at least one true detection of a downsweep (within a doublet or triplet) was verified for that day (Davis et al. 2020).

Sei whale vocalizations used in this study consist of low-frequency downsweeps that begin near 100 Hz and sweep downward to about 40 Hz (Figure 27). These calls, typically lasting 1 to 2 seconds, have been consistently attributed to sei whales in the western North Atlantic and are widely used in passive acoustic detection (Baumgartner & Fratantoni 2008; Baumgartner et al. 2008).

Sei whales are less frequently observed in the U.S. EEZ of the western North Atlantic, but acoustic and visual records confirm their presence along the shelf break from Georges Bank to Cape Hatteras (Davis et al. 2020; Baumgartner & Mussoline 2011). Most detections occur during spring and fall, suggesting that U.S. waters function primarily as a migratory corridor between high-latitude summer foraging grounds in the Gulf of Maine and Canadian waters, and possible wintering areas farther south (Payne et al. 1990; Davis et al. 2020). Occasional records off Cape Hatteras and the Blake Plateau indicate that these regions may serve as transitional habitats during seasonal movements (Davis et al. 2020).

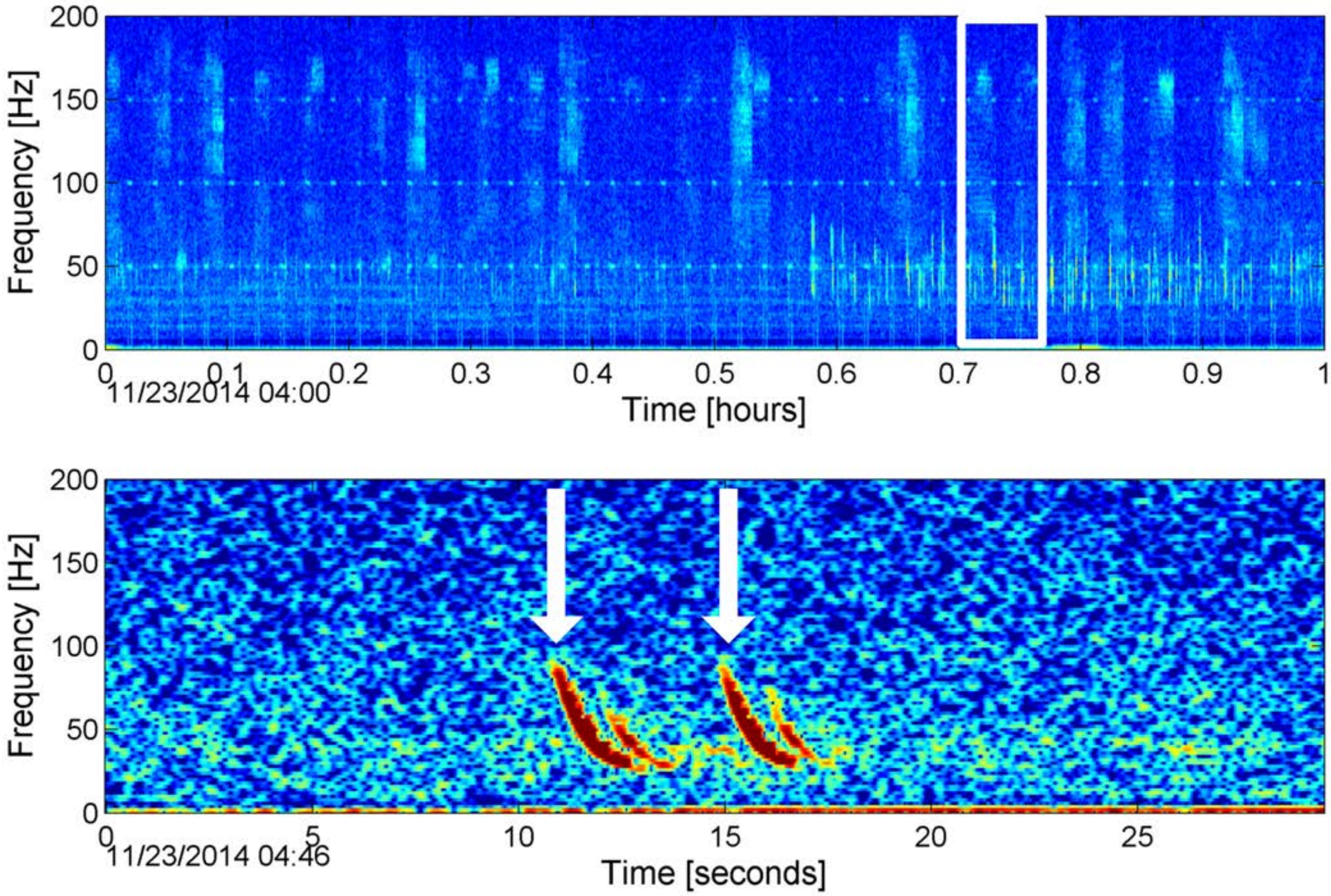

Figure 27: Sei whale downseep call in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

4.3.4 Humpback Whales

A day was marked as present for humpback whales if one true detection was found within at least three humpback whale vocalizations occurring over a 10-min window (Davis et al. 2020).

Humpback whales produce both complex songs and various non-song vocalizations (Figures 28 & 29). The vocalizations used for detection in this study fall within the 100-3,000 Hz range and may consist of either song units—repeating structures organized into phrases and themes (Payne & McVay 1971)—or social and feeding calls. These non-song vocalizations typically last between 0.15 and 2.5 seconds and exhibit variable frequency and amplitude modulation (Dunlop et al. 2007; Stimpert et al. 2011).

Humpback whales are regularly observed throughout the U.S. EEZ of the western North Atlantic, with strong seasonal patterns. They occur from the Gulf of Maine south through the Mid-Atlantic Bight and to Cape Hatteras, with detections extending onto Blake's Plateau (Davis et al. 2020; Kennedy et al. 2014). The Gulf of Maine and waters off southern New England are important feeding grounds, supporting large seasonal aggregations in spring and summer (Clapham & Mead 1999; Kenney & Winn 2001). In contrast, detections in the Mid-Atlantic and near Cape Hatteras are most frequent during migration periods in the spring and winter, indicating these regions function as a migratory corridor and transitional habitat (Davis et al. 2020; Kennedy et al. 2014). Some individuals remain in the Mid-Atlantic and southeastern U.S. waters year-round, but most migrate to the Caribbean for breeding and calving (Davis et al. 2020; Smith et al. 1999; Aschettino et al. 2020).

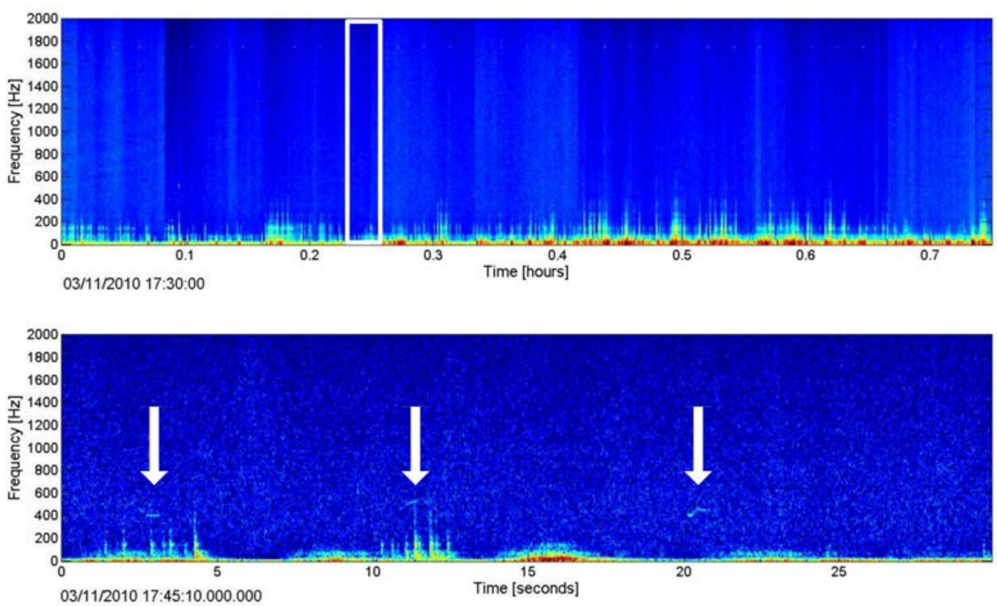

Figure 28: Humpback whale call in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the black arrows.

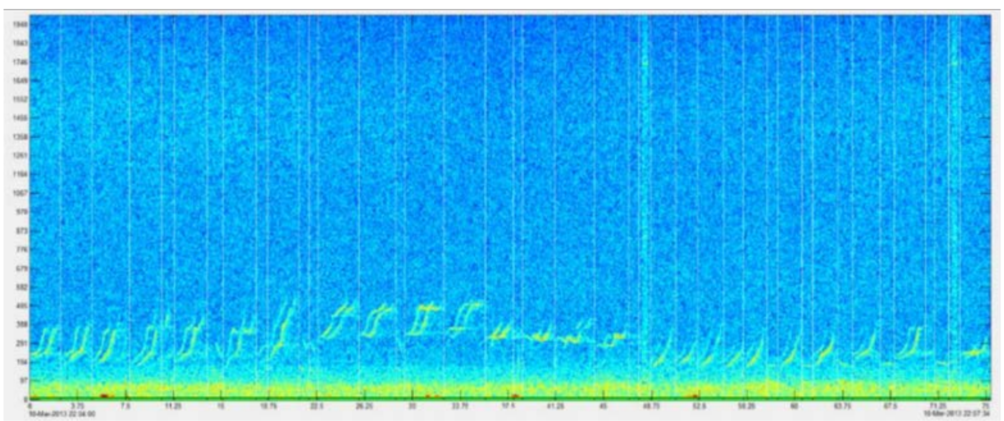

Figure 29: Concatenated humpback whale songs viewed in the software GPL review (Helble et al. 2012).

4.3.5 North Atlantic Right Whales

Three or more true upcall detections in one day were required for North Atlantic Right Whales to be marked as detected on that day (Davis et al. 2017).

The primary vocalization used to detect North Atlantic right whales is the upcall, a frequency-modulated tonal signal that typically sweeps upward from 80 Hz to 200 Hz over approximately 1 second (Figure 30). Harmonics may be present depending on individual variation and recording conditions. Upcalls are believed to function as contact calls and are consistently used in acoustic monitoring efforts due to their distinctiveness and frequent occurrence (Parks & Tyack 2005).

North Atlantic right whales are among the most critically endangered mysticete and have historically used U.S. waters extensively. Within the U.S. EEZ, they are most frequently observed from the Gulf of Maine to Cape Hatteras, with core foraging habitats in Cape Cod Bay, the Great South Channel, and the Gulf of Maine (Kenney & Winn 2001; Clapham & Mead 1999; Davis et al. 2020). Seasonal occurrence reflects a latitudinal migration: aggregations are common in the northeast U.S. during spring and summer, while movements southward in fall and winter bring individuals to the Mid-Atlantic, southeastern shelf waters, and the calving grounds off Florida and Georgia (Waring et al. 2010; Davis et al. 2020). Detections off Cape Hatteras and the Blake Plateau highlight their use of the mid-Atlantic as both a migratory corridor and transitional habitat (Davis et al. 2020). Despite this, right whales now appear less frequently in historical foraging habitats and increasingly occur farther north into Canadian waters, underscoring ongoing distributional shifts (Davis et al. 2020; Record et al. 2019).

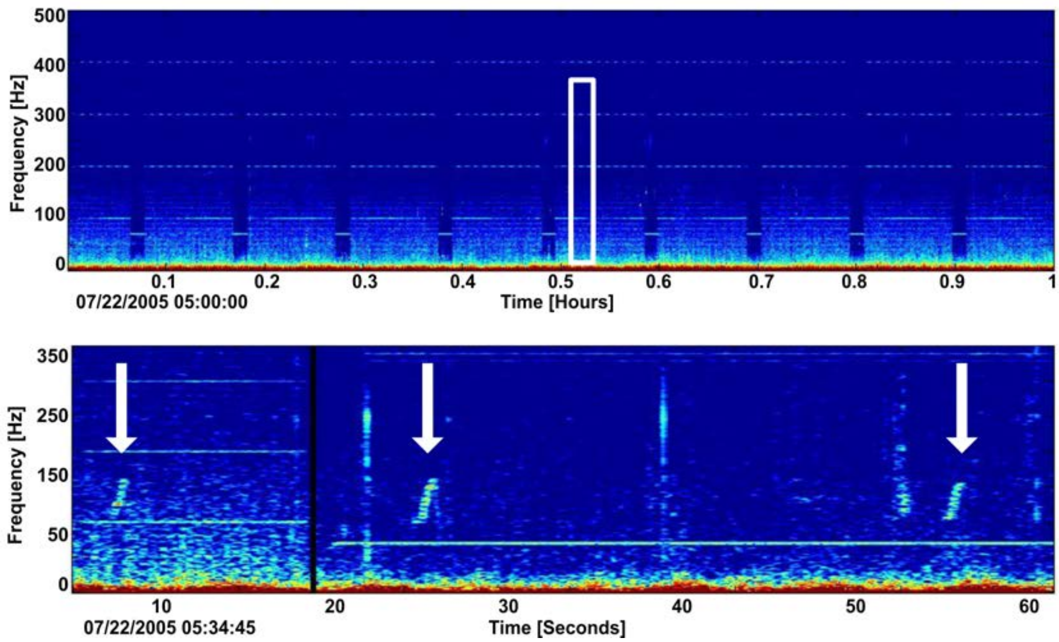

Figure 30: North Atlantic right whale upcall in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

4.3.6 Minke Whales

For NFC deployments 01-03, analysis of minke whale vocalizations was performed by manually scanning long-term spectral averages (LTSAs) and spectrograms. The recordings were decimated by a factor of 100 from the original 200 kHz sampling rate to obtain an effective bandwidth of 1 kHz. LTSAs were generated using the Triton software package with a 5-second time average and 1 Hz frequency bins. During visual analysis, the LTSA display range was typically set to 1-300 Hz over a 1-hour window, and the spectrogram view was set to 1-250 Hz with a 60-second duration. FFT lengths ranged from 1500 to 2000 data points, yielding approximately 1 Hz frequency resolution, with 85-95% overlap applied to enhance call visibility. When pulse trains were identified, presence was logged in hourly bins; however, analysts did not differentiate between the three known pulse train subtypes (speed-up, slow-down, constant-rate) during annotation.

For NFC deployments 04-06, recordings were processed with a custom-built detector in Python to identify common North Atlantic minke whale pulse trains (Mouy et al. 2025). This detector uses a binary ResNet18 deep neural network (DNN) to detect and automatically classify minke whale pulse trains based on spectrogram images. The network was trained using manually annotated sounds from minke whale and non-minke whale sounds collected across multiple regions. All detections with a model confidence threshold exceeding or equal to 0.6 were manually reviewed on a daily basis. If one true detection was verified, that day was marked as ’detected’ for minke whales. A formal performance evaluation for this detector is ongoing. Preliminary exploratory comparisons between manually logged and detector-derived detections suggest that the two approaches are not directly comparable, with the automated detector likely under-representing minke whale presence relative to manual review. Accordingly, the results presented here are interpreted conservatively.

North Atlantic minke whales produce long-duration pulse trains consisting of repeated broadband pulses (Figure 31). These have been categorized into several types: “speed-up” and “slow-down” trains, in which the pulse rate increases or decreases over time, respectively, and constant-rate pulse trains where the pulse interval remains stable. These call types were first described by (Mellinger & Clark 2000) near Puerto Rico and later expanded by (Risch et al. 2013) for use in the North Atlantic.

Minke whales are the smallest and among the most frequently sighted mysticete in the U.S. EEZ of the western North Atlantic. They occur year-round from the Gulf of Maine south to Cape Hatteras, with peak sightings and acoustic detections in spring and summer when they forage in nearshore and shelf waters (Mitchell 1991; Kenney & Winn 2001; Stanistreet et al. 2018; Davis et al. 2020). The Gulf of Maine and Georges Bank are primary feeding habitats, but animals are also reported farther south along the Mid-Atlantic shelf and near Cape Hatteras, where detections indicate the southern limit of their regular range (Kenney & Winn 2001; Davis et al. 2020). Seasonal distribution suggests a migratory pattern, with individuals moving northward in summer to feed and southward in winter, though some remain in the mid-Atlantic year-round (Mitchell 1991; Kenney & Winn 2001). Occasional records off Blake's Plateau and farther offshore suggest use of transitional habitats during migration (Davis et al. 2020).

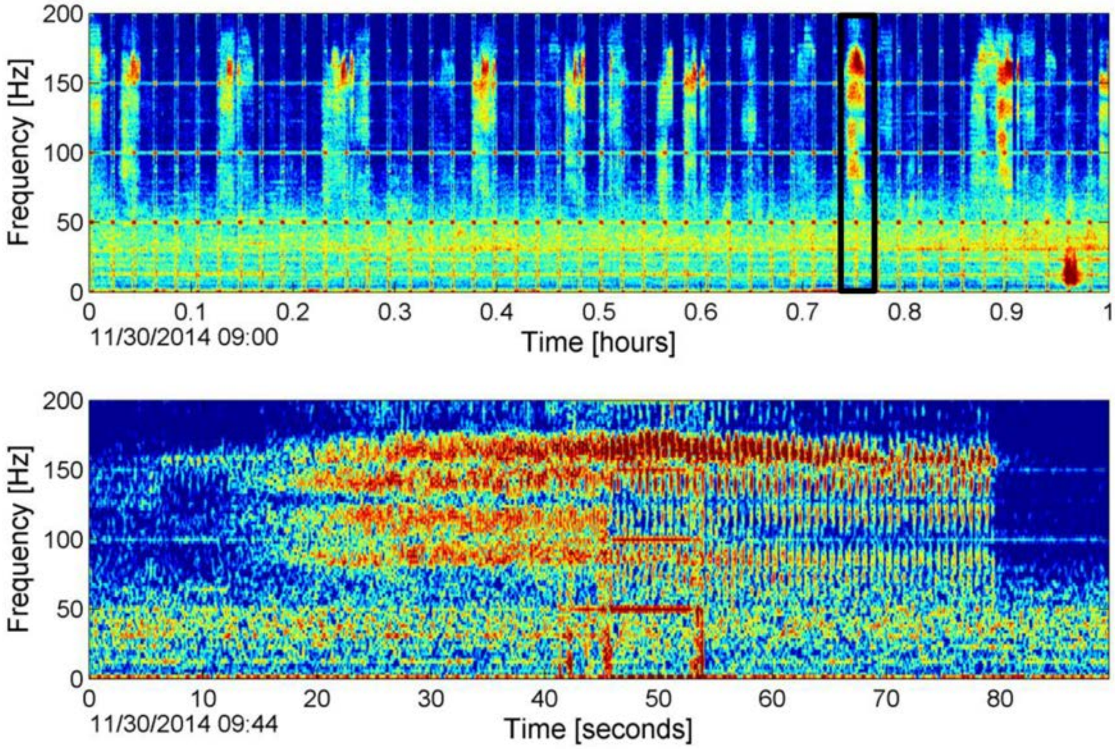

Figure 31: Minke whale pulse train in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom).

4.4 Ambient Noise Analysis

Analyses of ambient noise levels provide information on the natural and anthropogenic contributions of noise sources and how they vary over time and space. Hourly long-term spectrograms were produced at each site to document ambient noise levels over time.

Long-term spectrograms and ambient noise curves were estimated from the following methods from Wiggins et al. 2016 for low frequency, factor of 100 decimated data from 10 Hz to 1 kHz in 1 Hz bins.

In each case, consecutive, 5-second (s) waveforms were transformed into sequential sound pressure spectral density estimates with 1 Hz bin resolution using the Welch method ((Welch 1967)). During recording, HARPs write sequential 75 s acoustic records to standard laptop-style computer hard disk drives such that there were 15 5-s spectra for each 75 s acoustic record. However, system self-noise can be present when the HARP is writing to disk (12 s out of each 75 s record), so the first three 5-s spectra were not used for the following soundscape analyses. Statistical distributions of the noise spectra were computed per hour and per day after discarding partial days and days with deployment/recovery ships sounds or with known instrument self-noise problems. These distributions were calculated with custom MATLAB-based software to provide hourly and daily average of sound pressure spectrum levels over the monitoring period in addition to long-term spectrograms.

The data were also categorized by season, with winter represented by January, February March; spring as April, May, June; summer as July, August, September; and fall as October, November, and December.

5 Results

Multiple odontocete and mysticete species were acoustically present at Norfolk Canyon between 2014 and 2021 (Figure 32). The following results describe temporal patterns at the Norfolk Canyon recording site; we do not infer spatial gradients across the western North Atlantic, and references to other studies are provided only for context.

Odontocetes were generally characterized by year–round occurrence, with species- and group-specific seasonal structure. Sperm whales and larger-bodied delphinids producing low-frequency clicks (UD LF) were among the most frequently detected taxa across the monitoring period, with sustained presence and strong summer–fall peaks. Unidentified smaller-bodied delphinids (UD HF & 47) were similarly common during all years with effort, showing consistently high weekly activity and a pronounced winter–early spring maximum. Other delphinids showed more variable presence across years: *Kogia* spp. and Risso's dolphins exhibited elevated activity from late spring through summer, while the five beaked whale species (goose-beaked, Gervais', True's, Blainville's, and Sowerby's) occurred at lower to moderate levels with seasonal peaks generally aligned with winter–spring.

Mysticete occurrence followed a seasonal pattern, with most baleen whale species acoustically present from late fall through spring and largely absent during summer months. Fin whales showed the strongest and most persistent presence, with an extended peak from late summer through early spring. Sei, blue, and humpback whales also exhibited clear seasonal windows, with humpback and sei whales concentrated in late winter–spring and blue whales showing both winter–spring and late summer–fall activity. In contrast, minke whales and North Atlantic right whales were detected only intermittently, consistent with occasional transit through the Norfolk Canyon region rather than sustained seasonal occupancy.

Ambient noise conditions at Norfolk Canyon also varied over time and frequency band. Low-frequency sound levels were elevated during periods of seismic airgun activity and were persistently influenced by distant shipping, while higher-frequency bands showed episodic increases associated with storms and local weather events.

