Passive Acoustic Monitoring for Marine Mammals and Ambient Noise Offshore Cape Hatteras

Report Authors:

Natalie Posdaljian[1], Clara M. Schoenbeck[1], Annamaria DeAngelis[2], Lauren M. Baggett[1], Genevieve Davis[2], Lindsey Transue[2], Claire Williamson[1], Lucas Forsberg[1], Raquel Cuatrecasas[1], 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 Offshore Cape Hatteras*. Scripps Institution of Oceanography, University of California San Diego, and NOAA Northeast Fisheries Science Center. MPL Technical Memorandum #674.

Table of Contents

1 Executive Summary

The Virginia Capes Range Complex, adjacent to Cape Hatteras, North Carolina, encompasses dynamic shelf and slope waters that support a diverse community of marine mammals. This report summarizes findings from a long-term passive acoustic monitoring study conducted off Cape Hatteras (HAT) between 2012 and 2020 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 a key ecological transition zone.

HARPs were deployed continuously for over eight years at two locations: site HAT A (2012–2016) and site HAT B (2017–2020), the latter positioned approximately 17 nm to the northeast and north of the Gulf Stream. Acoustic recordings were analyzed for echolocation signals from odontocetes, vocalizations from mysticetes, and low-frequency ambient sound.

Among odontocetes, goose-beaked and sperm whales were the most consistently present species throughout the monitoring period, both exhibiting year-round acoustic presence with increased presence at HAT B. Goose-beaked whales exhibited seasonal increases in the fall at HAT A and in the summer at HAT B. Gervais' beaked whales were also regularly present, more so at HAT A, while True's, Blainville's, and Sowerby's beaked whales occurred at comparatively lower levels. A subset of Gervais' and True's detections could not be confidently assigned to either species and are reported as unclassified. 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. Sperm whales exhibited seasonal increases in the winter at HAT A and in the summer at HAT B.

Kogia spp. were intermittently present across the monitoring period, with somewhat greater occurrence at HAT B, with diel patterns suggesting elevated activity during nighttime hours. Risso's dolphins were present throughout the study, with acoustic presence spanning nearly the entire time series. Presumed smaller-bodied delphinids (UD HF & 47) were regularly acoustically present at both sites, with stronger presence during summer and fall and pronounced diel patterns indicating greater nighttime activity. Presumed larger-bodied delphinids (UD LF) were also common year-round, with higher presence during summer and fall. Smaller-bodied delphinids (UD LF) were generally more prevalent at site HAT A, while larger-bodied delphinids (UD HF & 47) showed higher presence at site HAT B, suggesting potential differences in spatial distribution or habitat preference between the two groups.

Most mysticetes at Cape Hatteras were acoustically present based on the calls we identified from fall through spring and not detected in summer, underscoring the role of the Cape Hatteras study area as a migratory passage with seasonal foraging opportunities. Fin, minke, and sei whales followed this general pattern, with higher occurrence at HAT A, suggesting that the warmer Gulf Stream–influenced waters supported greater foraging activity. Humpback whales were also acoustically present from fall through spring but

showed stronger occurrence at HAT B, indicating greater use of cooler waters north of the Gulf Stream. Blue whales differed from this general pattern, with acoustic presence from late summer through early winter and relatively consistent occurrence across years. North Atlantic right whales were occasionally acoustically present during spring and fall migratory periods. Together, these results highlight that while most mysticetes are acoustically present at Cape Hatteras from fall through spring, differences between HAT A and HAT B demonstrate how small spatial shifts in oceanographic setting can influence species occurrence.

Although HAT A and HAT B are separated by only 40 km, their placement relative to the Gulf Stream places them in different oceanographic regimes, with HAT A generally influenced by warmer Gulf Stream waters and HAT B situated in cooler waters to the north. This difference is reflected in the species composition and acoustic presence observed at each site, underscoring how small spatial shifts in instrument placement can yield distinct ecological perspectives. The Cape Hatteras region is a highly dynamic transition zone, and these results illustrate that patterns of marine mammal occurrence can change markedly over relatively short spatial scales. Acoustic monitoring studies in such regions should therefore be interpreted with consideration of local oceanographic context, recognizing that variability in presence across sites does not necessarily indicate strict habitat boundaries but rather reflects the fluid and shifting nature of the ecosystem. In addition, although these data provide exceptional temporal resolution at fixed locations off Cape Hatteras, 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 the bathymetric and oceanographic setting of monitoring sites (DeAngelis et al. 2025).