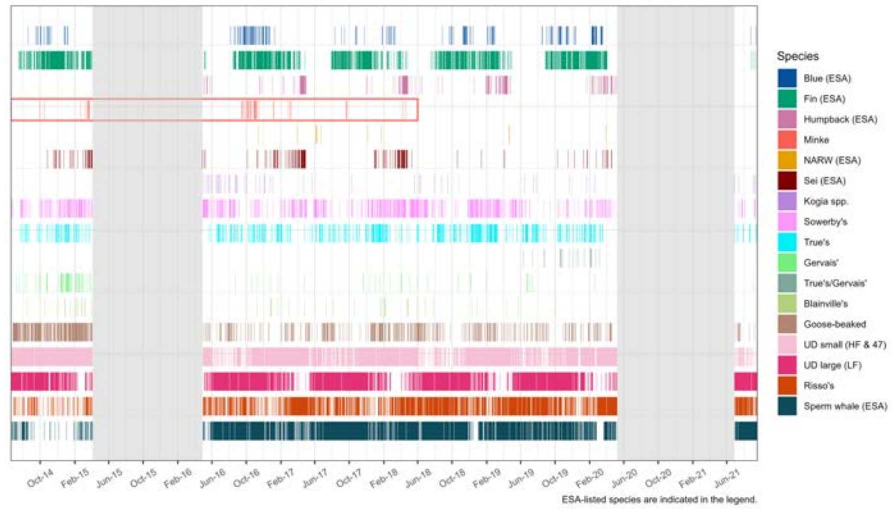

Figure 32: Daily presence of odontocetes and mysticetes at NFC from 2014 to 2021. Colored bars indicate days with confirmed acoustic presence for each species or species group. For UD small (UD HF & 47), UD large (LF), and sperm whales, a 25% daily-occurrence threshold was used to reduce visual saturation from high detection rates. The red box around the minke time series denotes the period when presence was manually logged, with the remaining periods derived from the automated detector; manual and automated detections for minke whales are not directly comparable. Shaded gray areas denote periods of missing data due to instrument recovery or malfunction. Species listed under the U.S. Endangered Species Act (ESA) are identified in the legend.

5.1 Odontocetes

Multiple species/groups of odontocetes were acoustically present at the Norfolk Canyon recording site between 2014 and 2021, with patterns of occurrence varying by species and season (Figure 32). Sperm whales and larger bodied delphinids producing clicks with lower peak frequencies (UD LF) were the most frequently occurring species across the monitoring period. Other beaked whales (Gervais', True's, Blainville's, and Sowerby's) and smaller bodied delphinids producing clicks with higher peak frequencies (UD HF/47) occurred less regularly, and *Kogia* spp. were present at low levels. Risso's dolphins showed moderate presence across years. The BWG signal was included in the neural network classifier, but no encounters were identified during the analysis period.

Seasonal patterns differed among species. Goose-beaked whales and Gervais'/True's showed a primary winter maximum with a second, smaller increase in mid-summer. Sowerby's and Blainville's beaked whales and presumed smaller-bodied dolphins producing clicks with higher peak frequencies (UD HF & 47) peaked in the winter through spring. Late spring through summer increases were typical of *Kogia* spp. and Risso's dolphins (with Risso's showing a March–April rise followed by another in July–August). Finally, a strong summer–early fall presence occurred for UD LF and sperm whales.

For most odontocete species/groups, diel patterns were weak or inconsistent, though True's beaked whales, *Kogia* spp., and UD HF & 47 showed diel foraging patterns with more activity in the evening and early morning hours.

Across the record, some groups exhibited changes in overall presence. UD HF & 47 showed a steep decline after 2015, followed by a second decline after 2019, and Sowerby's beaked whales were lower in 2020–2021.

5.1.1 Goose-Beaked Whale

Goose-beaked whales were acoustically present at Norfolk Canyon from 2014 to 2021, although occurrence was intermittent across the full monitoring period (Figure 33). Weekly acoustic presence typically remained below 6 hours. A seasonal increase in presence was observed in the winter and mid- summer, with reduced presence in the spring and fall months (Figure 34). No consistent diel pattern was evident in goose-beaked whale acoustic presence, suggesting relatively uniform activity throughout the day (Figure 35).

These results are consistent with previous studies that found goose-beaked whales occur at low levels near Norfolk Canyon, with a peak in summer (Haver et al. 2025; Cohen et al. 2022; Stanistreet et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025).

Summary of Results – Goose-beaked whale

- Goose-beaked whales were acoustically present across the recording period, though occurrence was intermittent across years.
- Seasonal increases in acoustic presence were observed in the winter and mid-summer, with lower presence in spring and fall.
- No clear diel pattern was observed.

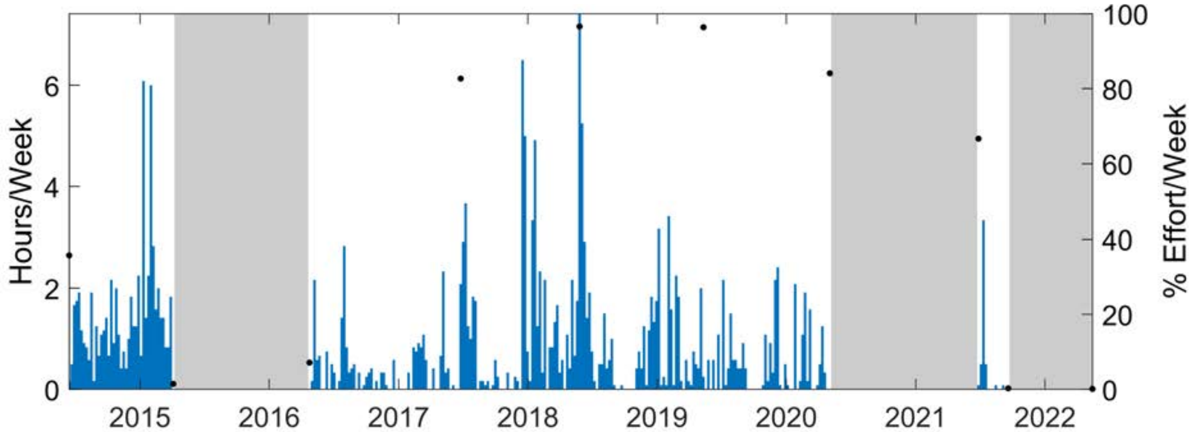

Figure 33: Cumulative hours/week of goose-beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

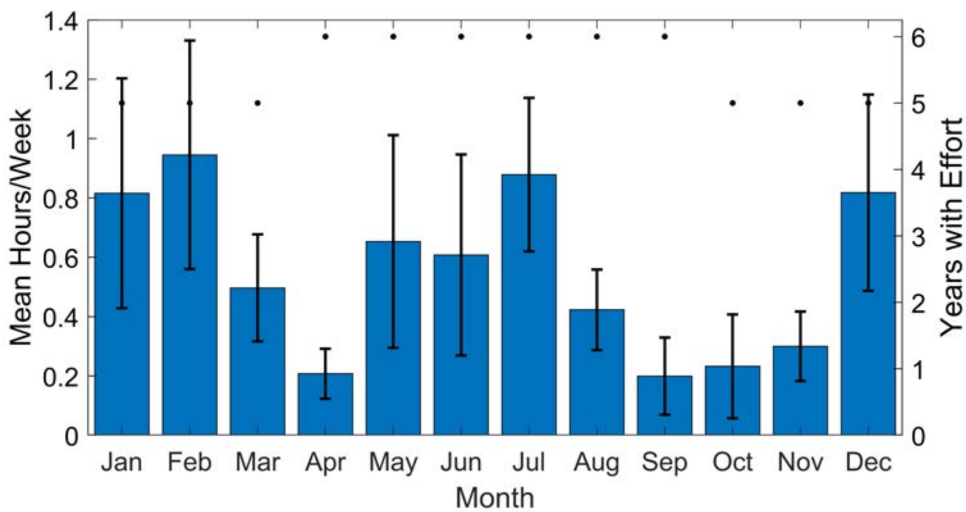

Figure 34: Monthly mean hours per week of goose-beaked whale acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

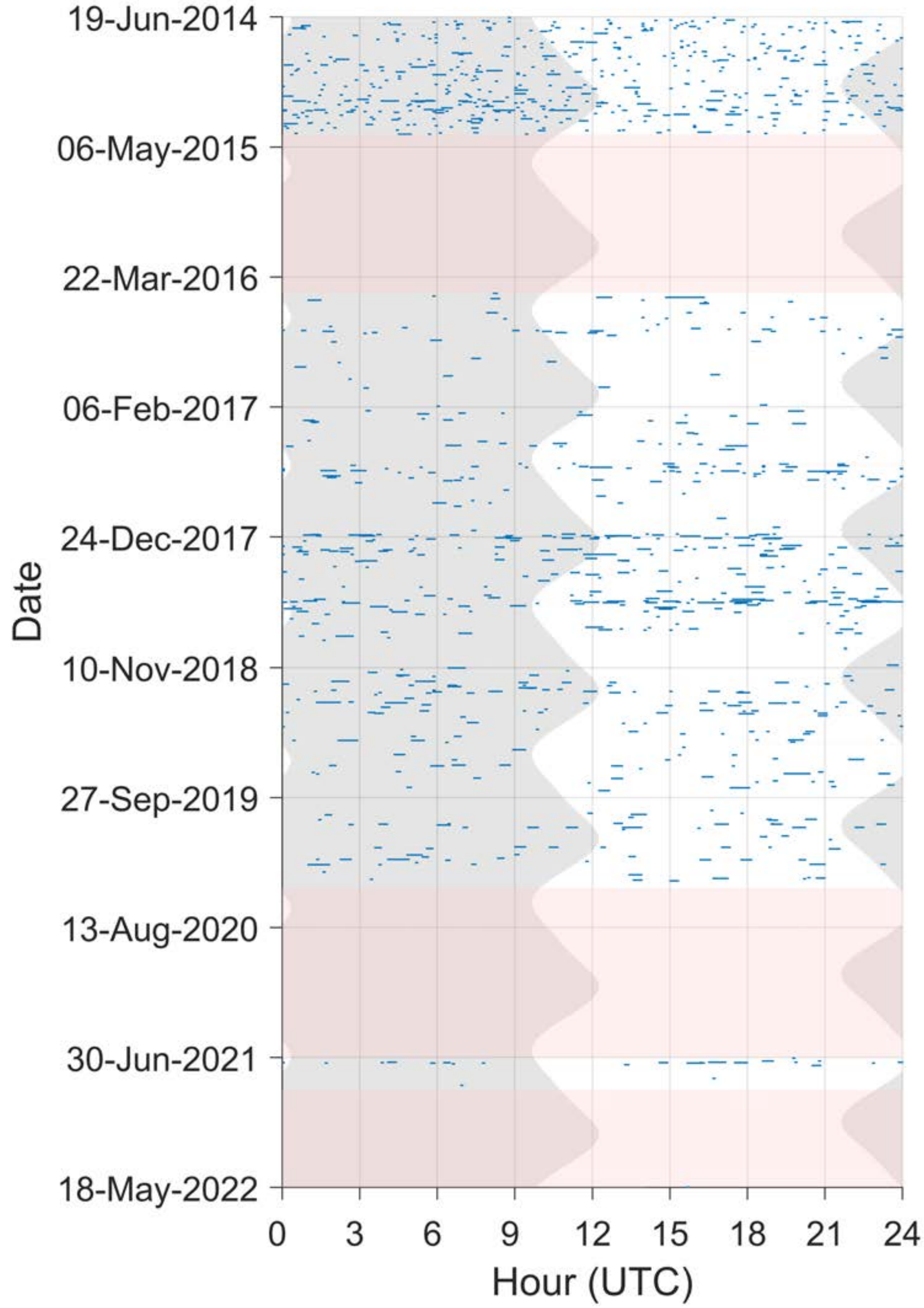

Figure 35: Goose-beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.2 Gervais’ and True’s Beaked Whales

Gervais’ and True’s beaked whales both occurred at Norfolk Canyon from 2014 to 2021, with True’s exhibiting higher levels of acoustic presence compared to Gervais’. Because their click types are acoustically similar, a subset of clicks could not be confidently assigned to either species, these are reported as unclassified True’s/Gervais’ clicks in the subsequent figures. Acoustic presence for both species occurred across months, with a seasonal increase during the winter and another and a smaller increase in mid-summer (Figure 37).

True’s beaked whales were generally present at low levels, with weekly acoustic presence typically <2 hours with occasional peaks up to 6-8 hours/week (Figure 36). A weak nocturnal diel pattern was evident, with slightly higher acoustic presence during nighttime hours (Figure 38).

Gervais’ beaked whales occurred less frequently during the recording period, with weekly presence generally <2 hours (Figure 36). No consistent diel pattern was observed, likely due to the limited occurrence of this species (Figure 38).

These results are consistent with previous studies that found Gervais’ beaked whales occur primarily south of Cape Hatteras and are rare as far north as Norfolk Canyon, while True’s beaked whales occur more regularly north of Cape Hatteras, with seasonal increases in winter and summer (Haver et al. 2025; Cohen et al. 2022; Stanistreet et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025).

Summary of Results – Gervais’ and True’s beaked whales

- True’s beaked whales had low but consistent presence, with seasonal increases in winter and summer.
- Gervais’ beaked whales occurred less frequently, reflecting their more southerly distribution and only rare occurrence as far north as Norfolk Canyon.
- No consistent diel pattern was evident for Gervais’ or True’s beaked whales.

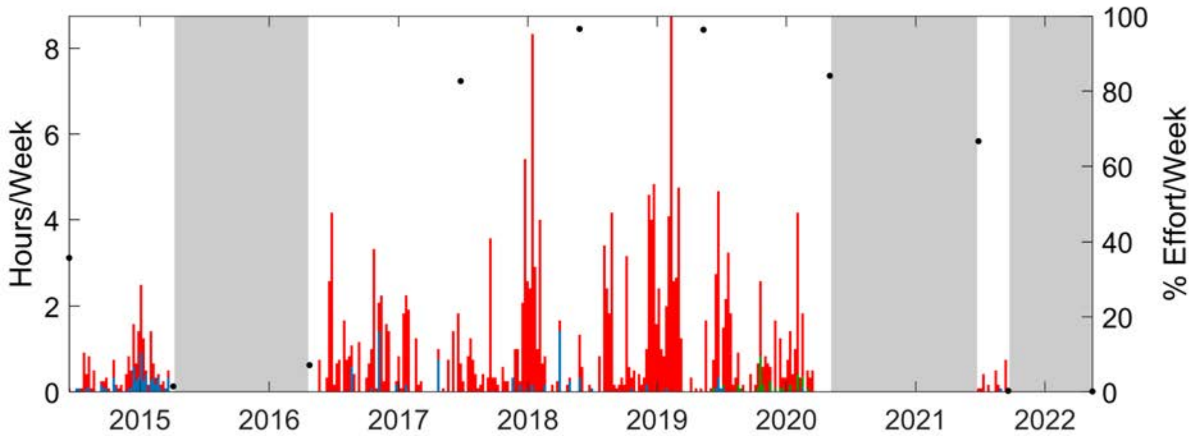

Figure 36: Cumulative hours/week of Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

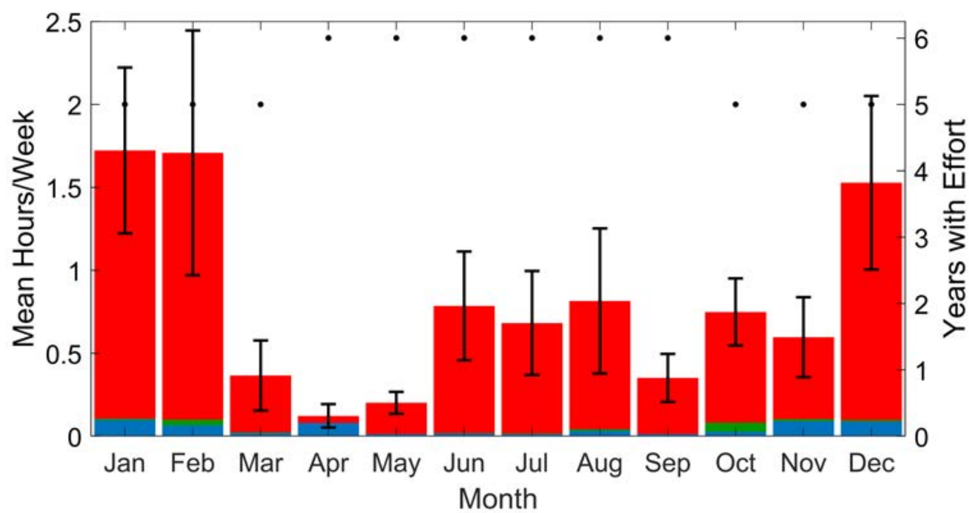

Figure 37: Monthly mean hours per week of Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

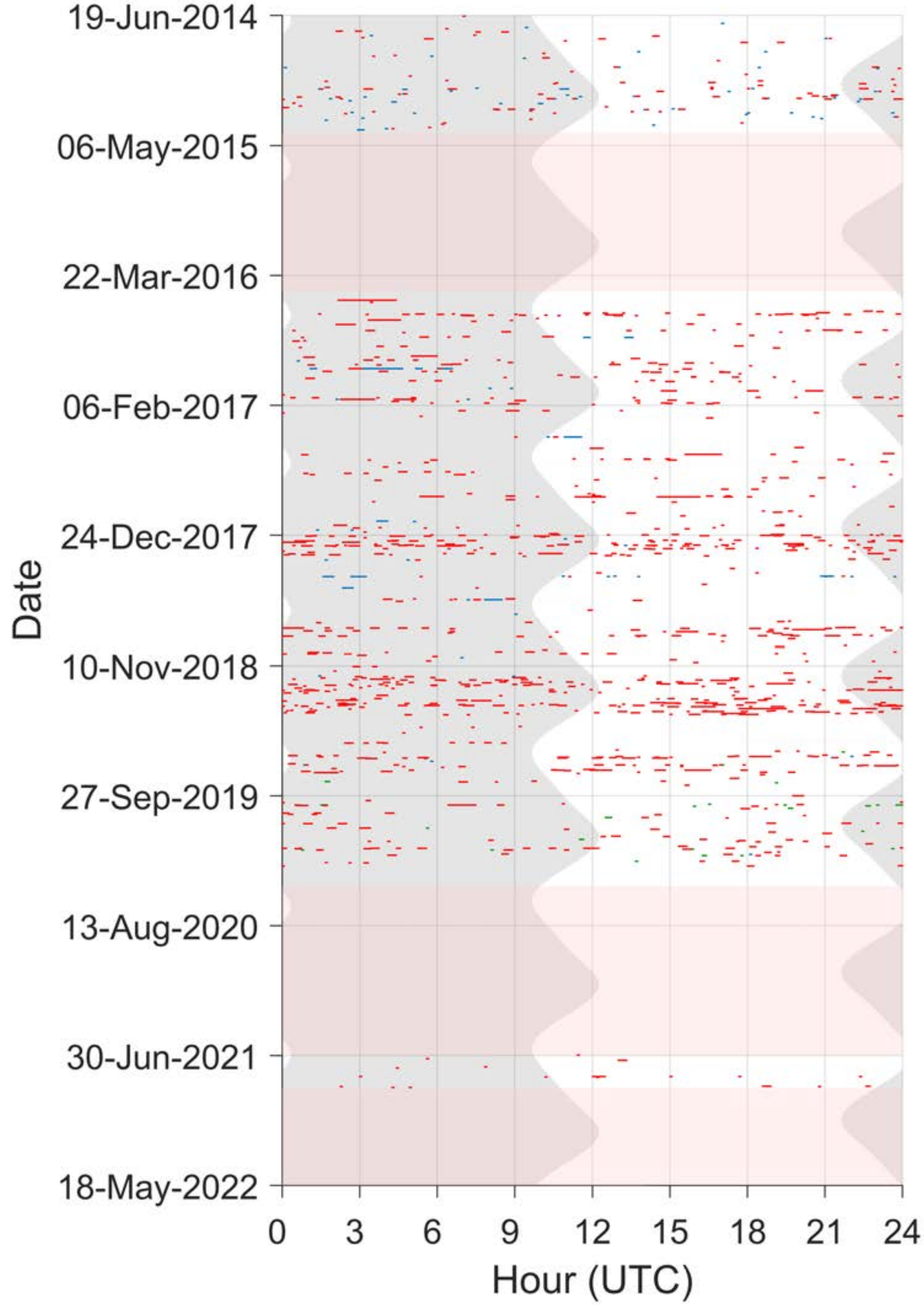

Figure 38: Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.3 Blainville's Beaked Whale

Blainville's beaked whales occurred only sporadically at Norfolk Canyon between 2014 and 2021, with acoustic presence remaining very low throughout the monitoring period (Figure 39). Weekly acoustic presence never exceeded 30 minutes, with detections scattered across years. A slight seasonal increase in presence was observed during the winter months (Figure 40). Due to the infrequency of acoustic presence, no consistent diel pattern was evident (Figure 41).

These results are consistent with previous studies that found Blainville's beaked whales are infrequently present north of Cape Hatteras, with limited occurrence at Norfolk Canyon and other offshore canyons, and are not associated with major foraging hotspots in this region (Haver et al. 2025; Cohen et al. 2022; Stanistreet et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025).

Summary of Results – Blainville's beaked whale

- Blainville's beaked whales occurred sporadically, with very low weekly acoustic presence throughout the monitoring period.
- A slight seasonal increase in presence was observed in winter.
- No consistent diel pattern was observed due to infrequent acoustic presence.

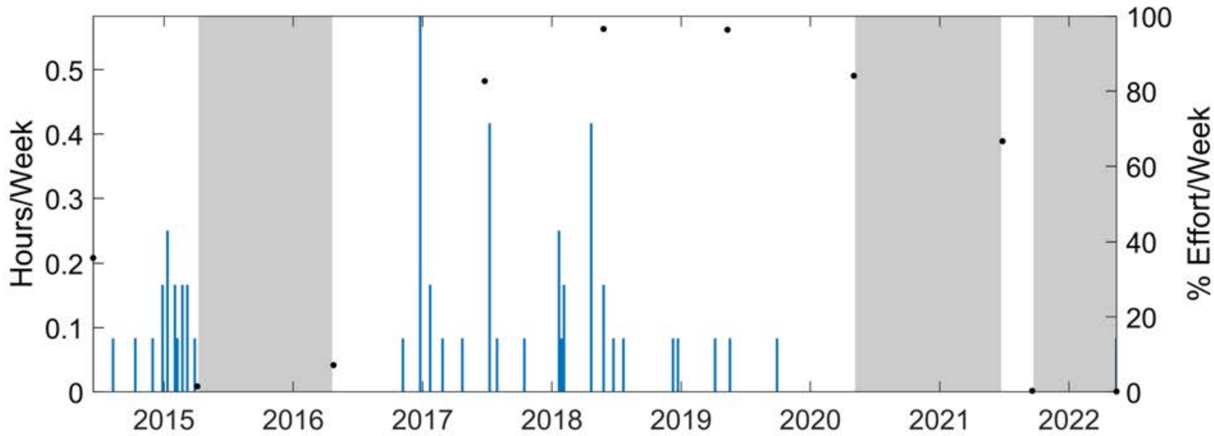

Figure 39: Cumulative hours/week of Blainville's beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

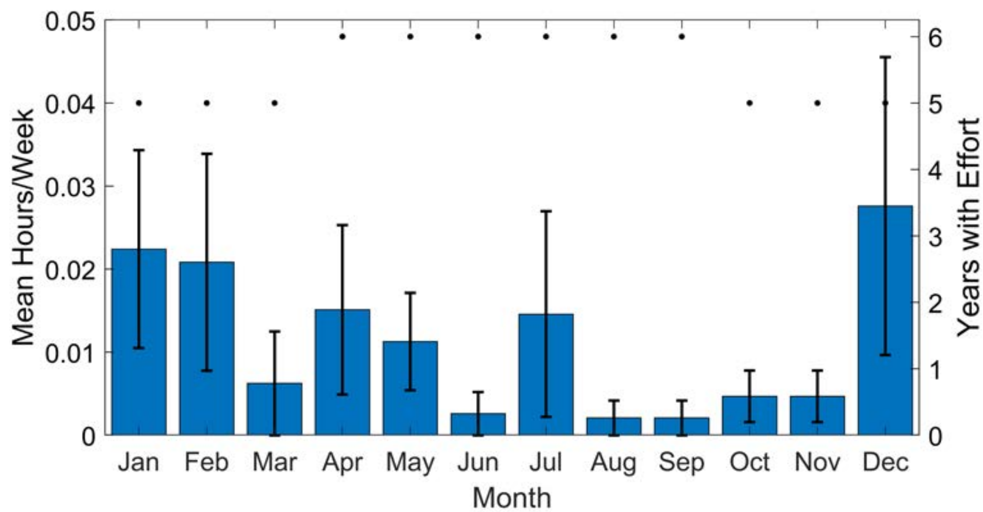

Figure 40: Monthly mean hours per week of Blainville's beaked whale acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

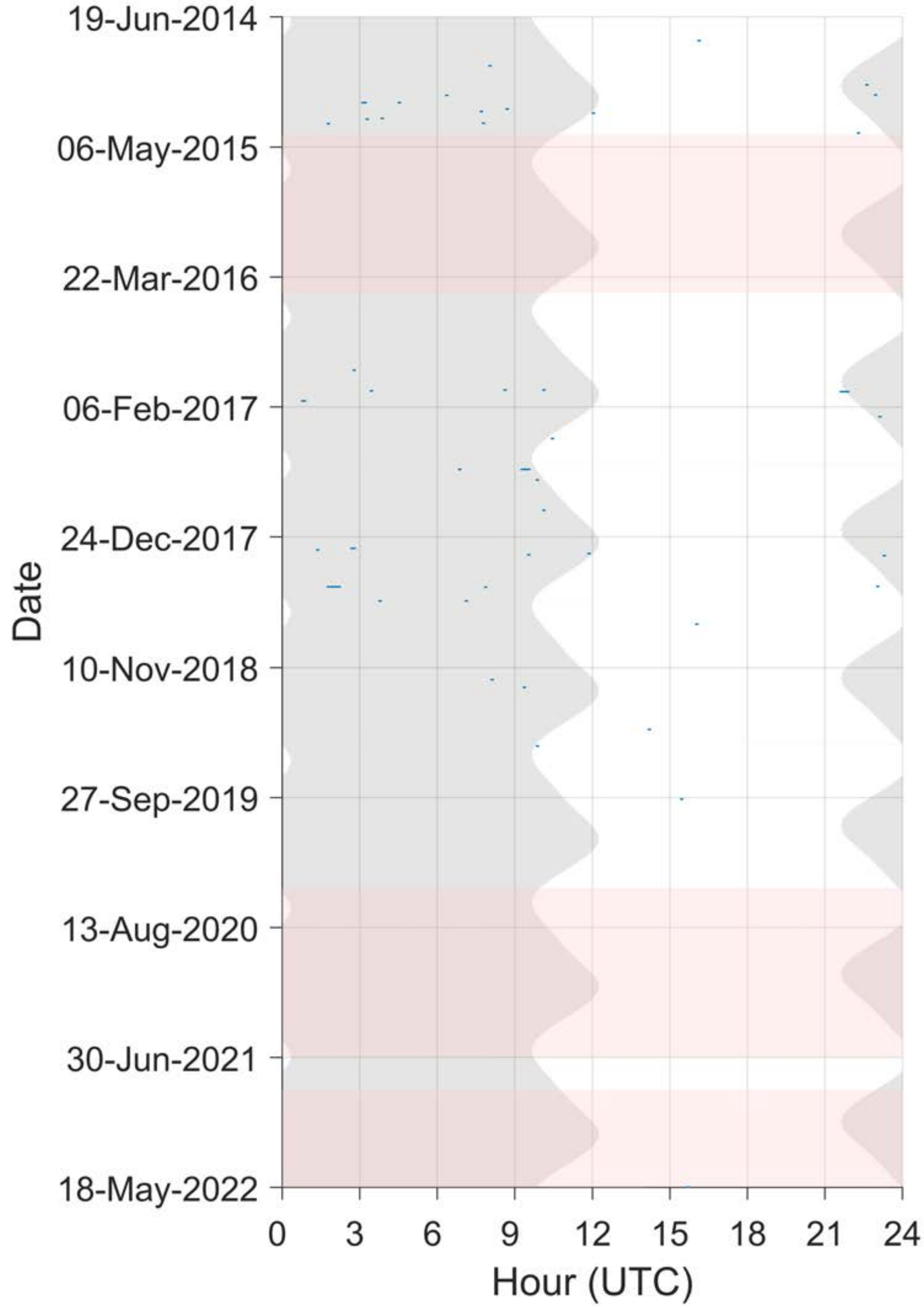

Figure 41: Blainville's beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.4 Sowerby's Beaked Whale

Sowerby's beaked whales were present at Norfolk Canyon from 2014 to 2021 with moderate presence. Weekly acoustic presence was usually below two hours, though brief peaks reached $\sim$6 hours in some years, with a decrease in presence in 2020 and 2021 (Figure 42). Presence was most consistent in winter through late spring, with much lower levels in late summer and early fall (Figure 43). No clear diel pattern was evident; activity was distributed across day and night (Figure 44).

These results are consistent with previous studies that found Sowerby's beaked whales are more common north of Cape Hatteras and that occurrence near Norfolk Canyon likely increases during cooler months (Haver et al. 2025; Cohen et al. 2022; Stanistreet et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025).

Summary of Results – Sowerby's beaked whale

- Sowerby's beaked whales had moderate presence, usually less than <2 hours/week with short peaks up to $\sim$6 hours/week and a dip in 2020-2021.
- Acoustic presence peaked in the winter through spring; lower in late summer and early fall.
- No consistent diel pattern was observed.

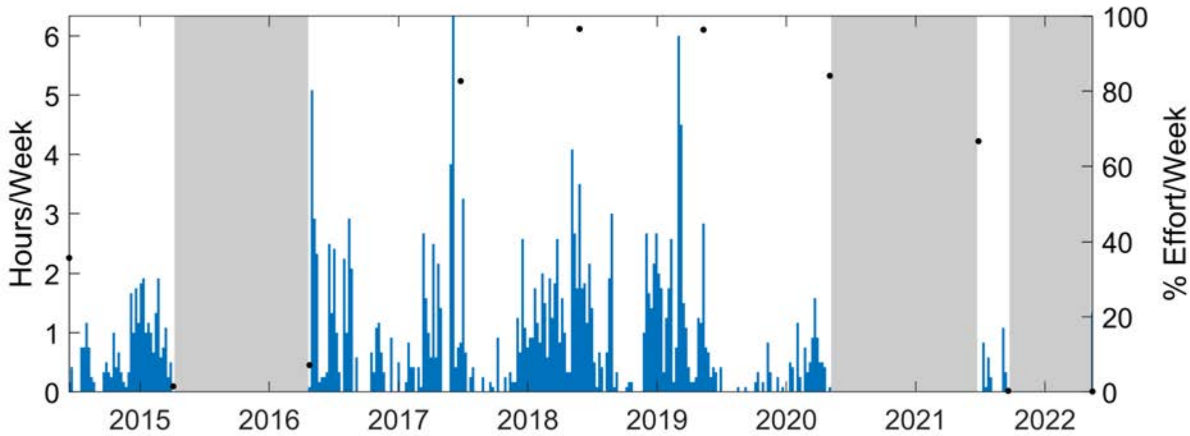

Figure 42: Cumulative hours/week of Sowerby's beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

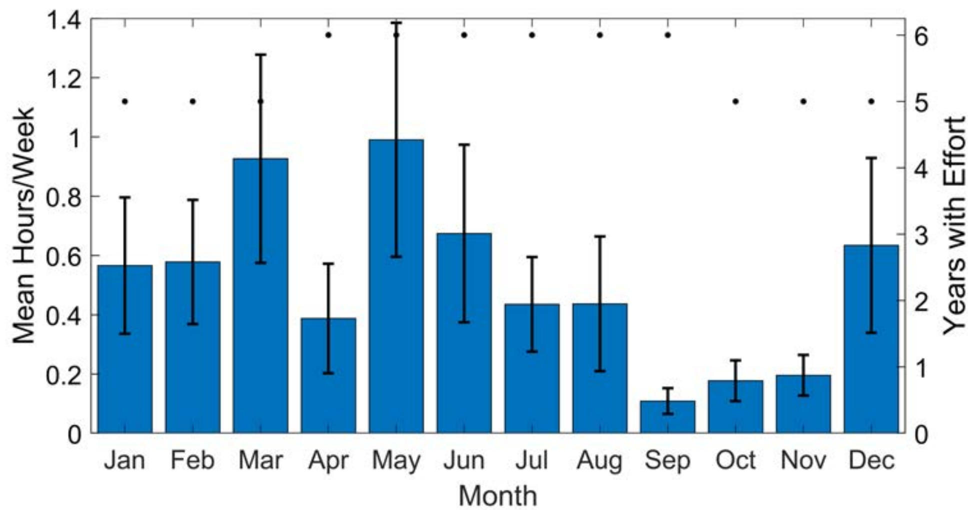

Figure 43: Monthly mean hours per week of Sowerby's beaked whale acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

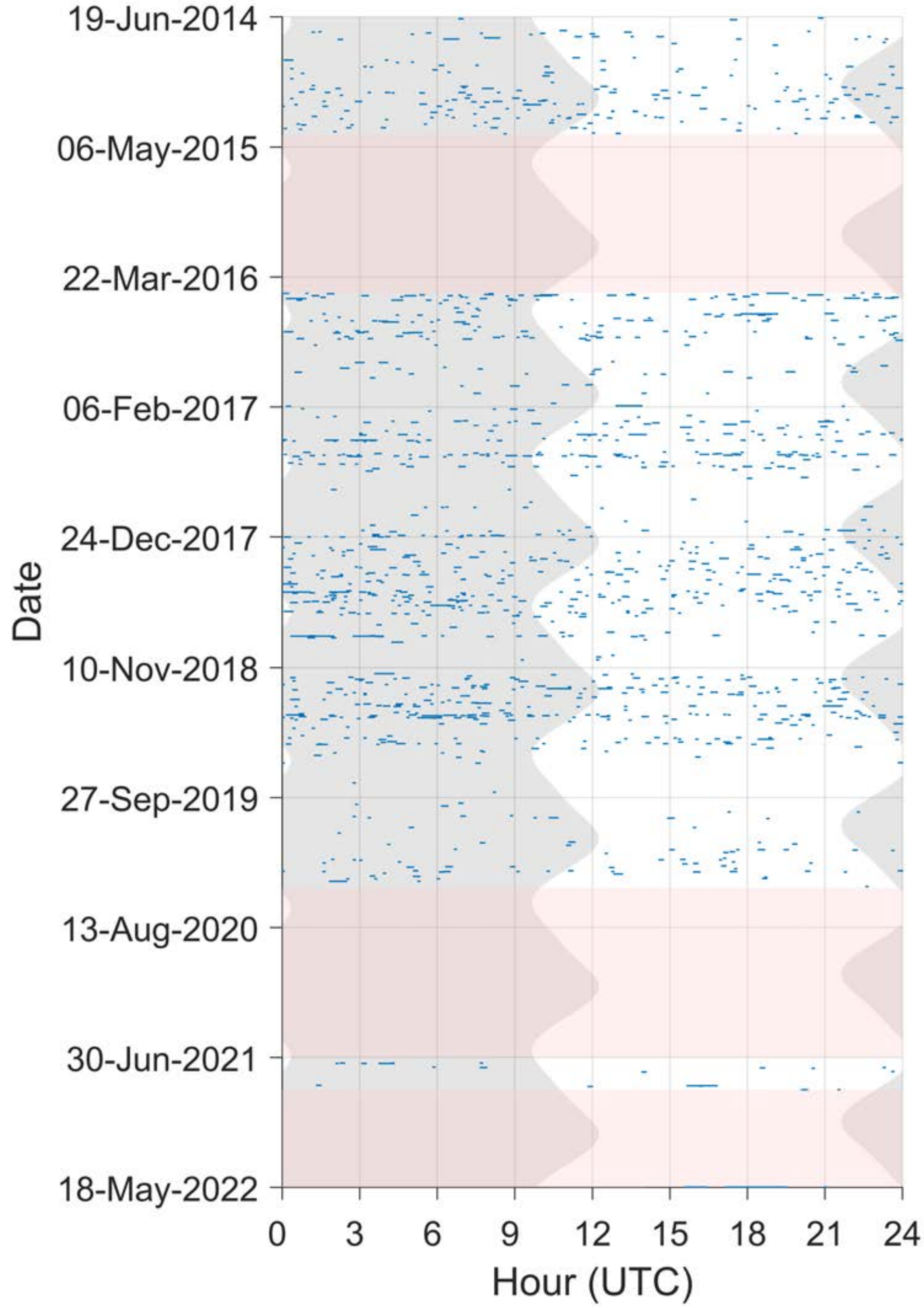

Figure 44: Sowerby's beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.5 Sperm Whale

Sperm whales consistently occurred at Norfolk Canyon from 2014 to 2021 with weekly presence ranging from 60-110 hours/week and occasional peaks approaching $\sim$150 hours (Figure 45). Presence was strongest in the late-summer through fall (Figure 46). No clear diel patterns were observed (Figure 47), indicating that sperm whales were vocally active during both day and night.

These results are consistent with previous studies showing regular, year-round sperm whale occurrence along the Mid-Atlantic slope, especially near Norfolk Canyon, with seasonal increases in summer through winter (Stanistreet et al. 2018).

Summary of Results – Sperm whale

- Sperm whale acoustic presence was consistent throughout the study period, with moderate to high levels of acoustic presence, often >100 hours/week.
- Strongest presence in late-summer through fall.
- No consistent diel pattern was observed.

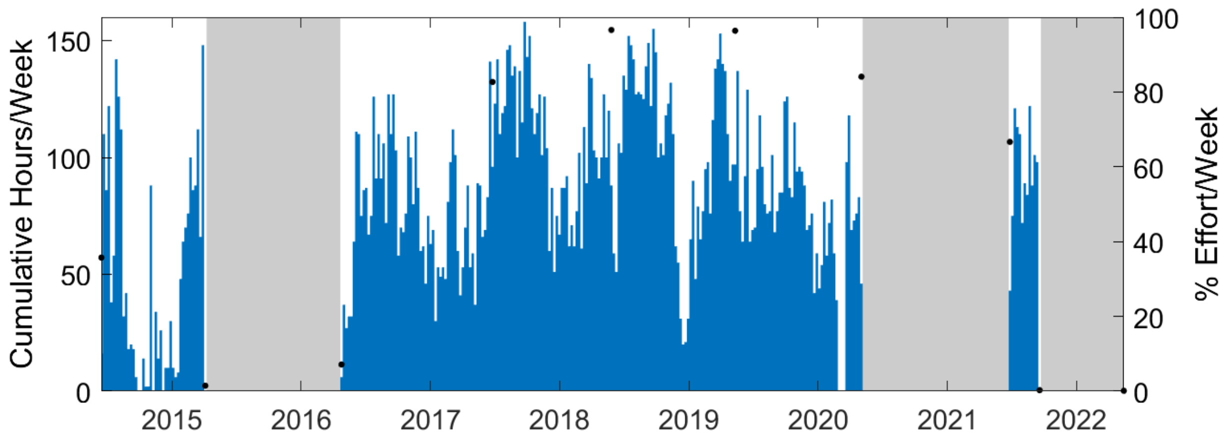

Figure 45: Cumulative hours/week of sperm whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

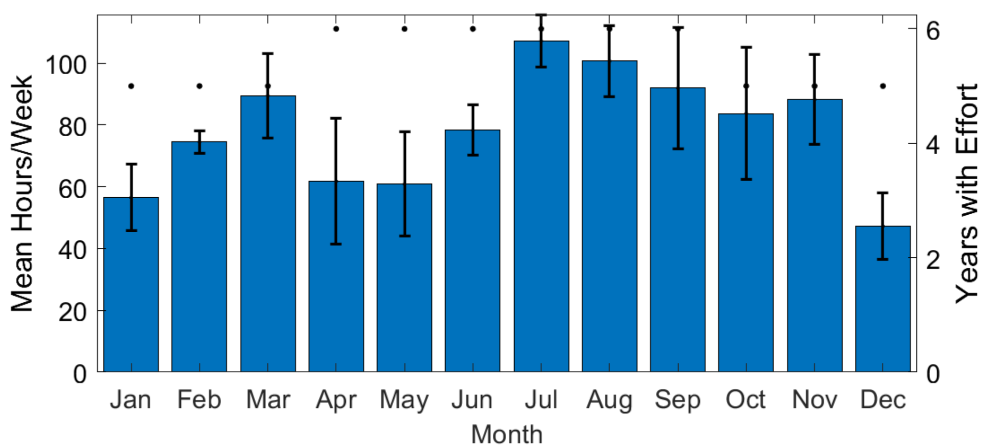

Figure 46: Monthly mean hours per week of sperm whale acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

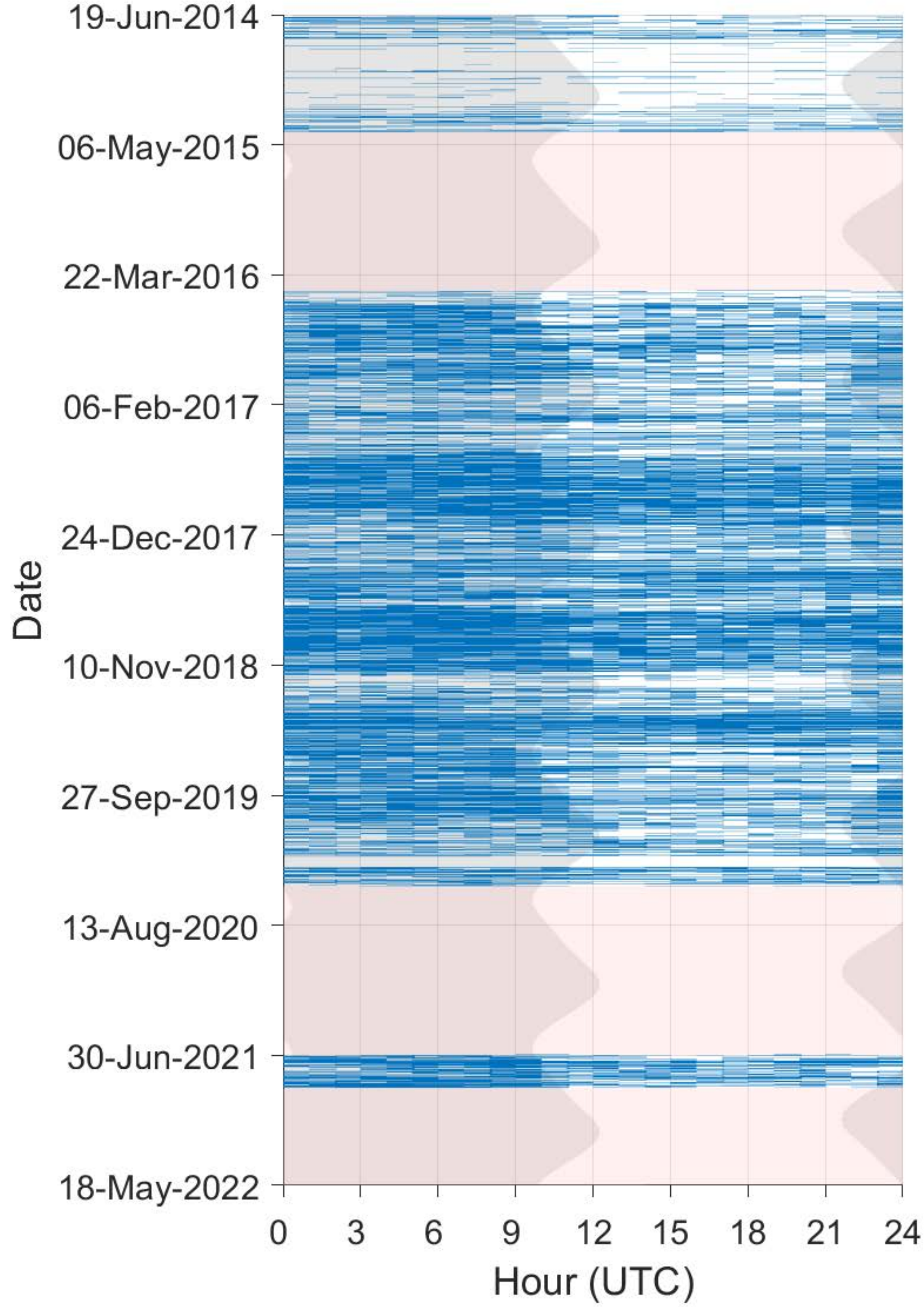

Figure 47: Sperm whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.1.6 *Kogia* spp.