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, wintertime spectral levels increased due to elevated sea states. The relocation of the hydrophone to a position north of the Gulf Stream revealed differences in ambient noise levels and species presence, highlighting the importance of spatial oceanographic context in interpreting passive acoustic data.

These findings contribute to the long-term understanding of species distribution and acoustic habitat use in a highly variable oceanographic setting and provide a valuable baseline for future studies assessing environmental change and anthropogenic impacts in the western North Atlantic.

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 Cape Hatteras study area 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 2012 to 2020, 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 12 High-frequency Acoustic Recording Packages (HARPs; Wiggins & Hildebrand 2007), which were strategically deployed offshore from Cape Hatteras within the southern portion of the Virginia Capes Range Complex (Figure 1 & Table 1).

Table 1: Recording effort for deployments at Hatteras sites A and B.

Site	Deployment	Start Date	End Date	Depth (m)	Recording Duration (Days)
A	01	03/15/2012	04/11/2012	950	26
	02	10/09/2012	05/09/2013	970	212
	03	05/29/2013	03/15/2014	970	289
	04	05/09/2014	12/11/2014	840	217
	05	04/07/2015	01/21/2016	980	289
	06	04/29/2016	02/06/2017	1021	283
B	01	05/09/2017	10/25/2017	1100	169
	03	10/26/2017	06/01/2018	1200	217
	04	06/01/2018	12/14/2018	1350	196
	05	12/14/2018	05/17/2019	1175	155
	06	05/18/2019	09/24/2019	1220	129
	07	10/25/2019	10/29/2020	1100	371