Kogia spp. exhibited low acoustic presence at Norfolk Canyon from 2014 to 2021, with weekly presence generally below ∼0.3 hours/week (Figure 48). Presence was highest from late spring through summer and was lowest in late-winter through early-spring months (Figure 49). A diel pattern was observed, with more acoustic presence occurring during nighttime (Figure 50), consistent with nocturnal foraging behavior reported for this genus.

These results are consistent with previous studies that found *Kogia* spp. occur at relatively low levels in this region with increased presence in the summer (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023).

Summary of Results – *Kogia* spp.

- Low, intermittent acoustic presence across recording period, with long gaps between events.
- Seasonal increase from late spring through summer.
- A diel pattern was evident, with increased presence at night.

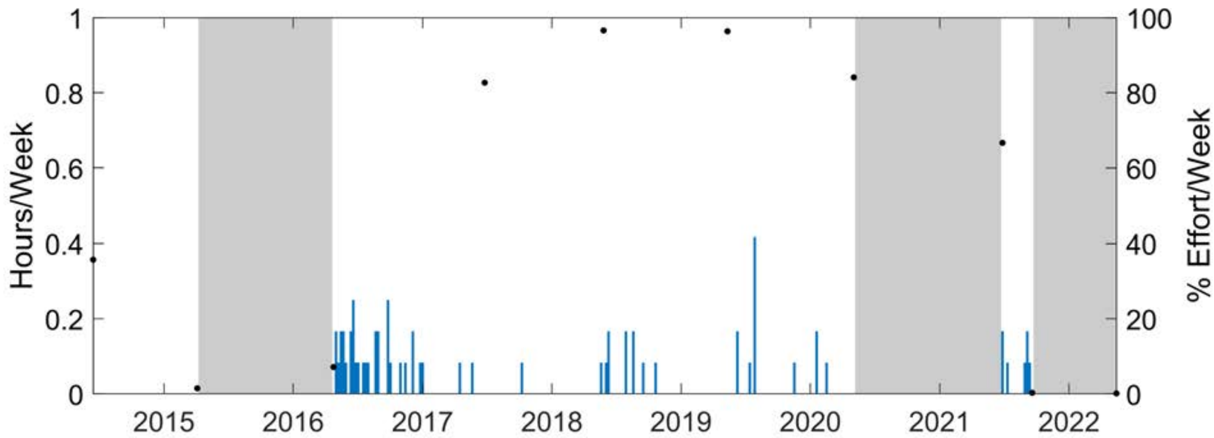

Figure 48: Cumulative hours/week of *Kogia* spp. presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

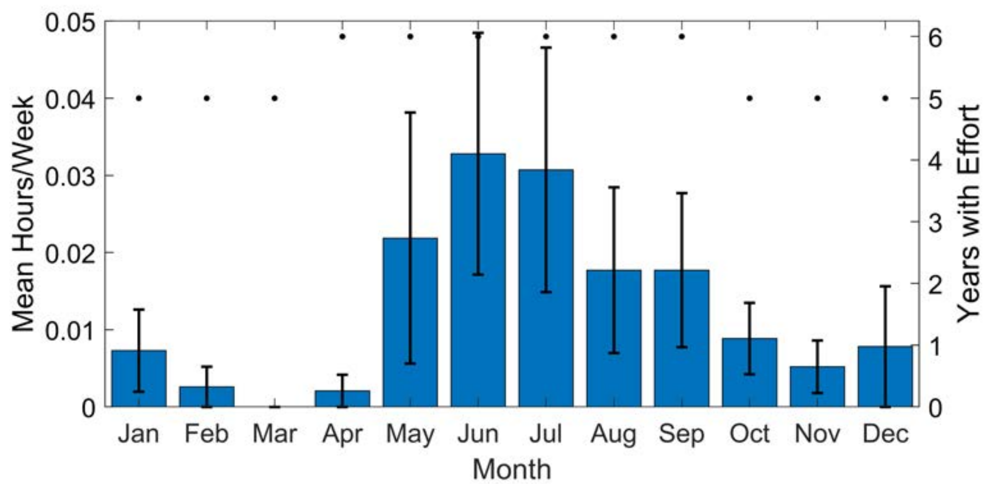

Figure 49: Monthly mean hours per week of *Kogia* spp. acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

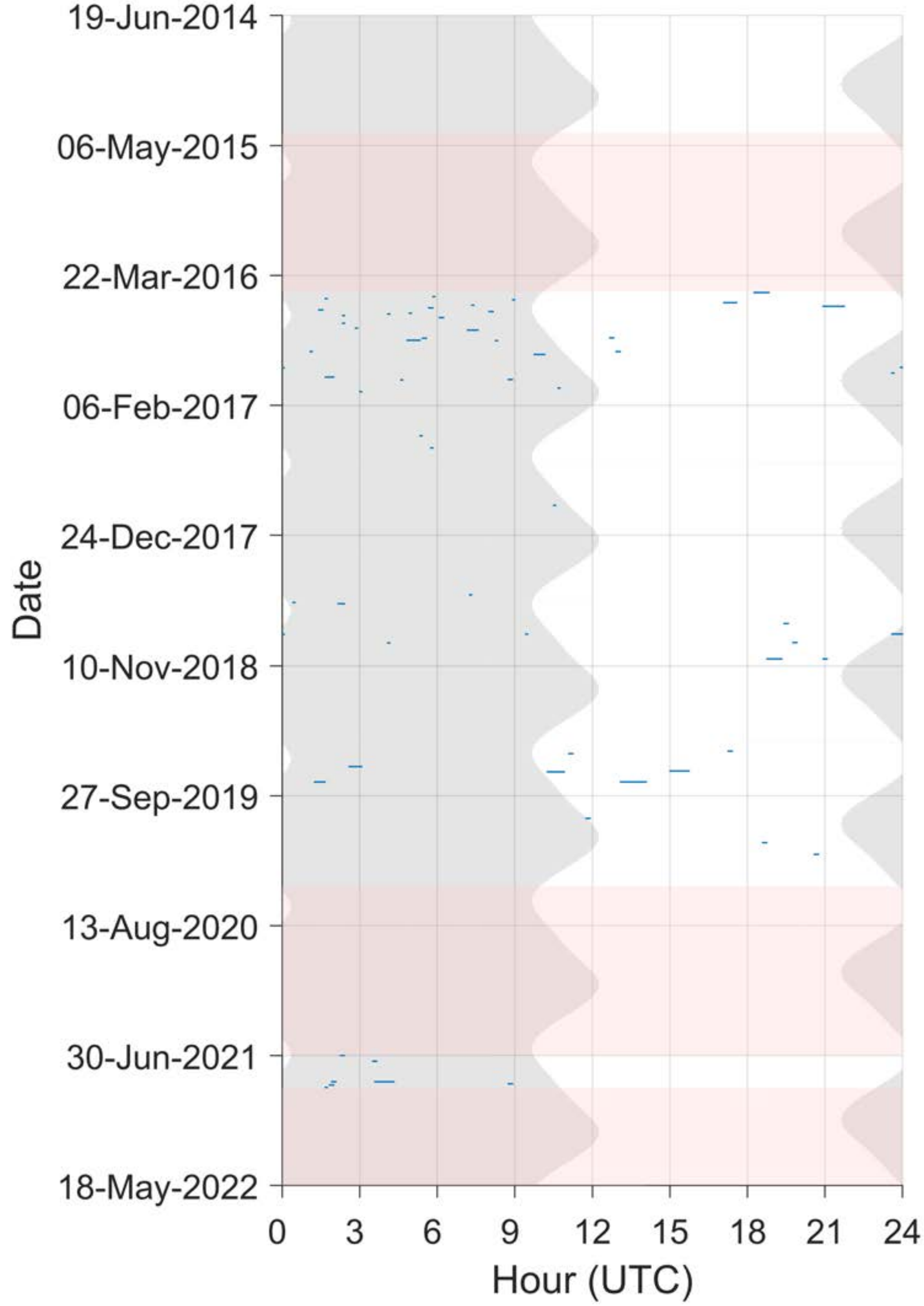

Figure 50: *Kogia* spp. acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.7 Risso's Dolphin

Risso's dolphins were present at Norfolk Canyon from 2014 to 2021 at moderate levels (Figure 51). Weekly acoustic presence generally stayed below $\sim$5 hours, with summer peaks approaching $\sim$8 hours/week. Presence increased from spring into late summer, peaking in March through April and again in July through August, and was lowest in winter (Figure 52). No diel pattern was evident, with consistent presence throughout day and night (Figure 53).

These patterns are consistent with previous work showing Risso's dolphins are common along the slope north of Cape Hatteras but mostly prevalent in summer–fall in this region (Baumgartner & Mussoline 2011; Haver et al. 2025; Cohen et al. 2023).

Summary of Results – Risso's Dolphin

- Moderate acoustic presence across the monitoring period with presence generally below $\sim$5 hours, with summer peaks approaching $\sim$8 hours/week.
- Seasonal increase from spring to late summer, peaking in March through April and again in July through August; lowest in winter.
- No consistent diel trend was observed, with presence distributed throughout day and night.

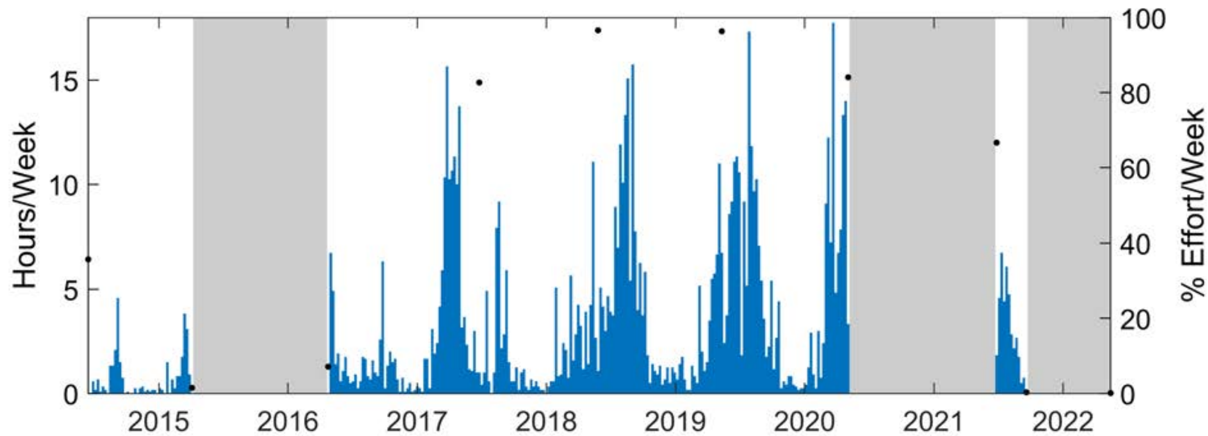

Figure 51: Cumulative hours/week of Risso's dolphin presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

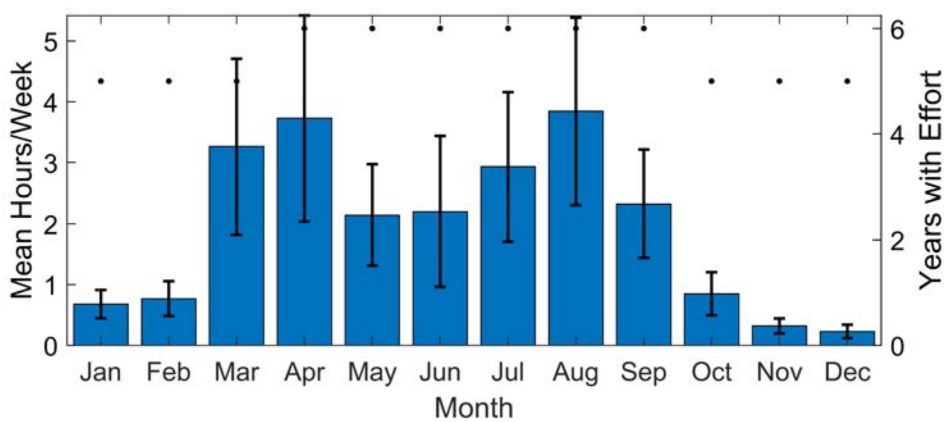

Figure 52: Monthly mean hours per week of Risso's dolphin acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

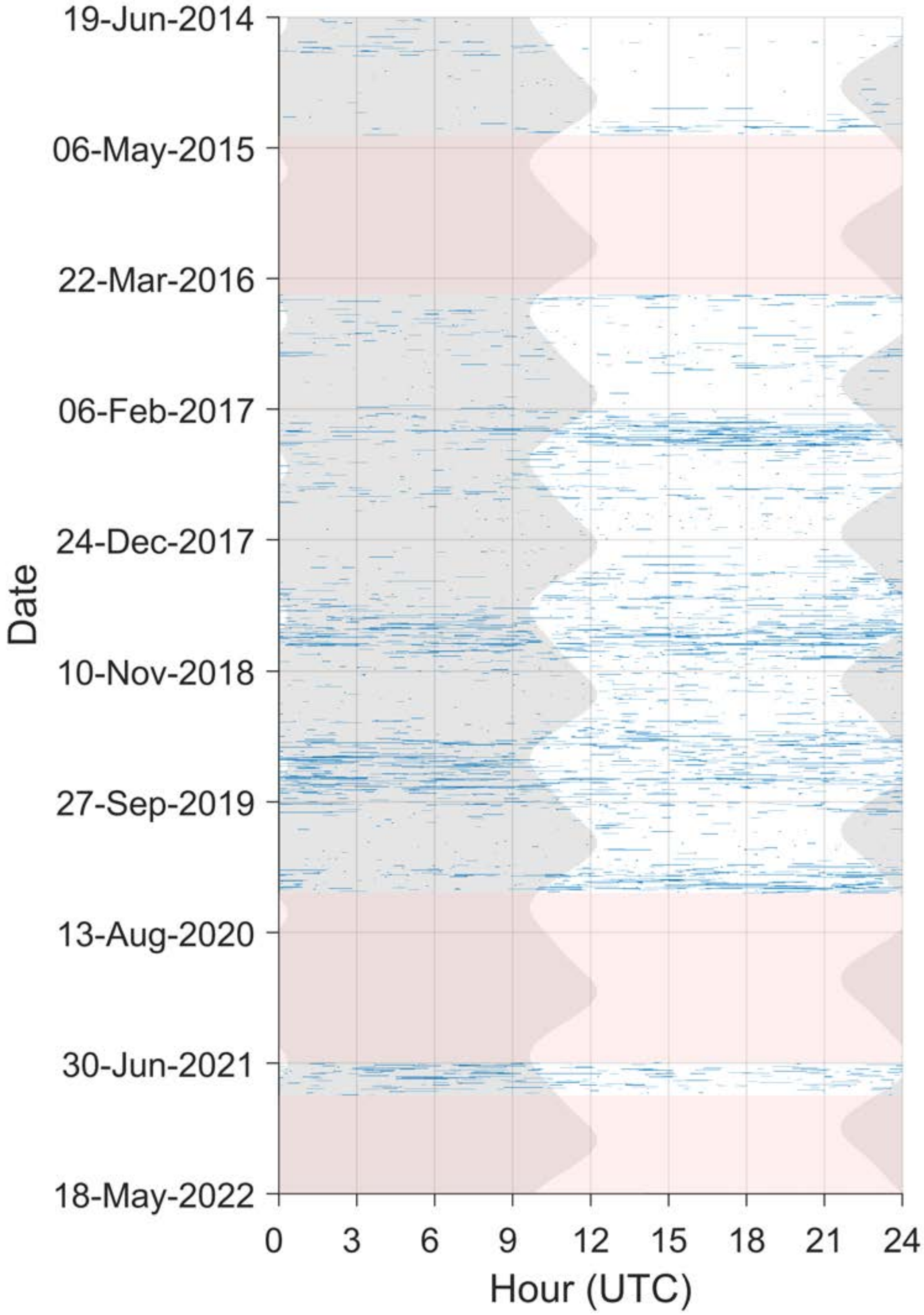

Figure 53: Risso's dolphin acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort.

5.1.8 Unidentified Dolphins – Smaller-Bodied Delphinids (UD HF & 47)

Smaller-bodied delphinids, represented by the high-frequency (UD HF) and 47 kHz (UD47) click types, were present at Norfolk Canyon from 2014 to 2021 with high presence and a clear seasonal pattern (Figure 54). Weekly values commonly reached 40–80 hours per week, and several weeks approached or exceeded 100 hours.

Seasonal patterns were very strong, with presence peaking in late fall and winter, remaining highest from December through March and decreasing in late spring into summer, with lowest presence from June to September (Figure 55). A clear diel pattern was evident, with activity concentrated during nighttime and early-morning hours, consistent with nocturnal or crepuscular foraging (Figure 56).

These results are consistent with previous studies showing UD HF & 47 clicks are common along the slope north of Cape Hatteras, most prevalent in winter–early spring and often more active at night (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023).

Summary of Results – Smaller-Bodied Delphinids (UD HF & UD47)

- Strong presence throughout the recording period, with weekly values frequently reaching 40–80 hours and occasional peaks near or above 100 hours.
- Seasonal maximum from late fall through winter (Dec–Mar) and minimum from late spring through summer (Jun–Sep).
- Pronounced nocturnal and early-morning activity, indicating a diel pattern consistent with nighttime or crepuscular foraging.

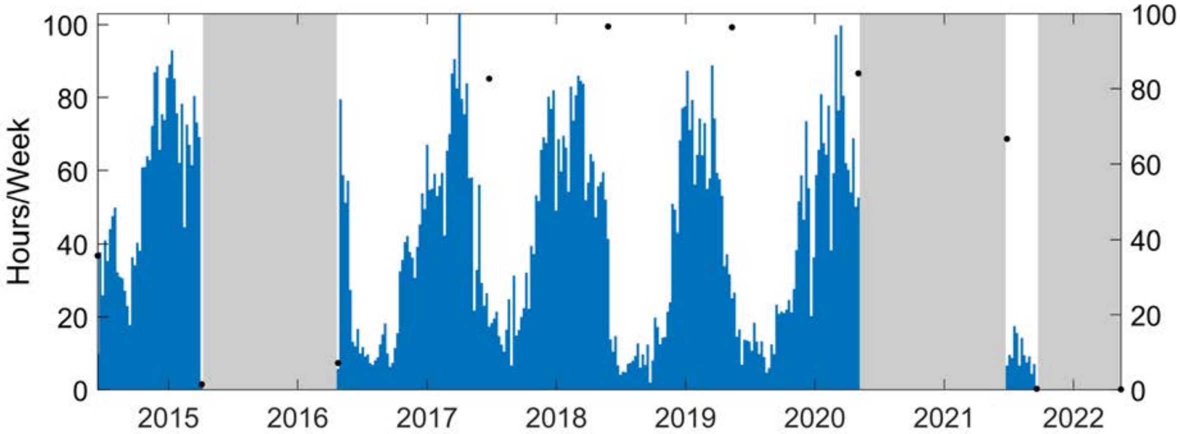

Figure 54: Cumulative hours/week of smaller-bodied delphinid (UD HF & 47) presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

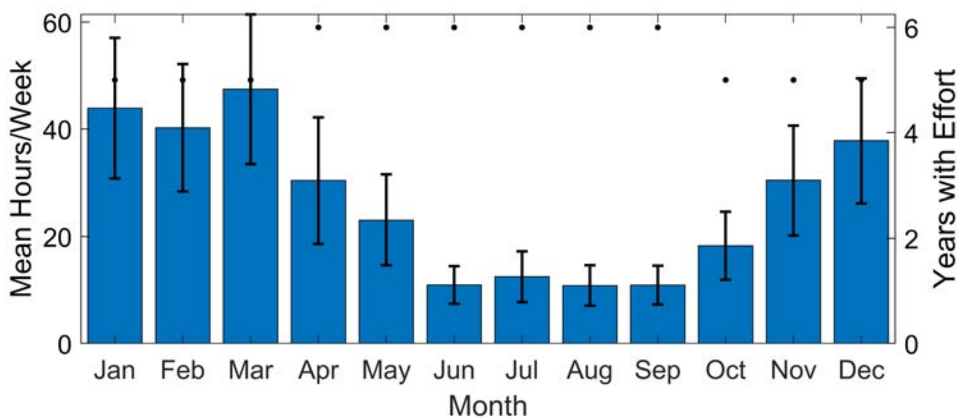

Figure 55: Monthly mean hours per week of smaller-bodied delphinid (UD HF & 47) acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

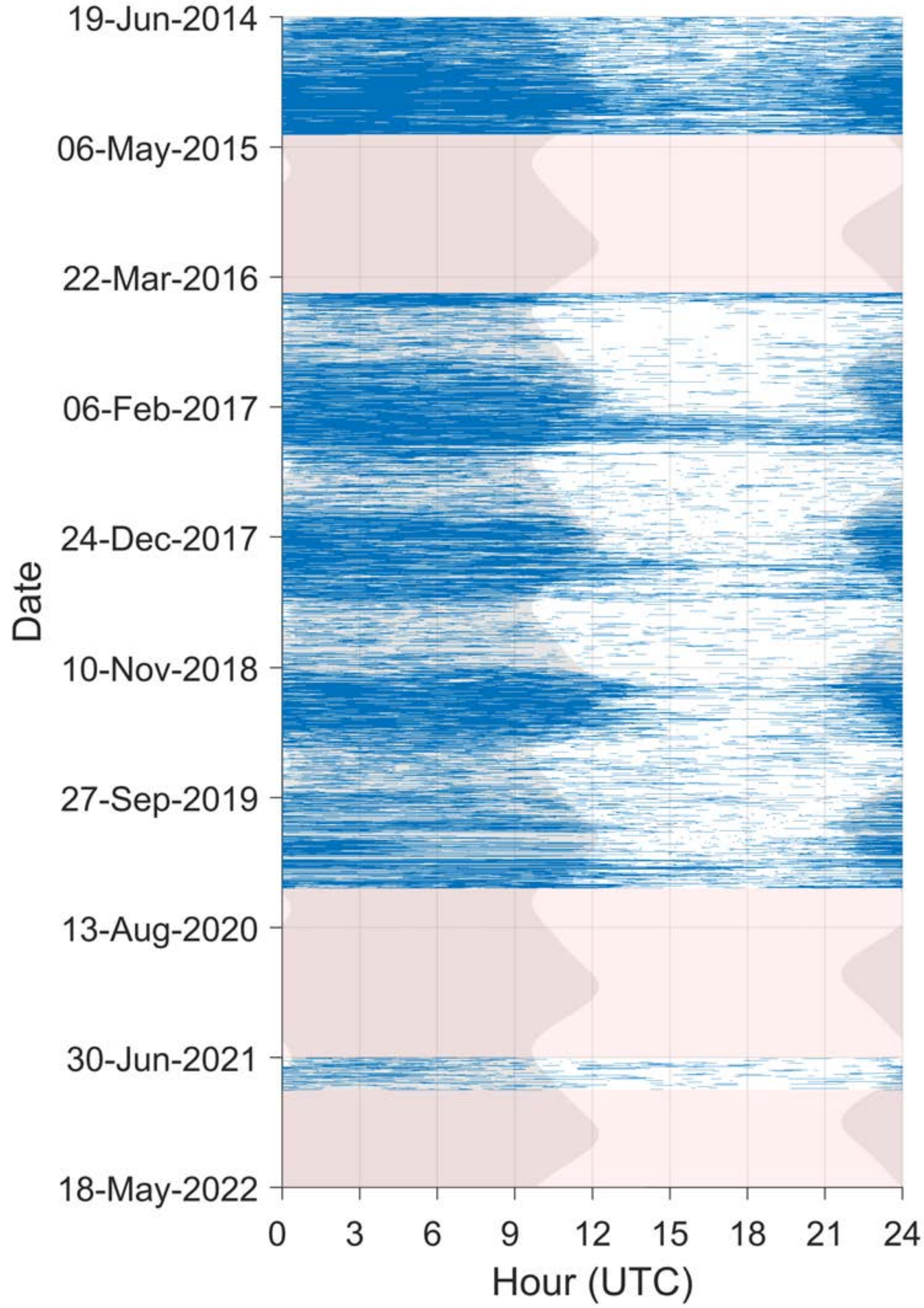

Figure 56: Smaller-bodied delphinid (UD HF & 47) acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.1.9 Unidentified Dolphins – Larger-Bodied Delphinids (UD LF)

Larger-bodied delphinids, represented by the low-frequency unidentified dolphin click type (UD LF), were common at Norfolk Canyon from 2014 to 2021, with weekly presence frequently ∼30–60 hours and occasional peaks >100 hours/week (Figure 57). Presence rose sharply from late spring and was highest in July–September, then tapered through autumn; January–April showed the lowest levels (Figure 58). No consistent diel pattern was evident and activity was spread across day and night (Figure 59).

These results are consistent with previous studies that showed year-round occurrence of larger-bodied delphinids along the slope, with a summer–fall maximum in this region (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; Leu et al. 2022).

Summary of Results – Larger-Bodied Delphinids (UD LF)

- Consistent presence from 2014–2021, commonly ∼30–60 hours/week with occasional weeks >100 hours.
- Clear seasonal peak in summer–early fall (Jul–Sep), lowest levels in late winter–spring (Jan–Apr).
- No consistent diel pattern; presence occurred across all hours.

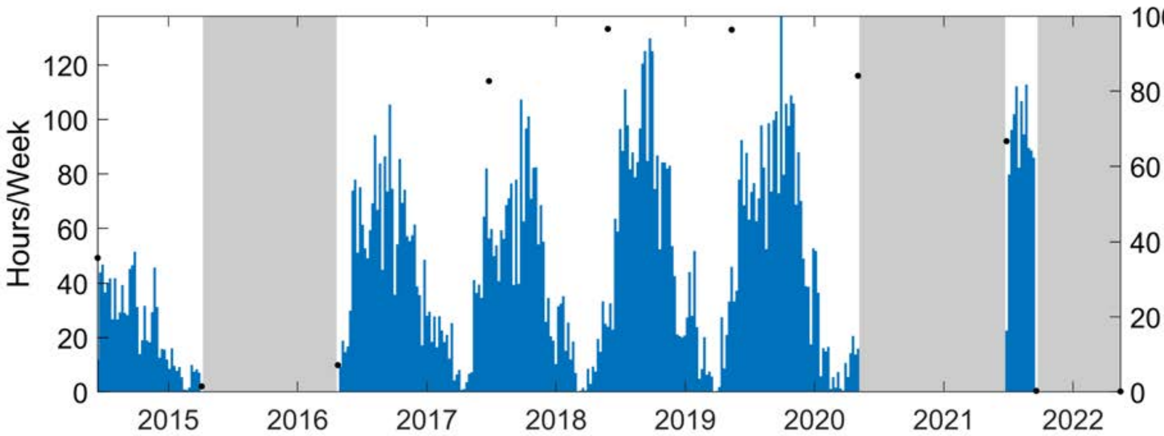

Figure 57: Cumulative hours/week for larger-bodied delphinid (UD LF) presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

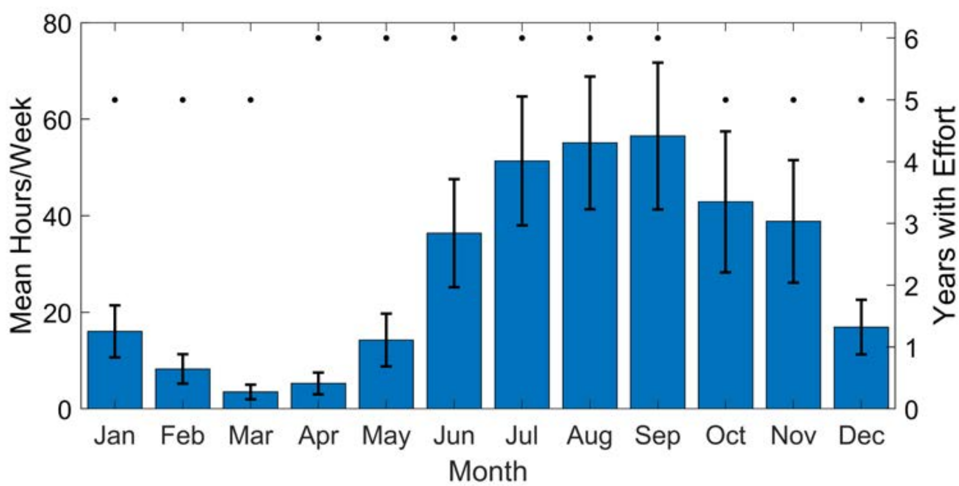

Figure 58: Monthly mean hours per week of larger-bodied delphinid (UD LF) acoustic presence. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

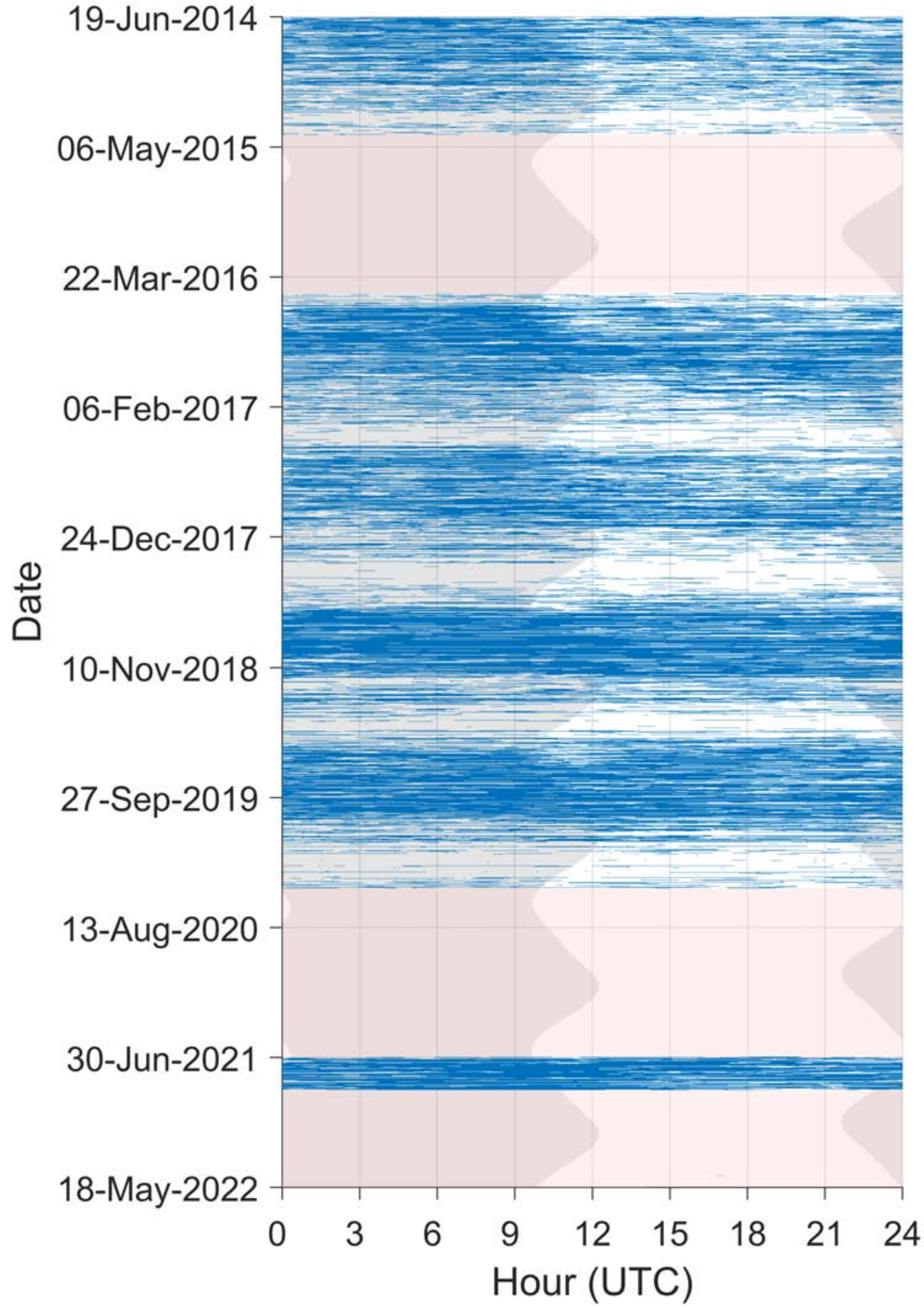

Figure 59: Larger-bodied delphinid (UD LF) acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.2 Mysticetes

Mysticetes at Norfolk Canyon exhibited distinct seasonal and interannual variation in acoustic presence (Figure 60 & 61). Across species, detections were strongest from late fall through spring, with limited or no acoustic presence during summer months. This seasonal structure is consistent with known broad-scale migratory and foraging movements of baleen whales along the U.S. East Coast.

Humpback whales showed a defined seasonal pulse, with most detections occurring between February and April, and occasional presence in late fall. Their activity increased in the latter years of the record, with multiple detections per week during peak months. This winter–spring presence aligns with the expected timing of northbound migratory movements along the Mid-Atlantic coast.

Minke whales occurred infrequently but displayed a weak bimodal pattern, with scattered detections in January–March and additional occurrences in September–November. Although overall presence was low, the repeated timing across multiple years suggests the species may transit through the region during both northbound and southbound migration periods.

North Atlantic right whales were detected only sporadically, with isolated occurrences in February–April, June, and November–December. Weekly presence never exceeded one or two days, and most years showed no detections. These scattered events likely reflect the offshore location of the HARP, which is positioned beyond the mid-shelf areas more commonly used by right whales. As such, detections at this site are consistent with occasional movements through the region rather than regular seasonal use within preferred mid-shelf habitat.

Sei whales were more regularly present, with detections spanning November through May and reaching a clear seasonal peak in March–April. Presence during peak years included multiple detections per week, indicating substantial early-spring activity. Although interannual variability was strong, the consistent timing of peak detections suggests recurring seasonal transit through the canyon region.

Fin whales showed the strongest and most persistent seasonal presence, occurring in most years from August through March. Activity peaked between September and February, often reaching several detections per week. Their extended seasonal window and consistent occurrence across years highlight the importance of the NFC region as part of their seasonal distribution.

Blue whales exhibited two seasonal pulses: one in February–March and a more sustained period from late summer through early winter, peaking in September–November. Their presence corresponds to known offshore and slope-associated movement patterns and suggests that the canyon system lies along a migratory or foraging corridor for this species.

Together, these results reveal both shared broad-scale seasonal structure and clear species-specific differences in timing and intensity of acoustic presence at Norfolk Canyon. Humpback, sei, fin, and blue whales showed the most pronounced and repeatable patterns, while minke and right whales occurred more sporadically. The overall patterns underscore the role of the Norfolk Canyon region as a seasonally used habitat and transit area for multiple baleen whale species.

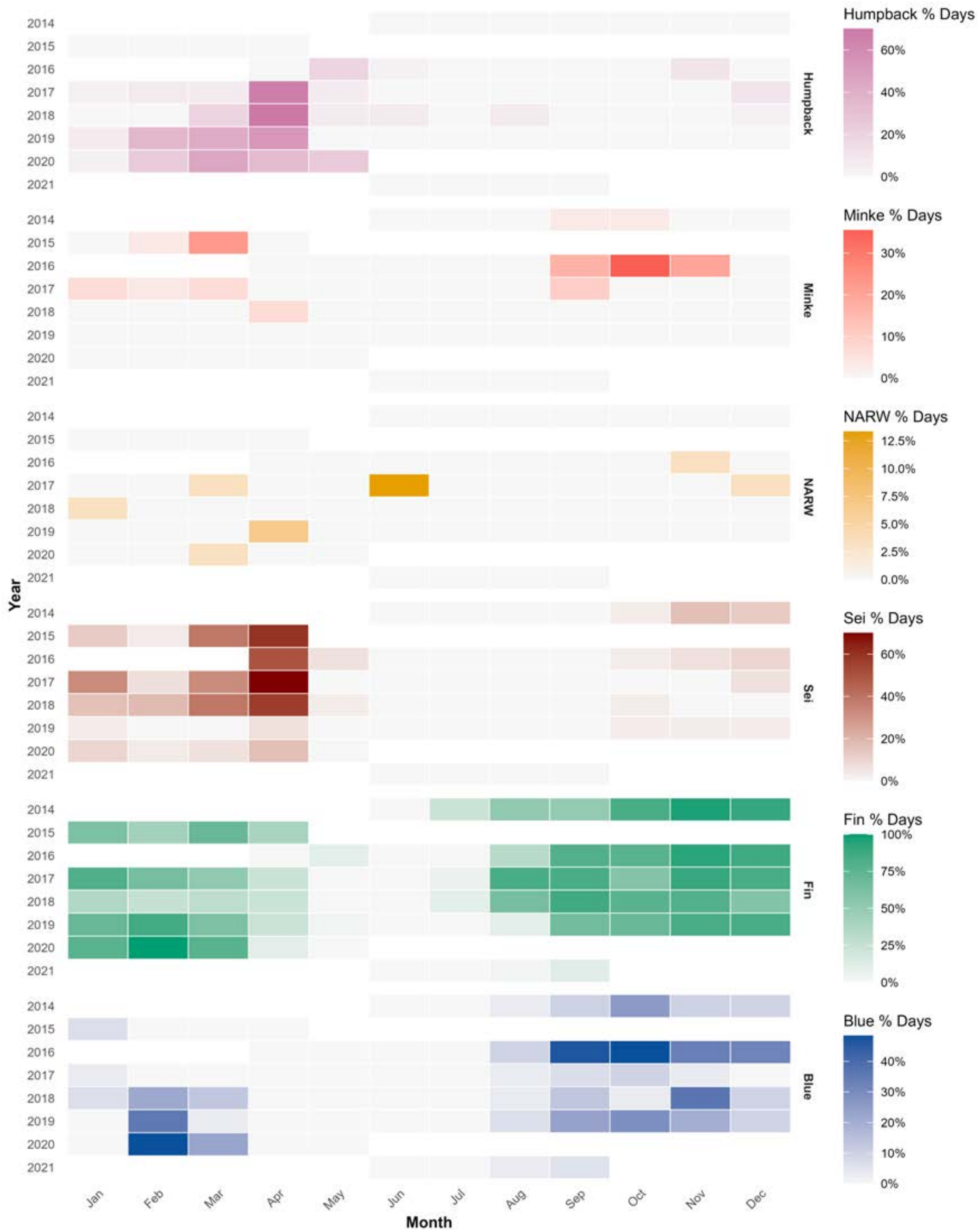

Figure 60: Annual monthly acoustic presence by species, represented as the percentage of days each species was detected per month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort. Note the difference in scale for each species. For minke whales only, differences in presence should be interpreted with consideration of the shift from manual review to automated detection.

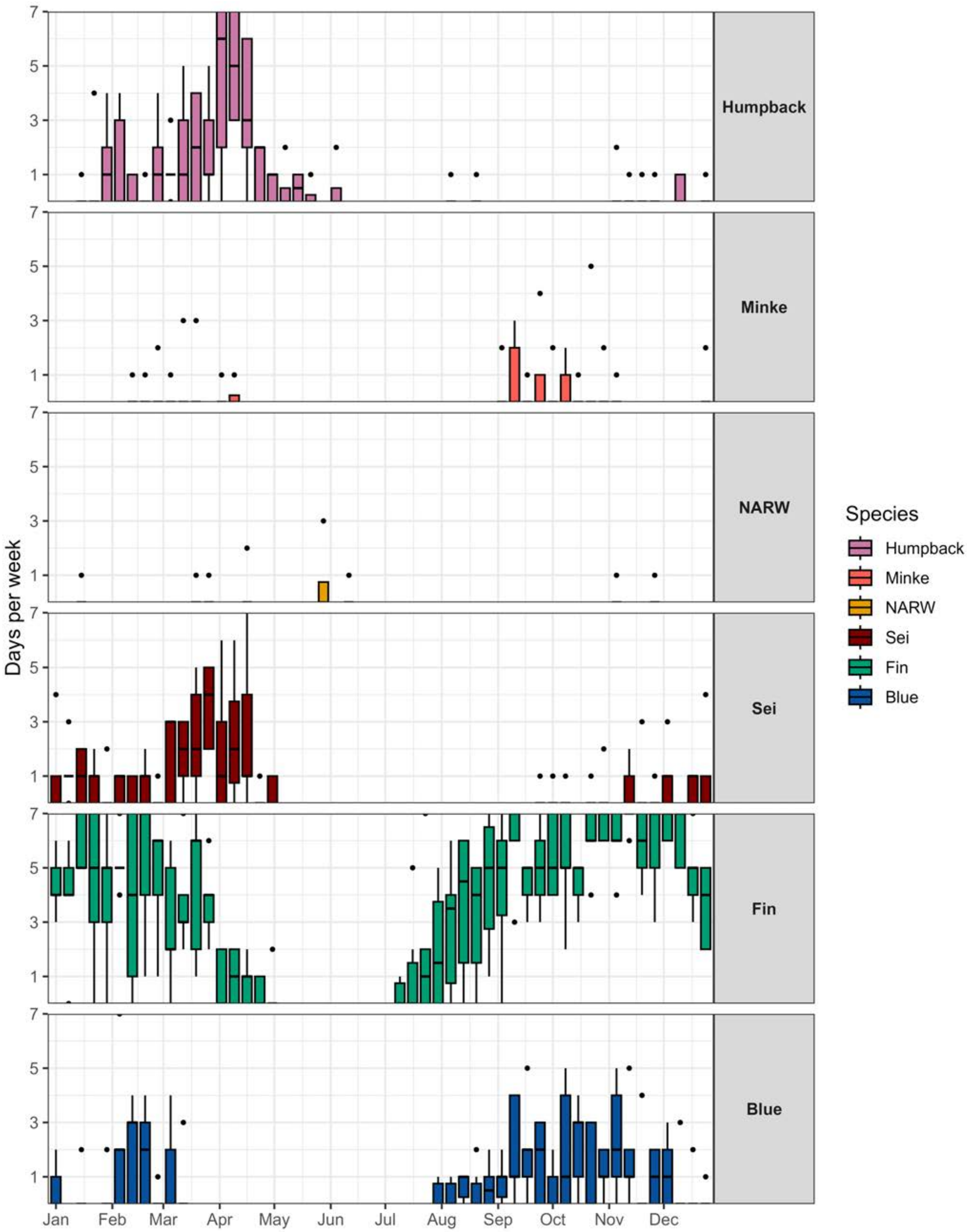

Figure 61: Average weekly acoustic presence (days per week) by species at NFC from 2014-2021. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.1 Humpback Whales

Humpback whale occurrence at NFC was seasonally concentrated and largely restricted to the late winter–spring period (Figure 62). Across recording years, detections were most frequent from February through May, with April showing the highest and most consistent levels of activity. During this core season, humpback whales were typically detected on 2–5 days per week, and in some years approached near-daily presence in April (Figure 63).

Outside of this seasonal window, detections were rare. Low-level presence occurred sporadically in June, August–September, and December, but these detections were limited to isolated days and did not form a sustained seasonal pattern.

Interannual variability was evident in the heatmap, with relatively strong April presence in 2017–2019 and broader winter–spring use in 2019–2020. Years with limited winter data coverage (e.g., 2015, parts of 2016, and 2021) showed correspondingly reduced detections. Despite this variability, the overall pattern indicates repeatable seasonal use of the NFC site during the northward spring migration, consistent with previous descriptions of broad-scale humpback whale movements along the U.S. East Coast (Davis et al. 2020), supporting the idea that the region lies along a migratory pathway.

Summary of Results – Humpback Whales

- Seasonal presence concentrated from February–May, with April consistently exhibiting the highest levels of occurrence.
- Weekly presence during the spring season commonly ranged from 2–5 days per week, occasionally approaching daily detections.
- Only sporadic detections occurred outside the core season (June, August, and November-January).
- Interannual variation was present, but the recurring spring peak suggests annual migratory use of the NFC region.