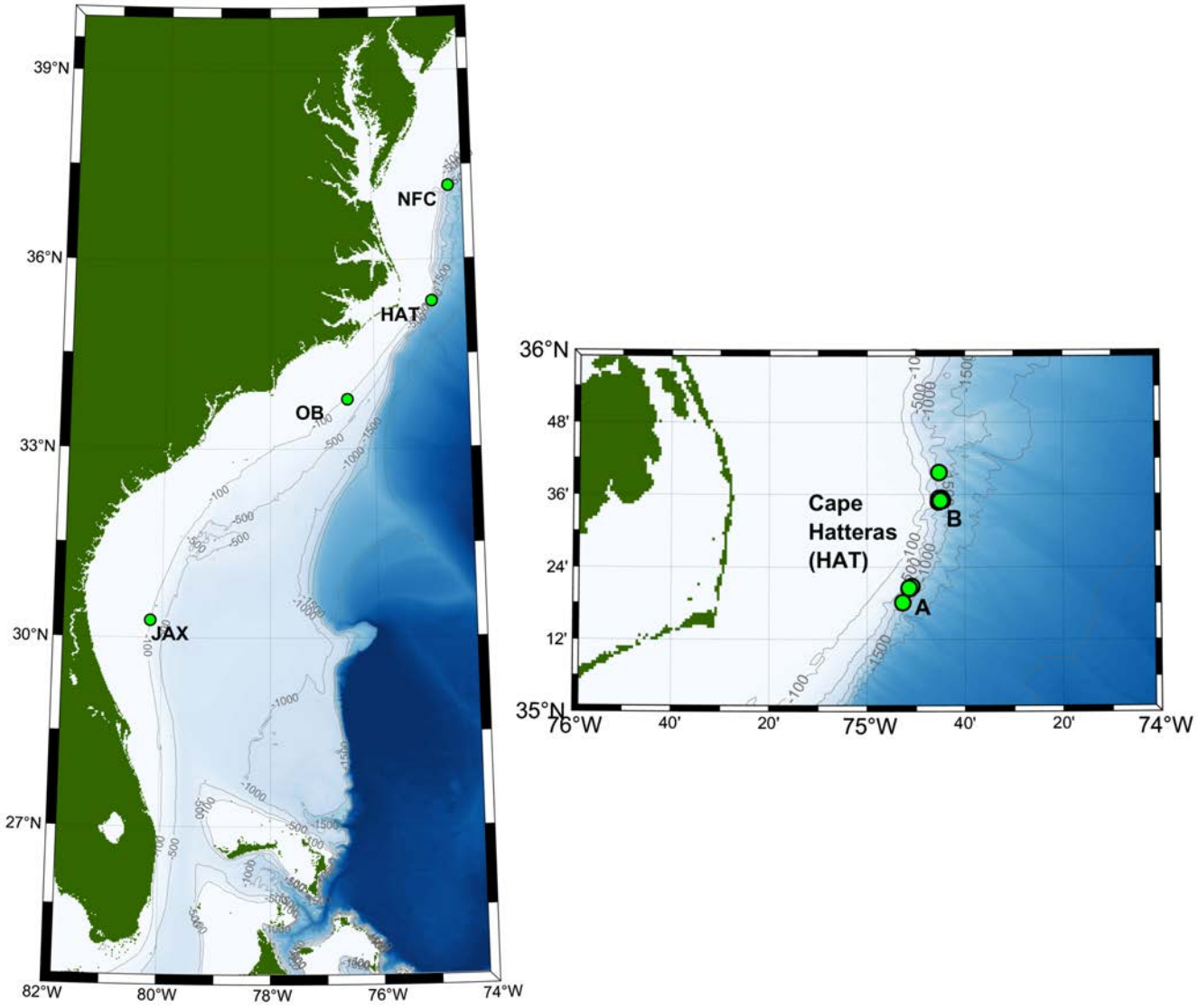

Figure 1: Location of the High-frequency Acoustic Recording Packages (HARPs) at the Cape Hatteras (HAT) site. Left: Large-scale view of the HAT project location along the U.S. East Coast. Right: Zoomed-in view showing the positions of individual deployments at the A and B sites.

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 continous 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 recieved sound field. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations (Wiggins & Hildebrand 2007). In May 2017, the location for HARP deployments was moved approximately 17 nm to the northeast (designated site B).

The vast majority of the data collected were found to be error free. Highly stereotyped broadband digital dropouts were identified in three of the deployments included in this reporting period: HAT02A and HAT03A. These dropouts are very short in duration (between 100 microseconds and 10 milliseconds). In all cases, they appear gradually around two-thirds of the way into the deployment and increase in occurrence toward the end of the dataset. These dropouts affect less than one percent of the impacted xwav-format data. To address them, the affected segments were corrected using a detector calibrated to the observed amplitude and duration of the dropouts. This procedure was carefully validated to ensure that no true broadband biological signals were altered. We do not believe either the dropouts or their correction have a significant impact on the resulting data analysis. The end of the HAT04A recording was cut short, likely due to disk write errors.

Intermittent data gaps appeared at the end of the HAT06A and HAT01B deployments due to a data logger malfunction. Recording coverage began as 100% and was 82% and 91%, respectively, at the end of the recording periods.

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 Cape Hatteras site, 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 Cape Hatteras sites, not spatial gradients across the western North Atlantic. Comparisons to other studies that include the Cape Hatteras 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 – presumed smaller-bodied delphinids (UD HF & 47)
- Unidentified delphinids – presumed 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 $1\mu Pa^2$.

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 the later deployments (HAT05A-HAT07B), 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.

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 Cape Hatteras study area. 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). These studies indicate that the Cape Hatteras study area is a key foraging hotspot for this species within the U.S. EEZ (Cohen et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025).