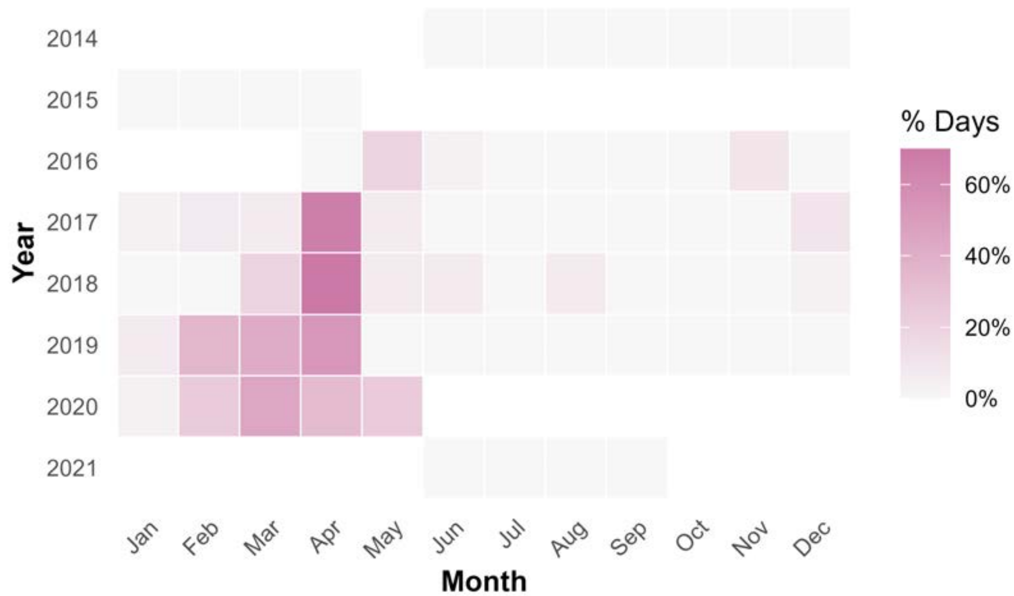

Figure 62: Annual monthly humpback whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort.

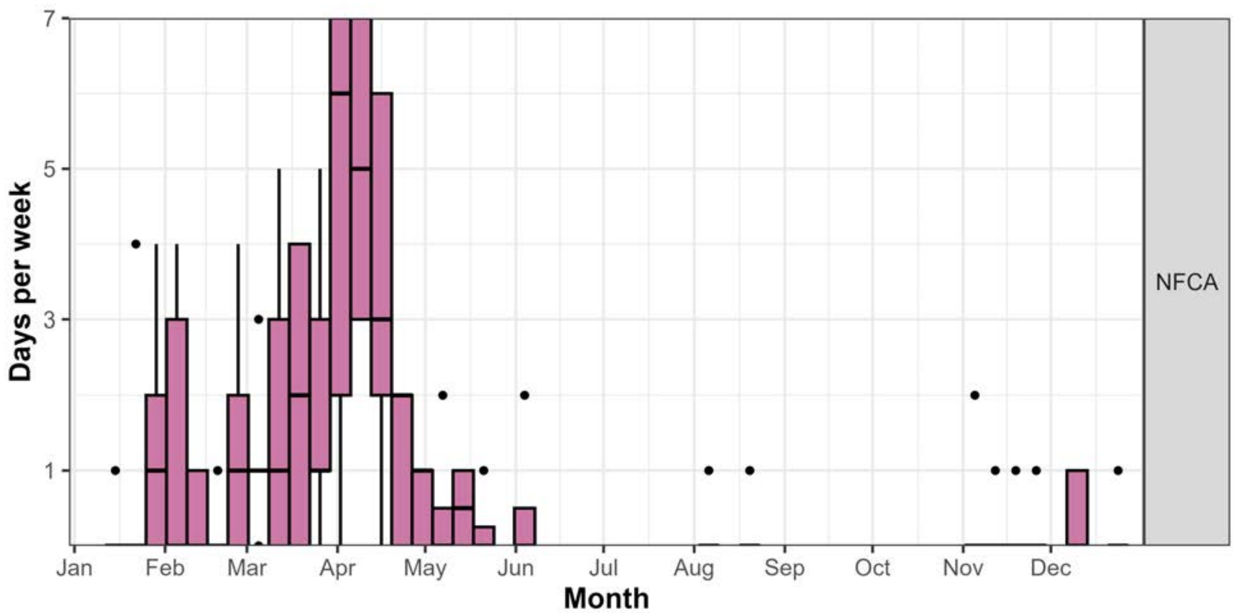

Figure 63: Average weekly acoustic presence of humpback whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.2 Minke Whales

Minke whale occurrence at NFC was low overall but exhibited a weakly bimodal seasonal pattern (Figures 64 & 65). The first peak occurred during the winter through early spring months, with intermittent detections from January through March. Presence during this period was limited, generally occurring on only a few days per week and not consistently observed every year. A second peak in detections occurred during the fall months, spanning September through November, with October showing the highest concentration of activity. As with the winter-spring period, fall detections were intermittent across years and did not form a prolonged seasonal presence.

This bimodal distribution may reflect migratory movements, with the winter-spring detections representing northbound travel along the shelf or slope and the fall detections corresponding to a southbound return migration. However, given the overall low occurrence and interannual inconsistency, this interpretation remains tentative.

Methodological differences introduced by the use of an automated detector after mid-2018 should be considered when interpreting interannual patterns.

Summary of Results – Minke Whales

- Low overall occurrence with a weakly bimodal seasonal pattern.
- January through March detections likely reflect intermittent winter through spring use, potentially associated with northbound migration.
- September through November detections, particularly in October, may reflect southbound migration through the region.
- Both seasonal peaks occurred irregularly across years and did not indicate sustained long-term presence.

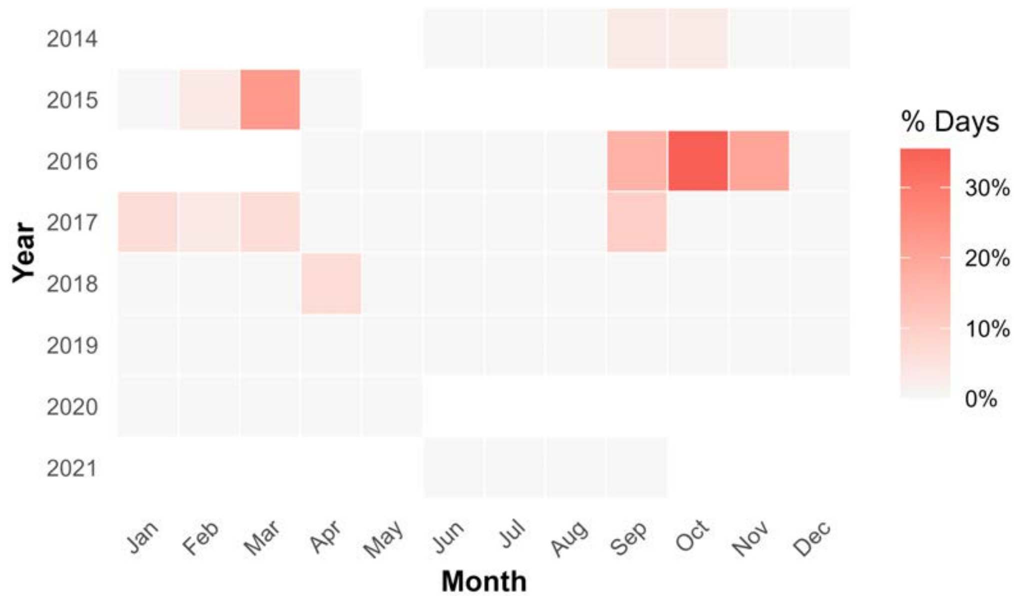

Figure 64: Annual monthly minke whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort. Manual and automated detection periods are shown together; differences between these approaches should be considered when interpreting changes in presence.

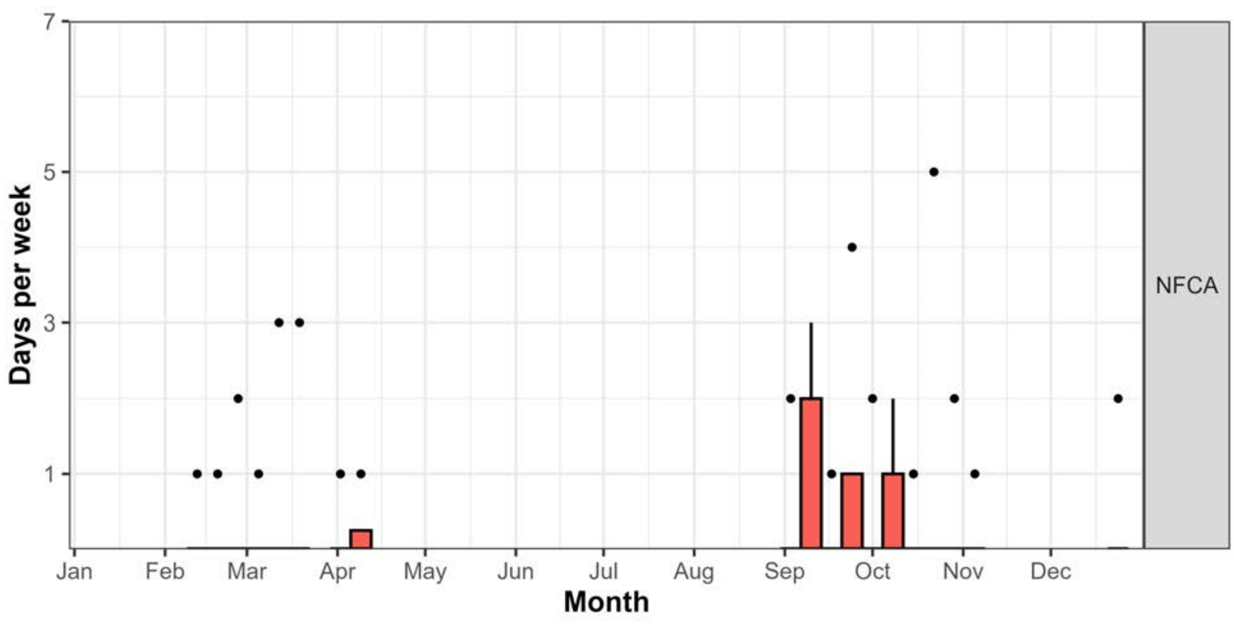

Figure 65: Average weekly acoustic presence of minke whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots). Differences between sites should be interpreted with consideration of the shift from manual review to automated detection.

5.2.3 Blue Whales

Blue whale occurrence at NFC was moderate and showed a clear seasonal pattern spanning both winter through spring and late summer through fall periods (Figures 66 & 67). Early-year detections were most common in February and March, with several years exhibiting presence on 2-4 days per week and occasional near-daily detections. These winter through spring detections were intermittent across years but formed a consistent seasonal window.

A second, more prolonged period of blue whale activity occurred from August through December. Within this period, detections peaked in September through November, with weekly presence frequently ranging from 2-4 days per week and occasionally reaching higher levels. This late-year aggregation appeared more sustained and regularly observed than the early-year detections.

Interannual variability was evident, with particularly strong fall presence in 2017 and 2019 and weaker activity in 2018. Despite these fluctuations, the recurring early-year and late-year peaks suggest that blue whales regularly transit or occupy the broader NFC region during multiple portions of the year, potentially reflecting different phases of seasonal movement or foraging use. The seasonal pattern observed here aligns with the broad distributional shifts and offshore movements described by (Davis et al. 2020), suggesting that individuals occasionally transit through this portion of the shelf break during migratory or foraging movements.

Summary of Results – Blue Whale

- Moderate occurrence with two main seasonal peaks.
- February through March detections formed a winter through spring presence window, occurring intermittently across years.
- August through December detections represented a more sustained late summer through fall presence, peaking in September through November.
- Weekly presence commonly ranged from 2-4 days, with some years showing higher activity.
- Interannual variation was present, but both seasonal peaks recurred across multiple years.

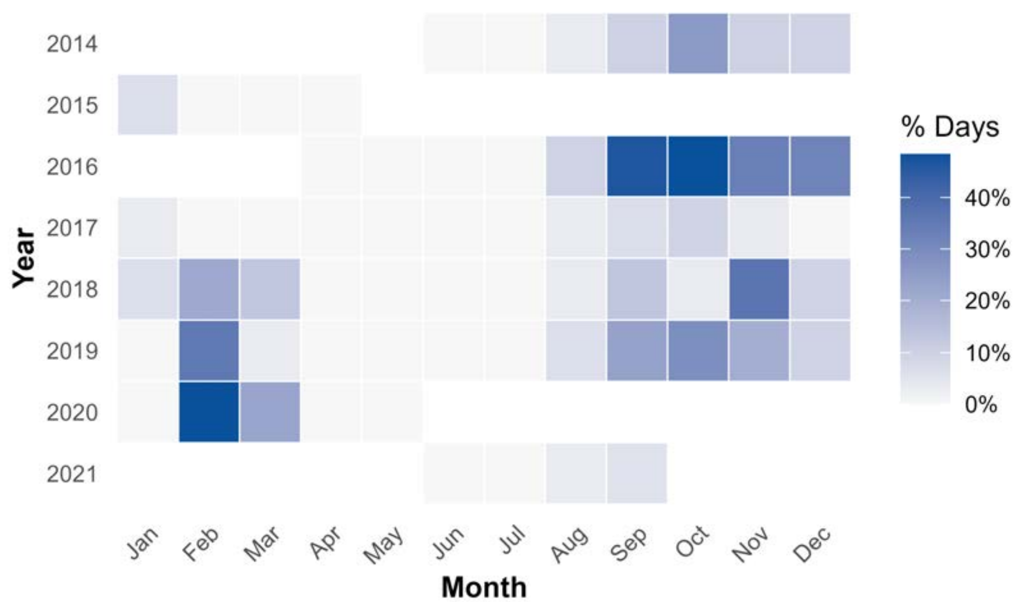

Figure 66: Annual monthly blue whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort.

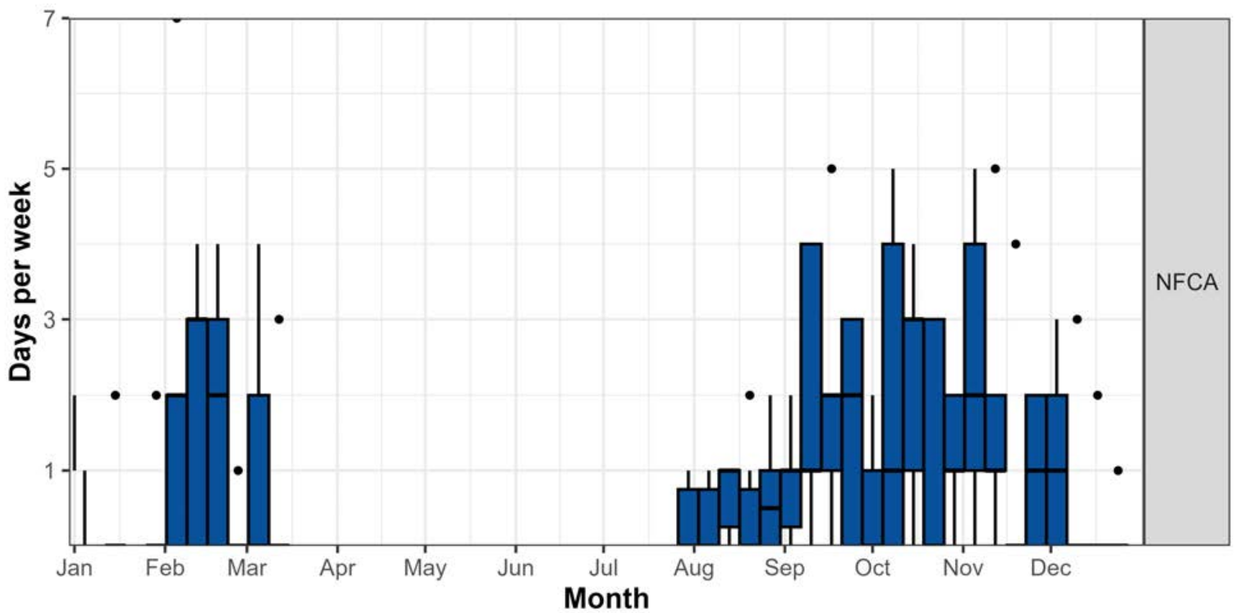

Figure 67: Average weekly acoustic presence of blue whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.4 Fin Whales

Fin whale occurrence at NFC was high, with detections in most months across the monitoring period (Figures 68 & 69). The primary seasonal peak extended from August through March, during which detections were frequent and often reached 4-7 days per week. This sustained period of activity indicates regular and repeated use of the region over much of the year. Detections were strongest from September through February, when many years showed presence on most days of the week.

Although interannual variability was present, such as stronger early-year detections in 2019-2020 and more moderate activity in 2017-2018, the overall seasonal pattern remained consistent. The extended period of fin whale activity from late summer through early spring is consistent with (Davis et al. 2020), who report regular seasonal movements and year-round habitat use along the U.S. East Coast, indicating that the NFC region may fall within a migratory or foraging corridor for this species.

Summary of Results – Fin Whale

- High occurrence with a clear seasonal peak from August through March.
- Strongest presence observed September through February, often on most days of the week.
- Weekly detections frequently reached 4-7 days per week, indicating sustained regional use.
- Seasonal pattern was consistent despite moderate interannual variation.

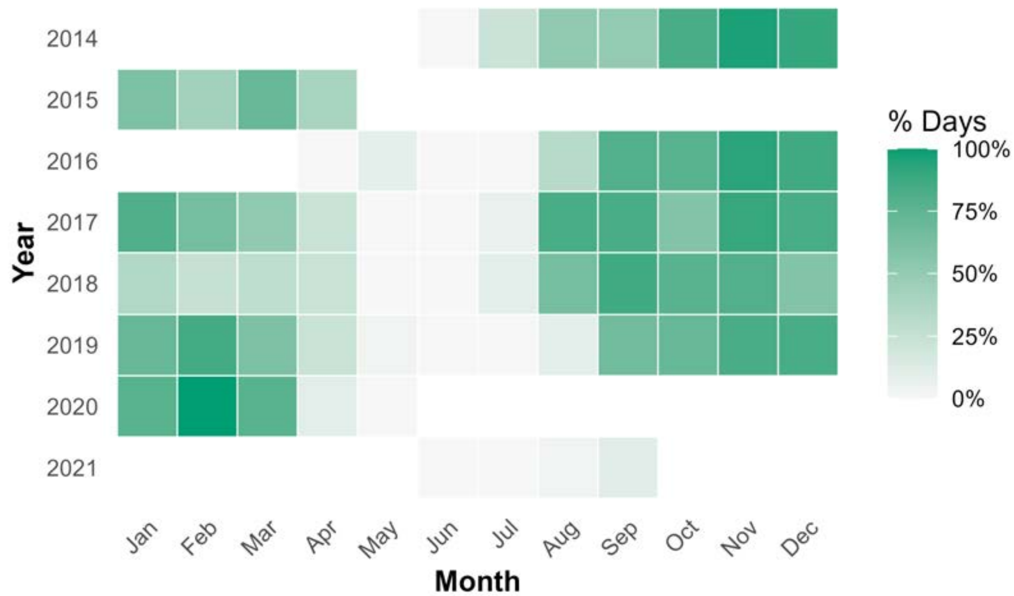

Figure 68: Annual monthly fin whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort.

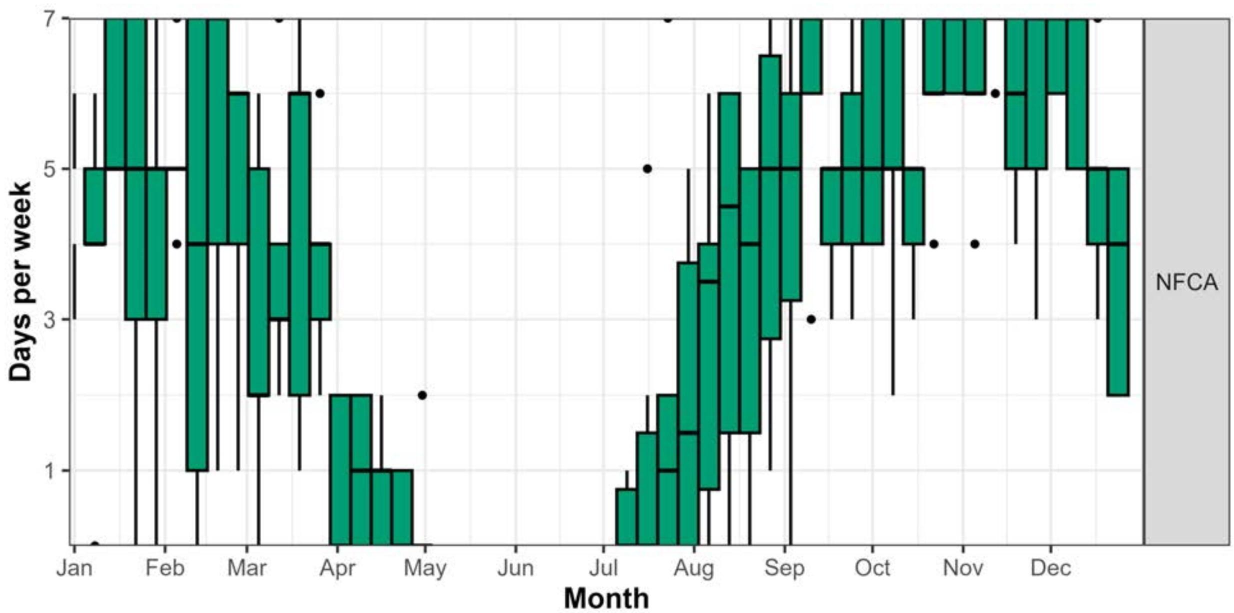

Figure 69: Average weekly acoustic presence of fin whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.5 Sei Whales

Sei whale occurrence at NFC showed substantial seasonal presence, with detections regularly occurring from November through May and reaching their highest levels in March through April (Figures 70 & 71). During these peak spring months, sei whales were frequently detected on multiple days per week, with 2017 and 2018 showing the strongest activity.

Detections in November through January were less frequent but appeared in several years, indicating early-season arrival to the region. Activity increased in February, leading into the pronounced peak in March through April, which was the most consistent feature across the time series. Presence declined in May, marking the end of their seasonal occurrence.

Interannual variability was evident, with strong peaks limited to select years. Even so, the repeated pattern of detections across late fall, winter, and early spring indicates that sei whales use the NFC area seasonally, with March through April representing their primary period of activity.

Summary of Results – Sei Whale

- Seasonal presence from November through May, recurring in multiple years.
- Peak detections in March through April, often occurring on several days per week.
- Early-season detections in November through January, increasing into February.
- Strong interannual variability but consistent seasonal timing when present.