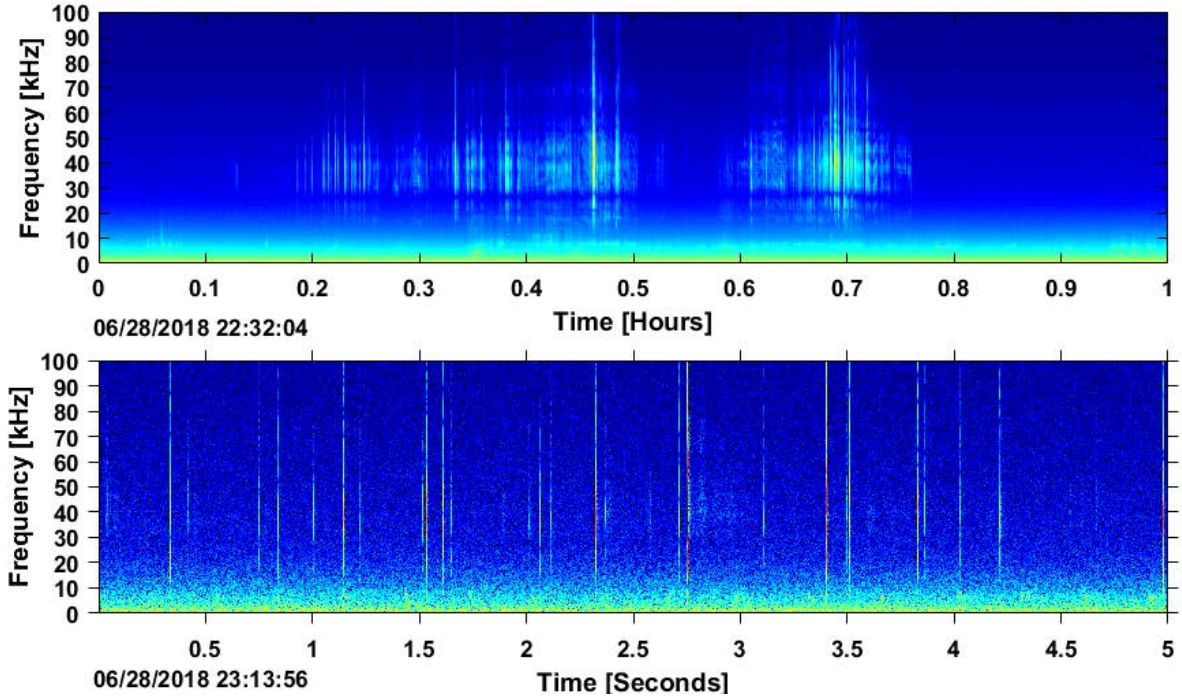

Figure 2: Goose-beaked whale signal in LTSA (top) and spectrogram (bottom).

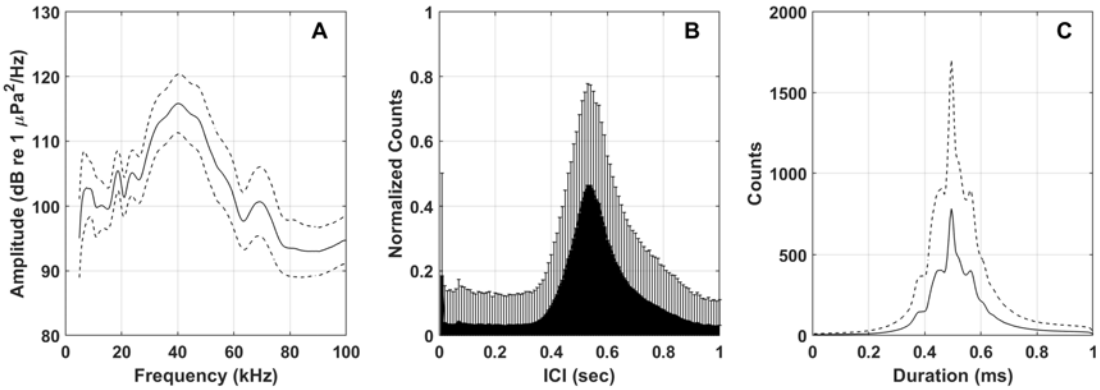

Figure 3: Left: Mean frequency spectrum of goose-beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.5 s; Right: Mean waveform envelope (solid line) and standard deviation (dashed line) of representative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

4.2.2 Gervais' Beaked Whale

Gervais' beaked whale echolocation signals have energy concentrated in the 30-50 kHz band (Gillespie et al. 2009b), 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. 2009a).

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).

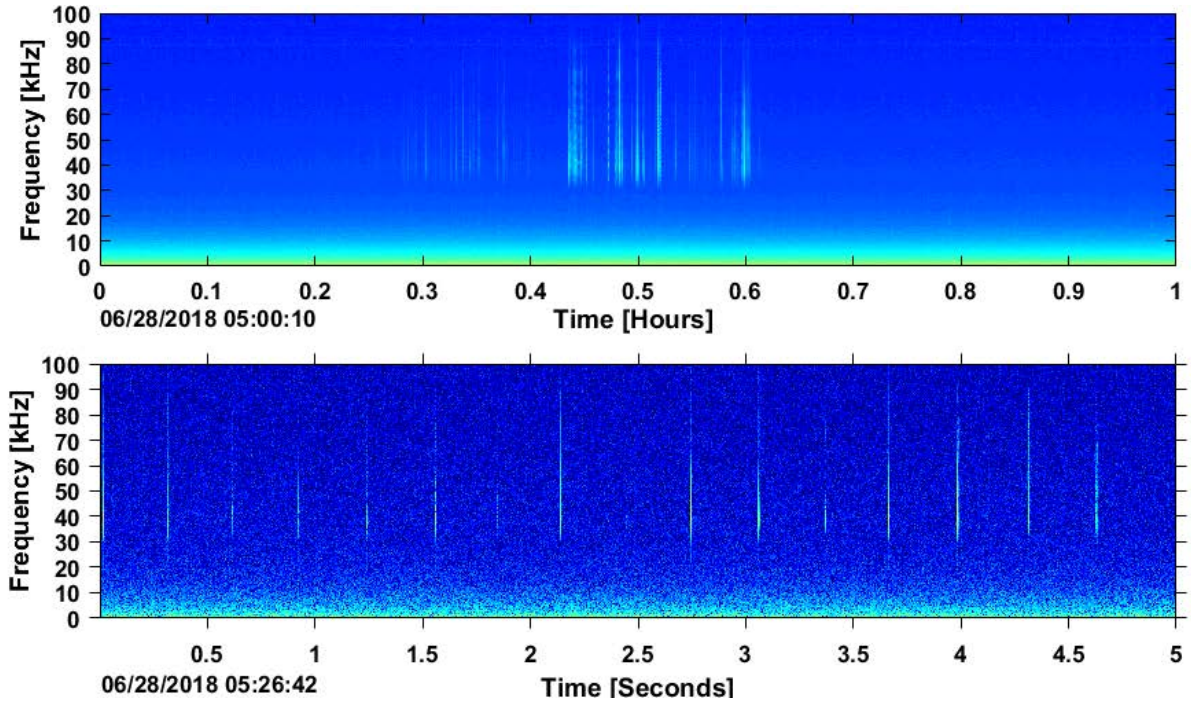

Figure 4: Gervais' beaked whale signal in LTSA (top) and spectrogram (bottom).

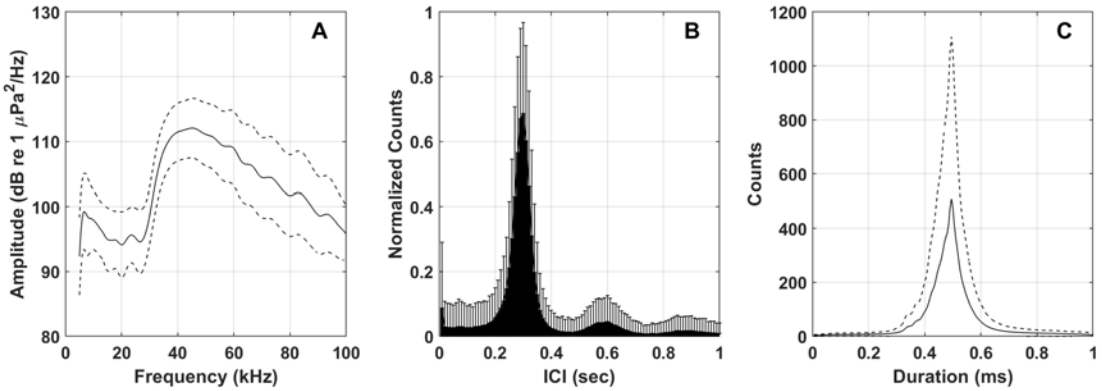

Figure 5: Left: Mean frequency spectrum of Gervais' beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.3 s. Smaller peaks can occur at multiples of the main peak, and represent cases where a subset of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