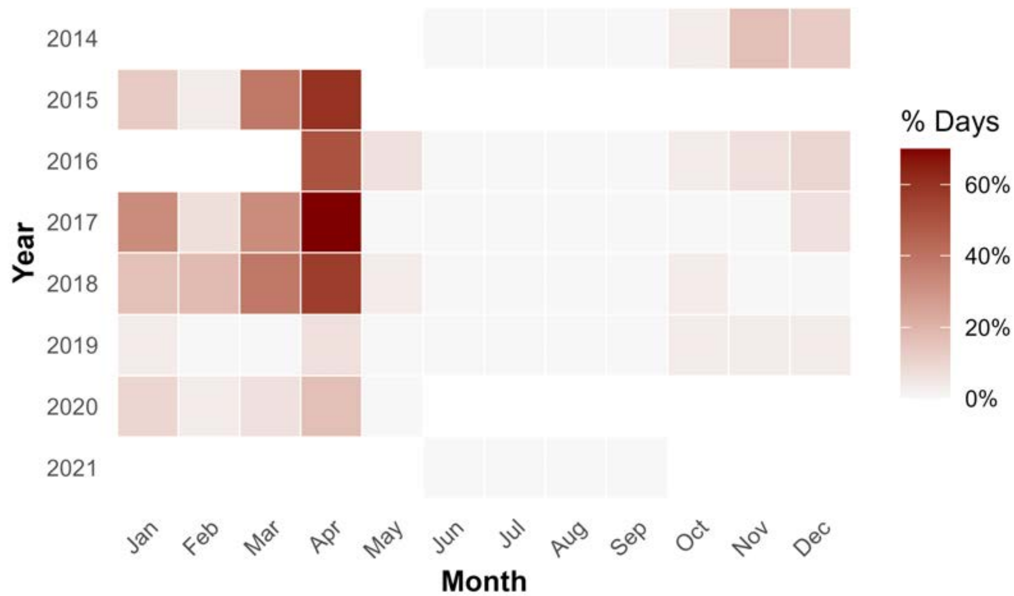

Figure 70: Annual monthly sei whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort.

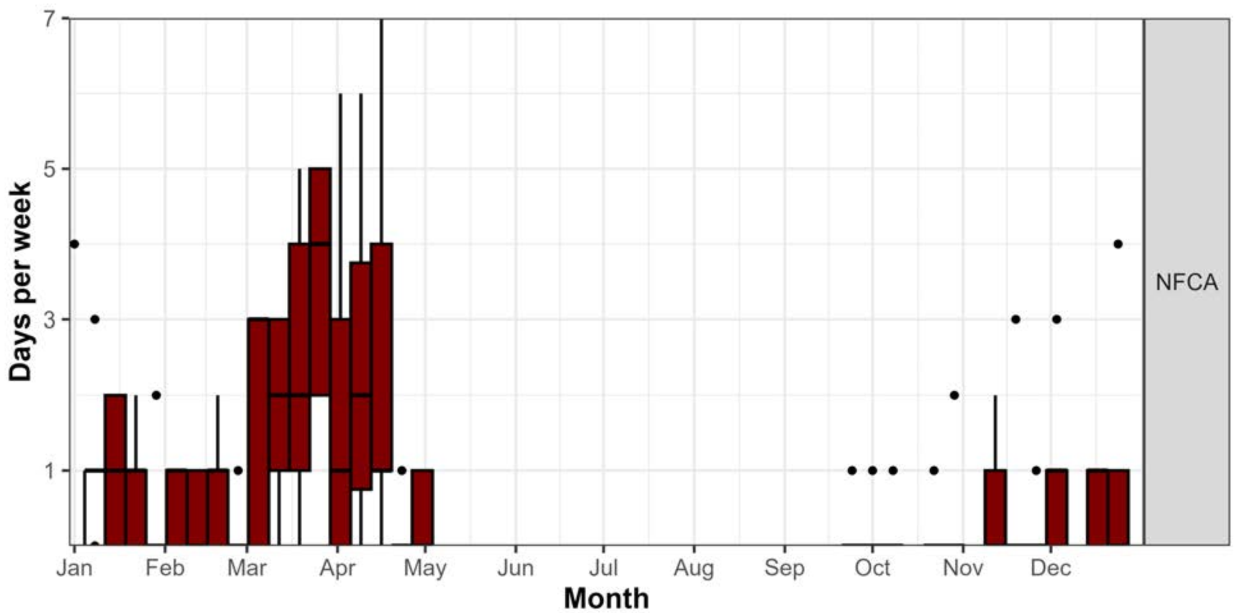

Figure 71: Average weekly acoustic presence of sei whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.6 North Atlantic Right Whales

North Atlantic right whale occurrence at NFC was extremely limited, with only a small number of isolated detections throughout the monitoring period (Figures 72 & 73). Presence did not follow any clear seasonal pattern and appeared in only a few scattered months across different years.

Detections included isolated events in February through April, occasional presence in June, and a small number of detections in November through December. In all cases, right whales were detected on only one or a few days per month, and weekly presence never exceeded 1-2 days. Many years showed no detections at all.

Overall, the low and irregular nature of detections at this site is consistent with occasional transits past the offshore recording location rather than regular seasonal use at this specific position. The recorder is situated offshore near the shelf break, whereas right whales are more commonly associated with mid-shelf habitats at this latitude. As such, these results likely reflect the spatial placement of the monitoring instrument and should not be interpreted as representative of right whale habitat use across the broader shelf. These scattered detections are consistent with the occasional broad-scale movements of right whales described by (Davis et al. 2020), and may reflect transient offshore movements during migration or movements between core habitats.

Summary of Results – North Atlantic Right Whale

- Extremely sparse and irregular occurrence at the offshore NFC HARP location.
- Scattered detections in February through April, June, and November through December, with no recurring seasonal pattern at this site.
- Weekly presence never exceeded 1-2 days.
- Many years showed no detections.
- Patterns likely reflect the offshore shelf-break position of the recorder and are consistent with occasional movement past this location rather than sustained use of this specific habitat.

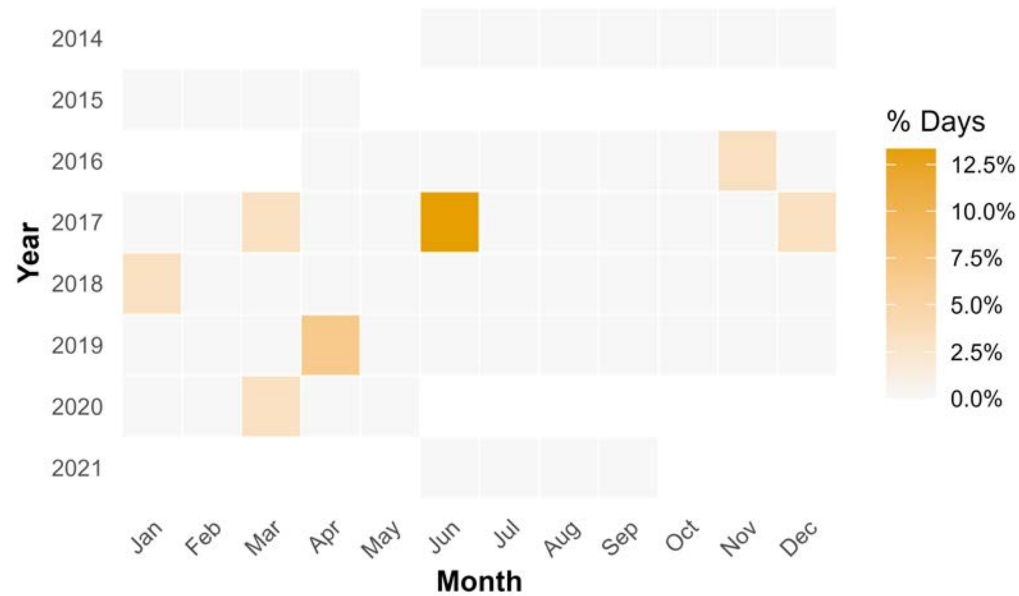

Figure 72: Annual monthly North Atlantic right whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. White spaces represent months with no effort.

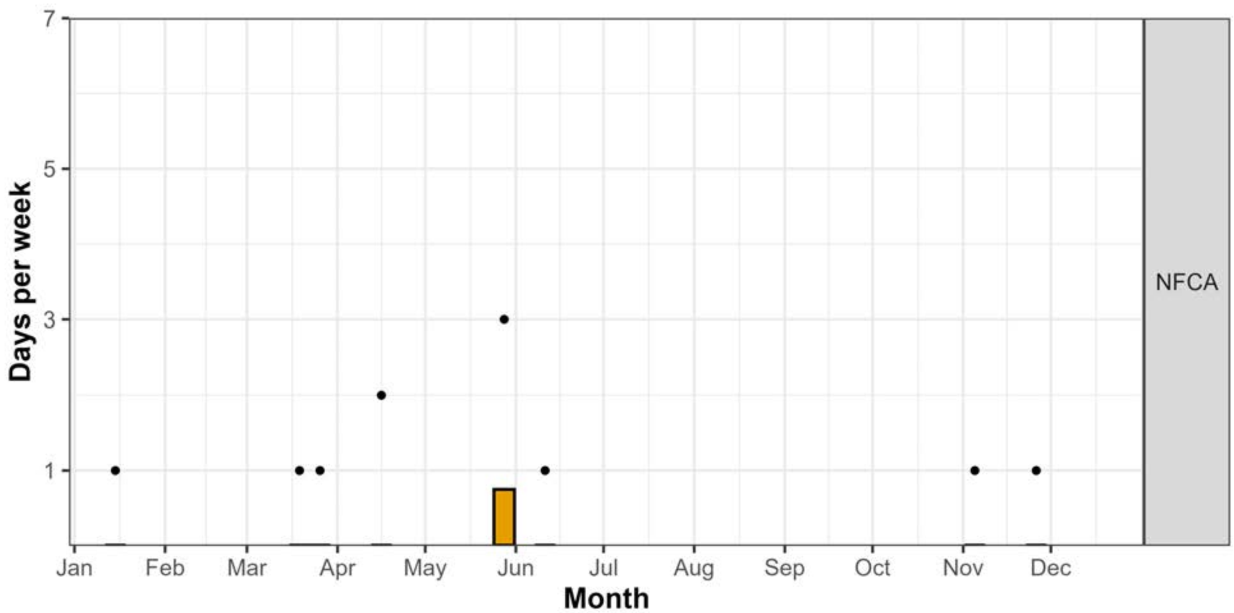

Figure 73: Average weekly acoustic presence of North Atlantic right whales (days per week) at NFC. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.3 Ambient Noise

Ambient sound levels at Norfolk Canyon between 2014 and 2021 exhibited temporal and spectral variability driven by biological, oceanographic, and anthropogenic sources. Long-term spectral averages indicated that background levels below 100 Hz were strongly influenced by shipping noise and seasonal mysticete presence, while higher frequencies showed elevated energy during winter months, likely due to increased sea state and wind activity.

Shipping noise consistently dominated the 30–60 Hz band with ambient sound levels of 80–85 dB re 1 μPa^2 / Hz and broad spectral peaks centered near 45 Hz. Shipping noise peaked in the winter and spring, with short-term variability likely due to changes in vessel traffic patterns and sea state conditions. The prominence of this band suggests persistent exposure to regional commercial shipping activity, potentially from basin-wide commercial shipping and traffic transiting the Gulf Stream or regional ports.

Spectral energy between 12–40 Hz showed seasonal enhancements attributable to increased seismic survey activity, particularly during spring and fall. These signals were intermittent yet detectable across multiple deployments, highlighting the potential for long-distance propagation of airgun pulses.

Biological contributions to the soundscape were also evident. Seasonal peaks at 20 Hz aligned with increased presence of fin whale vocalizations during winter and fall. Elevated spectral energy at approximately 120 Hz and 170 Hz occurred primarily during winter months and corresponded with minke whale pulse train detections, supporting the utility of these bands as biological indicators in long-term monitoring.

At higher frequencies (200–1000 Hz), seasonal increases in spectral levels during winter and fall months were attributed to increased surface wind and wave action.

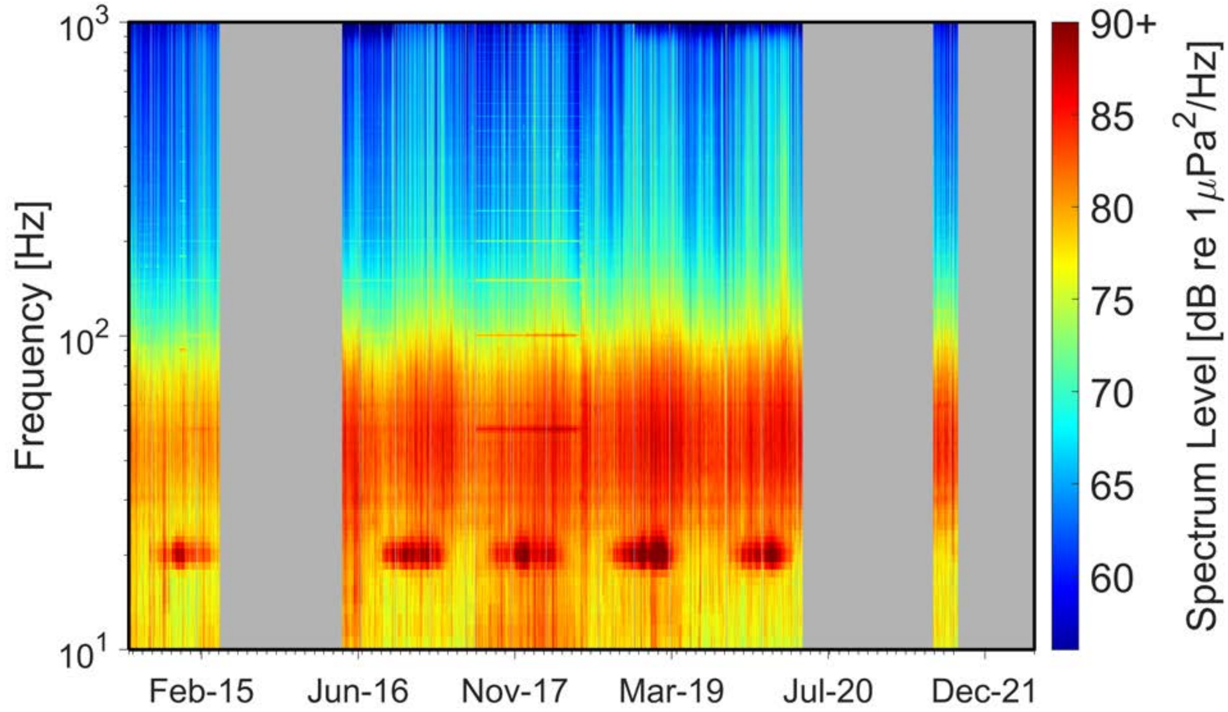

Figure 74: Long spectrograms using daily-averaged spectra for the Norfolk Canyon monitoring site from 2014 to 2021. Gray blocks represent periods with no effort.

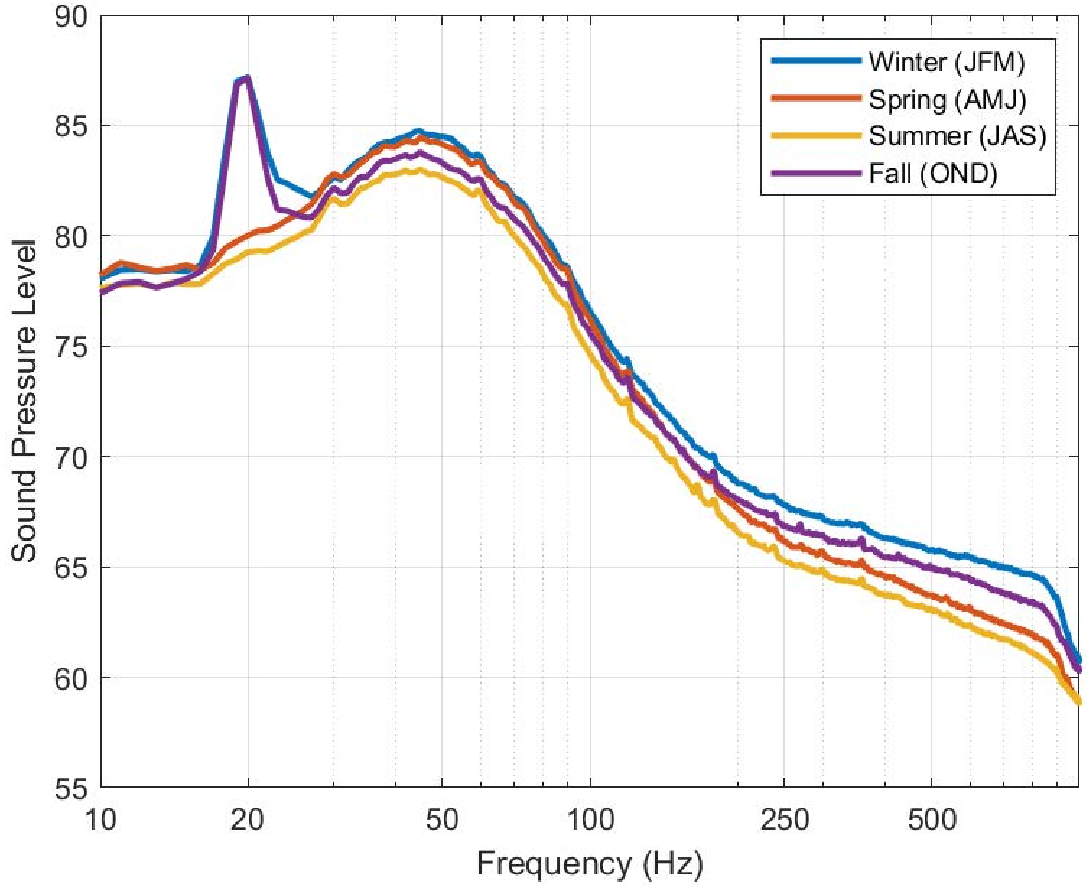

Figure 75: Full spectra averaged over each season for the Norfolk Canyon monitoring site from 2014 to 2021. Winter is represented by January, February March; spring as April, May, June; summer as July, August, September; and fall as October, November, and December.

6 Applications of this Dataset

6.1 Publications

- Baumann-Pickering, S., Trickey, J.S., Solsona-Berga, A., Rice, A., Oleson, E.M., Hildebrand, J.A. and Frasier, K.E., 2023. Geographic differences in Blainville's beaked whale (*Mesoplodon densirostris*) echolocation clicks. *Diversity and Distributions*, 29(4), pp.478-491.
- 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. *The Journal of the Acoustical Society of America*, 134(5), pp.3905-3912.
- Cohen, R.E., Frasier, K.E., Baumann-Pickering, S., Wiggins, S.M., Rafter, M.A., Baggett, L.M. and Hildebrand, J.A., 2022. Identification of western North Atlantic odontocete echolocation click types using machine learning and spatiotemporal correlates. *PLoS ONE*, 17(3), p.e0264988.
- Cohen, R.E., Frasier, K.E., Baumann-Pickering, S. and Hildebrand, J.A., 2023. Spatial and temporal separation of toothed whales in the western North Atlantic. *Marine Ecology Progress Series*, 720, pp.1-24.
- Davis, G.E., Baumgartner, M.F., Bonnell, J.M., Bell, J., Berchok, C., Bort Thornton, J., Brault, S., Buchanan, G., Charif, R.A., Cholewiak, D. and Clark, C.W., 2017. Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific Reports*, 7(1), p.13460.
- Davis, G.E., Baumgartner, M.F., Corkeron, P.J., Bell, J., Berchok, C., Bonnell, J.M., Bort Thornton, J., Brault, S., Buchanan, G.A., Cholewiak, D.M. and Clark, C.W., 2020. Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology*, 26(9), pp.4812-4840.
- DeAngelis, A.I., Westell, A., Baumann-Pickering, S., Bell, J., Cholewiak, D., Corkeron, P.J., Soldevilla, M.S., Solsona-Berga, A., Trickey, J.S. and Van Parijs, S.M., 2025. Habitat utilization by beaked whales in the western North Atlantic Ocean using passive acoustics. *Marine Ecology Progress Series*, 754, pp.137-153.
- Engelhaupt, D.T., Pusser, T., Aschettino, J.M., Engelhaupt, A.G., Cotter, M.P., Richlen, M.F. and Bell, J.T., 2020. Blue whale (*Balaenoptera musculus*) sightings off the coast of Virginia. *Marine Biodiversity Records*, 13(1), p.6.
- Haver, S., Corkeron, P., DeAngelis, A., Baumann-Pickering, S., Cholewiak, D., Davis, G., Frasier, K., Posdaljian, N., Kadifa, M., Solsona-Berga, A. and Westell, A., 2025. Exploring the biodiversity of cetacean communities along the western North Atlantic Ocean shelf-break. *Royal Society Open Science*, 12(7), p.241658.
- Hodge, L.E., Baumann-Pickering, S., Hildebrand, J.A., Bell, J.T., Cummings, E.W., Foley, H.J., McAlarney, R.J., McLellan, W.A., Pabst, D.A., Swaim, Z.T. and Waples, D.M., 2018. Heard but not seen: occurrence of *Kogia* spp. along the western North Atlantic shelf

break. *Marine Mammal Science*, 34(4), pp.1141-1153.

- Solsona-Berga, A., DeAngelis, A.I., Cholewiak, D.M., Trickey, J.S., Mueller-Brennan, L., Frasier, K.E., Van Parijs, S.M. and Baumann-Pickering, S., 2024. Machine learning with taxonomic family delimitation aids in the classification of ephemeral beaked whale events in passive acoustic monitoring. *PLoS ONE*, 19(6), p.e0304744.
- Stanistreet, J.E., Nowacek, D.P., Baumann-Pickering, S., Bell, J.T., Cholewiak, D.M., Hildebrand, J.A., Hodge, L.E., Moors-Murphy, H.B., Van Parijs, S.M. and Read, A.J., 2017. Using passive acoustic monitoring to document the distribution of beaked whale species in the western North Atlantic Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, 74(12), pp.2098-2109.
- Stanistreet, J.E., Nowacek, D.P., Bell, J.T., Cholewiak, D.M., Hildebrand, J.A., Hodge, L.E., Van Parijs, S.M. and Read, A.J., 2018. Spatial and seasonal patterns in acoustic detections of sperm whales *Physeter macrocephalus* along the continental slope in the western North Atlantic Ocean. *Endangered Species Research*, 35, pp.1-13.
- Stanistreet, J.E., Nowacek, D.P., Read, A.J., Baumann-Pickering, S., Moors-Murphy, H.B. and Van Parijs, S.M., 2016. Effects of duty-cycled passive acoustic recordings on detecting the presence of beaked whales in the northwest Atlantic. *The Journal of the Acoustical Society of America*, 140(1), pp.EL31-EL37.

6.2 Theses

- Cohen, R.E., 2022. Clicks and Currents: Leveraging Passive Acoustic Data to Gain Fundamental Insights into Toothed Whale Ecology in the Western North Atlantic. University of California, San Diego.
- Hodge, L.E.W., 2011. Monitoring marine mammals in Onslow Bay, North Carolina, using passive acoustics. Doctoral dissertation, Duke University.
- Posdaljian, N., 2023. A deep dive into sperm whale ecology using passive acoustic monitoring. University of California, San Diego.
- Stanistreet, J.E., 2017. Ecology of Beaked Whales and Sperm Whales in the Western North Atlantic Ocean: Insights from Passive Acoustic Monitoring. Doctoral dissertation, Duke University.

7 Acknowledgments

This project used data collected through collaborations between the Marine Bioacoustics Research Collective (MBARC), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Navy. We are grateful to Sofie Van Parijs and Danielle Cholewiak (NOAA Northeast Fisheries Science Center, NEFSC), Joel Bell (Naval Facilities Engineering Systems Command, NAVFAC Atlantic), Michael Richlen (HDR), and Andrew Read (Duke University) for project support and sampling-design development. We also thank Eric Matzen (NEFSC) and the crew of the Tiki XIV—Drexel "Stormy" Harrington, Drex Harrington, and Bev Harrington—for fieldwork support enabling instrument deployment and recovery. For acoustic instrument development, testing, deployment, and recovery, we thank Bruce Thayre, John Hurwitz, Jennifer Trickey, Ryan Griswold, Chris Garsha, Tim Boynton, Lynne E. W. Hodge, Zach Swaim, Joy E. Stanistreet, Tim Christianson, Frank Chang, and Kieran Lenssen. We are grateful to Erin O'Neill, Diego Majewski, and Shelby Bloom for data preprocessing and quality control. We also thank colleagues who contributed to data analysis, instrument development, and software: Amanda J. Debich, Simone Baumann-Pickering, Ana Širović, Hana Koilpillai, Sara M. Kerosky, Lauren K. Roche, Sarah C. Johnson, Rachel S. Gottlieb, Zoe E. Gentes, Sean M. Wiggins, John A. Hildebrand, Jasmine S. Buccowich, Alexa L. Alldredge, Sean T. Herbert, Ally C. Rice, Leah M. Varga, Arial M. Brewer, Rohen T. Gresalfi, Macey Kadifa, Melissa Soldevilla, Rebecca Cohen, Emily Reagan, McKenna Merrifield, and Alba Solsona Berga.

8 Funding Sources

This project is funded by U.S. Fleet Forces Command and managed by Naval Facilities Engineering Systems Command Atlantic as part of the U.S. Navy's Marine Species Monitoring Program.

References

Aschettino, Joseph M, David T Engelhaupt, Angela G Engelhaupt, Andrew DiMatteo, Timothy Pusser, Michael F Richlen, and Jessica T Bell (2020). “Satellite telemetry reveals spatial overlap between vessel high-traffic areas and humpback whales (Megaptera novaeangliae) near the mouth of the Chesapeake Bay”. In: *Frontiers in Marine Science* 7, p. 121.

Au, Whitlow WL (1993). *The sonar of dolphins*. Springer Science & Business Media.

Backus, Richard H. and William E. Schevill (1966). “Physeter clicks”. In: *Whales, Dolphins and Porpoises*. Ed. by Kenneth S. Norris. Berkeley, CA: University of California Press, pp. 510–527.

Baumann-Pickering, Simone, Mark A McDonald, Anne E Simonis, Alba Solsona Berga, Karlina PB Merkens, Erin M Oleson, Marie A Roch, Sean M Wiggins, Shannon Rankin, Tina M Yack, et al. (2013). “Species-specific beaked whale echolocation signals”. In: *The Journal of the Acoustical Society of America* 134.3, pp. 2293–2301.

Baumann-Pickering, Simone, Marie A Roch, Robert L Brownell Jr, Anne E Simonis, Mark A McDonald, Alba Solsona-Berga, Erin M Oleson, Sean M Wiggins, and John A Hildebrand (2014). “Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific”. In: *PloS one* 9.1, e86072.

Baumgartner, Mark F, David M Fratantoni, Timothy P Hurst, Michael W Brown, Thomas V N Cole, Mark Johnson, Scott D Kraus, Jim Partan, Lisa P Pelletier, and A Selina M Vanderlaan (2013). “Real-time reporting of baleen whale passive acoustic detections from ocean gliders”. In: *The Journal of the Acoustical Society of America* 134.3, pp. 1814–1823.

Baumgartner, Mark F and Stephanie E Mussoline (2011). “A generalized baleen whale call detection and classification system”. In: *The Journal of the Acoustical Society of America* 129.5, pp. 2889–2902.

Baumgartner, Mark F. and David M. Fratantoni (2008). “Diel periodicity in both sei whale vocalization rates and the vertical migration of their copepod prey observed from ocean gliders”. In: *Limnology and Oceanography* 53.5, pp. 2197–2209.

Baumgartner, Mark F., Sofie M. Van Parijs, Frederick W. Wenzel, Christopher J. Tremblay, Hilary C. Esch, and Andrew M. Warde (2008). “Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*)”. In: *The Journal of the Acoustical Society of America* 124.2, pp. 1339–1349.

Bonnell, Jennifer M, Sofie M Van Parijs, and Phillip J Clapham (2016). “Using ship-based passive acoustic monitoring to estimate cetacean density and distribution”. In: *Marine Mammal Science* 32.4, pp. 1329–1359.

Clapham, P.J. and J.G. Mead (1999). “Megaptera novaeangliae”. In: *Mammalian Species* 604, pp. 1–9.

Clark, C.W. and G.C. Gagnon (2004). “Low-frequency vocal behaviors of baleen whales in the North Atlantic: Insights from integrated undersea surveillance system detections, locations, and tracking from 1992 to 1996”. In: *The Journal of the Acoustical Society of America* 117.4, pp. 2618–2628.

Clarke, Elizabeth, Laura J. Feyrer, Hilary Moors-Murphy, and Jamie Stanistreet (2019). “Click characteristics of northern bottlenose whales (Hyperoodon ampullatus) and Sowerby’s beaked whales (Mesoplodon bidens) off eastern Canada”. In: *The Journal of the Acoustical Society of America* 146.1, pp. 307–315.

Cohen, R.E., K.E. Frasier, J.E. Stanistreet, S.M. Wiggins, J.A. Hildebrand, and S. Baumann-Pickering (2023). “Spatiotemporal patterns of beaked whale occurrence along the western North Atlantic continental slope”. In: *Marine Mammal Science* 39.2, pp. 456–478.

Cohen, Rebecca E, Kaitlin E Frasier, Simone Baumann-Pickering, Sean M Wiggins, Macey A Rafter, Lauren M Baggett, and John A Hildebrand (2022). “Identification of western North Atlantic odontocete echolocation click types using machine learning and spatiotemporal correlates”. In: *PloS one* 17.3, e0264988.

Davis, Genevieve E, Mark F Baumgartner, Peter J Corkeron, Julianne Bell, Catherine Berchok, Jason Bort Thornton, Solange Brault, Gretchen Buchanan, Robert A Charif, Danielle Cholewiak, et al. (2017). “Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (Eubalaena glacialis) in the western North Atlantic”. In: *Scientific Reports* 7.1, p. 13460.

Davis, Genevieve E, Joy E Stanistreet, Mark F Baumgartner, Peter J Corkeron, Catherine L Berchok, Jason Bort Thornton, Solange Brault, Robert A Charif, Danielle Cholewiak, et al. (2020). “Exploring movement and habitat use of baleen whales in the western North Atlantic using passive acoustic monitoring”. In: *Ecological Indicators* 110, p. 105869.

DeAngelis, Annamaria I., Annabel Westell, Simone Baumann-Pickering, Joel Bell, Danielle Cholewiak, Peter J. Corkeron, Melissa S. Soldevilla, Alba Solsona-Berga, Jennifer S. Trickey, and Sofie M. Van Parijs (2025). “Habitat utilization by beaked whales in the western North Atlantic Ocean using passive acoustics”. In: *Marine Ecology Progress Series* 754, pp. 137–153. DOI: 10.3354/meps14771.

DeAngelis, Annamaria Izzi, Simone Baumann-Pickering, Jennifer S. Trickey, Nina D. Shapiro, Karl P. Merkens, Sean M. Wiggins, and John A. Hildebrand (2018). “A description of echolocation clicks recorded in the presence of True’s beaked whale (*Mesoplodon mirus*)”. In: *The Journal of the Acoustical Society of America* 144.5, pp. 2691–2700.

Dunlop, Rebecca A., Michael J. Noad, Douglas H. Cato, and David Stokes (2007). “The social vocalization repertoire of east Australian migrating humpback whales (*Megaptera novaeangliae*)”. In: *The Journal of the Acoustical Society of America* 122.5, pp. 2893–2905.

Frasier, Kaitlin E, Marie A Roch, Melissa S Soldevilla, Sean M Wiggins, Lance P Garrison, and John A Hildebrand (2017). “Automated classification of dolphin echolocation click types from the Gulf of Mexico”. In: *PLoS computational biology* 13.12, e1005823.

Frasier, Kaitlin E, Sean M Wiggins, Danielle Harris, Tiago A Marques, Len Thomas, and John A Hildebrand (2016). “Delphinid echolocation click detection probability on near-seafloor sensors”. In: *The Journal of the Acoustical Society of America* 140.3, pp. 1918–1930.

Frasier, Katlin E. (2021). “A machine learning pipeline for classification of cetacean echolocation clicks in large underwater acoustic datasets”. In: *PLoS Computational Biology* 17.12.

Gillespie, Douglas, Charlotte Dunn, Jonathan Gordon, Diane Claridge, Clare Embling, and Ian Boyd (2009). "Field recordings of Gervais' beaked whales Mesoplodon europaeus from the Bahamas". In: *The Journal of the Acoustical Society of America* 125.5, pp. 3428–3433.
Goold, John C and Sarah E Jones (1995). "Time and frequency domain characteristics of sperm whale clicks". In: *The Journal of the Acoustical Society of America* 98.3, pp. 1279–1291.
Hain, J.H.W., M.J. Ratnaswamy, R.D. Kenney, and H.E. Winn (1992). "The fin whale, *Balaenoptera physalus*, in waters of the northeastern United States continental shelf". In: *Reports of the International Whaling Commission* 42, pp. 653–669.
Haver, S.M., H. Klinck, S.L. Nieukirk, H. Matsumoto, R.P. Dziak, and J.L. Miksis-Olds (2025). "Exploring the biodiversity of cetacean communities along the western North Atlantic Ocean shelf break". In: *Deep Sea Research Part I: Oceanographic Research Papers* 169, p. 103474.
Helble, T. A., G. R. Ierley, G. L. D'Spain, M. A. Roch, and J. A. Hildebrand (2012). "A generalized power-law detection algorithm for humpback whale vocalizations". In: *The Journal of the Acoustical Society of America* 131.4, pp. 2682–2699.
Hildebrand, John A, Simone Baumann-Pickering, Kaitlin E Frasier, Jennifer S Trickey, Karlina P Merkens, Sean M Wiggins, Mark A McDonald, Lance P Garrison, Danielle Harris, Tiago A Marques, et al. (2015). "Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico". In: *Scientific reports* 5.1, pp. 1–15.
Johnson, Mark, Peter T Madsen, Walter MX Zimmer, Natacha Aguilar de Soto, and Peter L Tyack (2004). "Beaked whales echolocate on prey". In: *Proceedings of the Royal Society of London. Series B: Biological Sciences* 271.suppl_6, S383–S386.
Kennedy, A.S., A.N. Zerbini, O.V. Vásquez, N. Gandilhon, P.J. Clapham, and O. Adam (2014). "Local and migratory movements of humpback whales (*Megaptera novaeangliae*) satellite-tracked in the North Atlantic Ocean". In: *Canadian Journal of Zoology* 92.1, pp. 9–18.
Kenney, R.D. and H.E. Winn (2001). "Cetaceans in the Great South Channel, 1979–1989: right whale (*Eubalaena glacialis*) and minke whale (*Balaenoptera acutorostrata*) distributions". In: *The Right Whale: Balaena glacialis*. Ed. by J.H.W. Hain. Special Issue of the Journal of Cetacean Research and Management, pp. 231–241.
Lesage, V., K. Gavrilchuk, R.D. Andrews, and R. Sears (2017). "Foraging areas, migratory movements and winter destinations of blue whales from the western North Atlantic". In: *Endangered Species Research* 34, pp. 27–43.
Leu, Amanda A, John A Hildebrand, Ally Rice, Simone Baumann-Pickering, and Kaitlin E Frasier (2022). "Echolocation click discrimination for three killer whale ecotypes in the Northeastern Pacific". In: *The Journal of the Acoustical Society of America* 151.5, pp. 3197–3206.
Madsen, PT, R Payne, NU Kristiansen, M Wahlberg, I Kerr, and B Møhl (2002). "Sperm whale sound production studied with ultrasound time/depth-recording tags". In: *Journal of Experimental Biology* 205.13, pp. 1899–1906.

McDonald, Mark A., John A. Hildebrand, and Stephen C. Webb (1995). “Blue and fin whales observed on a seafloor array in the Northeast Pacific”. In: *The Journal of the Acoustical Society of America* 98.2, pp. 712–721.
Mellinger, David K. and Christopher W. Clark (2000). “Recognizing transient low-frequency whale sounds by spectrogram correlation”. In: *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pp. 3573–3576.
– (2003). “Blue whale (Balaenoptera musculus) sounds from the North Atlantic”. In: *The Journal of the Acoustical Society of America* 114.2, pp. 1108–1119.
Mitchell, E.D. (1991). “Winter records of the minke whale (*Balaenoptera acutorostrata*) in the southern North Atlantic”. In: *Cetaceans and Cetacean Research in the North Atlantic*. Ed. by G.P. Donovan. International Whaling Commission, pp. 124–138.
Møhl, Bertel, Magnus Wahlberg, Peter T Madsen, Anders Heerfordt, and Anders Lund (2003). “The monopulsed nature of sperm whale clicks”. In: *The Journal of the Acoustical Society of America* 114.2, pp. 1143–1154.
Morano, J.L., D.P. Salisbury, A.N. Rice, K.L. Conklin, K.L. Falk, and C.W. Clark (2012). “Seasonal and geographical patterns of fin whale song in the western North Atlantic Ocean”. In: *The Journal of the Acoustical Society of America* 132.2, pp. 1207–1212.
Mouy, Xavier, Thomas Awbery, Genevieve Davis, Olivia Fernandez-Betelu, Valeria Iorio-Merlo, Laura Transue, Sofie Van Parijs, and Denise Risch (2025). *North Atlantic minke whale pulse-train detector (Version 20240829)*. Zenodo. DOI: `10.5281/zenodo.15151160`. URL: `https://doi.org/10.5281/zenodo.15151160`.
Muirhead, C.A., A.M. Warde, I.S. Biedron, A.N. Mihnovets, C.W. Clark, and A.N. Rice (2018). “Seasonal acoustic occurrence of blue, fin, and North Atlantic right whales in the New York Bight”. In: *Aquatic Conservation: Marine and Freshwater Ecosystems* 28.3, pp. 744–753.
Nieukirk, S.L., K.M. Stafford, D.K. Mellinger, R.P. Dziak, and C.G. Fox (2004). “Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean”. In: *The Journal of the Acoustical Society of America* 115.4, pp. 1832–1843.
Norris, Kenneth S. and George W. Harvey (1972). *A Theory for the Function of the Spermaceti Organ of the Sperm Whale (Physeter catodon L.)* Tech. rep. CONTRIB-74. San Diego, CA: Naval Undersea Research and Development Center.
Parks, Susan E. and Peter L. Tyack (2005). “Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups”. In: *The Journal of the Acoustical Society of America* 117.5, pp. 3297–3306.
Payne, P.M., J.R. Nicolas, L. O’Brien, and K.D. Powers (1990). “The distribution of the humpback whale, *Megaptera novaeangliae*, on Georges Bank and in the Gulf of Maine in relation to densities of the sand eel, *Ammodytes americanus*”. In: *Fishery Bulletin* 88, pp. 687–696.
Payne, Roger and Scott McVay (1971). “Songs of humpback whales”. In: *Science* 173.3997, pp. 585–597.
Record, N.R., J.A. Runge, D.E. Pendleton, W.M. Balch, K.T. Davies, A.J. Pershing, C.L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S.D. Kraus, R.D. Kenney, C.A. Hudak, C.A. Mayo, C. Chen, J.E. Salisbury, and C. Thompson (2019). “Rapid climate-driven circulation changes

threaten conservation of endangered North Atlantic right whales”. In: *Oceanography* 32.2, pp. 162–169.
Risch, Denise, Christopher W. Clark, Patrick J. Dugan, Mihaela Popescu, Ursula Siebert, and Sofie M. Van Parijs (2013). “Minke whale acoustic behavior and multi-year seasonal and diel vocalization patterns in Massachusetts Bay, USA”. In: *Marine Ecology Progress Series* 489, pp. 279–295.
Roch, Marie A, Holger Klinck, Simone Baumann-Pickering, David K Mellinger, Simon Qui, Melissa S Soldevilla, and John A Hildebrand (2011). “Classification of echolocation clicks from odontocetes in the Southern California Bight”. In: *The Journal of the Acoustical Society of America* 129.1, pp. 467–475.
Roch, Marie A., J. Stinner-Sloan, S. Baumann-Pickering, and S. M. Wiggins (2015). “Compensating for the effects of site and equipment variation on delphinid species identification from their echolocation clicks”. In: *The Journal of the Acoustical Society of America* 137.1, pp. 22–29.
Smith, T.D., J. Allen, P.J. Clapham, P.S. Hammond, S. Katona, F. Larsen, J. Lien, D.K. Mattila, P.J. Palsbøll, J. Sigurjónsson, P.T. Stevick, and N. Øien (1999). “An ocean-basin-wide mark–recapture study of the North Atlantic humpback whale (*Megaptera novaeangliae*)”. In: *Marine Mammal Science* 15.1, pp. 1–32.
Soldevilla, Melissa S, Simone Baumann-Pickering, Danielle Cholewiak, Lynne EW Hodge, Erin M Oleson, and Shannon Rankin (2017). “Geographic variation in Risso’s dolphin echolocation click spectra”. In: *The Journal of the Acoustical Society of America* 142.2, pp. 599–617.
Solsona-Berga, Alba, Annamaria I DeAngelis, Danielle M Cholewiak, Jennifer S Trickey, Liam Mueller-Brennan, Kaitlin E Frasier, Sofie M Van Parijs, and Simone Baumann-Pickering (2024). “Machine learning with taxonomic family delimitation aids in the classification of ephemeral beaked whale events in passive acoustic monitoring”. In: *PLoS One* 19.6, e0304744.
Solsona-Berga, Alba, Kaitlin E Frasier, Simone Baumann-Pickering, Sean M Wiggins, and John A Hildebrand (2020). “DetEdit: A graphical user interface for annotating and editing events detected in long-term acoustic monitoring data”. In: *PLoS computational biology* 16.1, e1007598.
Solsona-Berga, Alba, Natalie Posdaljian, John A Hildebrand, and Simone Baumann-Pickering (2022). “Echolocation repetition rate as a proxy to monitor population structure and dynamics of sperm whales”. In: *Remote Sensing in Ecology and Conservation*.
Stanistreet, J.E., K.E. Frasier, S. Baumann-Pickering, J.S. Trickey, S.M. Wiggins, J.A. Hildebrand, and D.M. Cholewiak (2022). “Long-term passive acoustic monitoring of beaked whale occurrence at multiple sites along the western North Atlantic continental slope”. In: *Endangered Species Research* 47, pp. 1–16.
Stanistreet, J.E., L.T. Hatch, and C.W. Clark (2018). “Passive acoustic monitoring of sperm whales in the western North Atlantic Ocean: Seasonal and geographic patterns”. In: *Endangered Species Research* 35, pp. 1–13.
Stanistreet, J.E., H. Klinck, L.T. Hatch, and C.W. Clark (2018). “Seasonal acoustic occurrence of minke whales (*Balaenoptera acutorostrata*) in the western North Atlantic Ocean”. In: *Endangered Species Research* 35, pp. 289–302.

Stimpert, Alison K., Whitlow W. L. Au, Susan E. Parks, Travis Hurst, and David N. Wiley (2011). "Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring". In: *The Journal of the Acoustical Society of America* 129.1, pp. 476–482.

Thompson, Paul O., Lloyd T. Findley, and Octavio Vidal (1992). "20-Hz pulses and other vocalizations of fin whales, *Balaenoptera physalus*, in the Gulf of California, Mexico". In: *The Journal of the Acoustical Society of America* 92.6, pp. 3051–3057.

Waring, G.T., E. Josephson, K. Maze-Foley, and P.E. Rosel (2010). *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2010*. Tech. rep. NOAA Technical Memorandum NMFS-NE-219.

Watkins, William A. (1981). "Activities and underwater sounds of fin whales". In: *Scientific Reports of the Whales Research Institute* 33, pp. 83–117.

Watwood, Stephanie L, Patrick JO Miller, Mark Johnson, Peter T Madsen, and Peter L Tyack (2006). "Deep-diving foraging behaviour of sperm whales (Physeter macrocephalus)". In: *Journal of Animal Ecology* 75.3, pp. 814–825.

Welch, Peter (1967). "The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms". In: *IEEE Transactions on audio and electroacoustics* 15.2, pp. 70–73.

Wiggins, Sean M, Jesse M Hall, Bruce J Thayre, and John A Hildebrand (2016). "Gulf of Mexico low-frequency ocean soundscape impacted by airguns". In: *The Journal of the Acoustical Society of America* 140.1, pp. 176–183.

Wiggins, Sean M and John A Hildebrand (2007). "High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring". In: *2007 Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*. IEEE, pp. 551–557.

Zimmer, Walter MX, Mark P Johnson, Peter T Madsen, and Peter L Tyack (2005). "Echolocation clicks of free-ranging Cuvier's beaked whales (Ziphius cavirostris)". In: *The Journal of the Acoustical Society of America* 117.6, pp. 3919–3927.