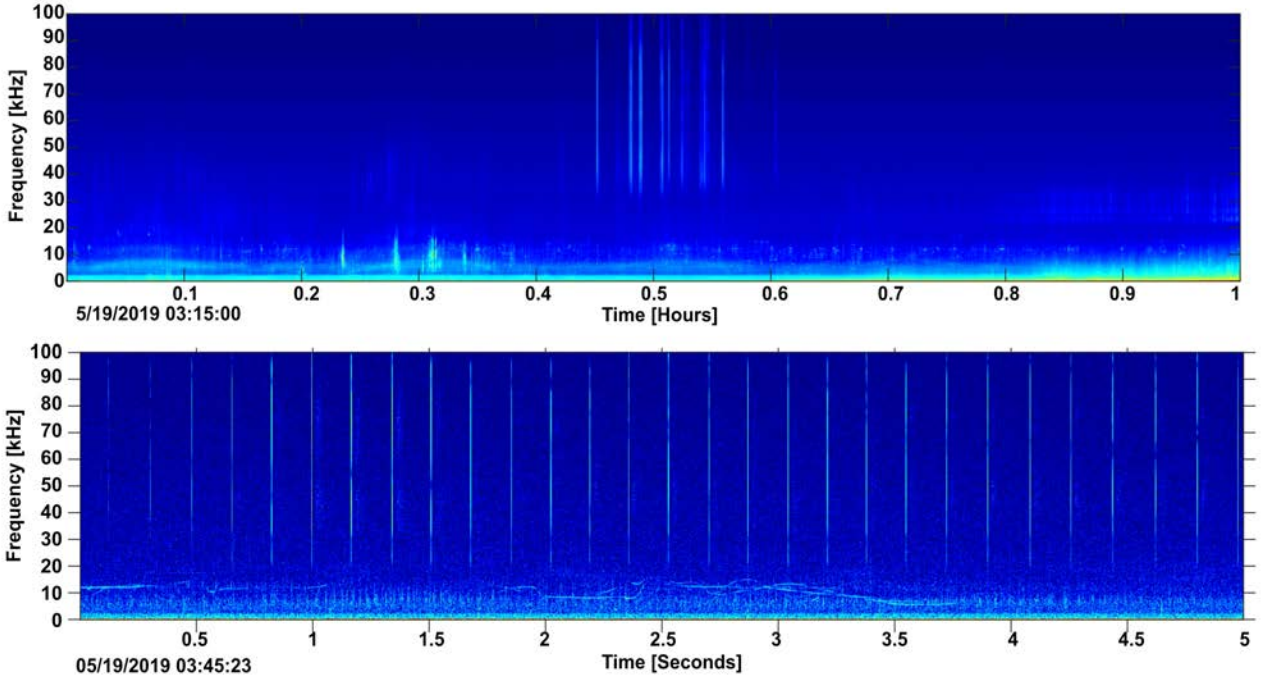

Figure 6: True's beaked whale signal in LTSA (top) and spectrogram (bottom).

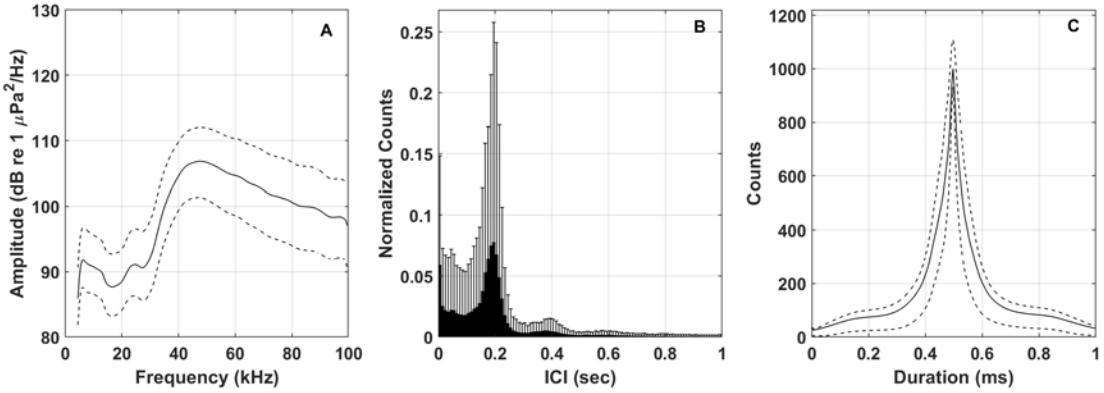

Figure 7: Left: Mean frequency spectrum of True's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.18 s; Right: Mean waveform envelope of representative clicks.

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).

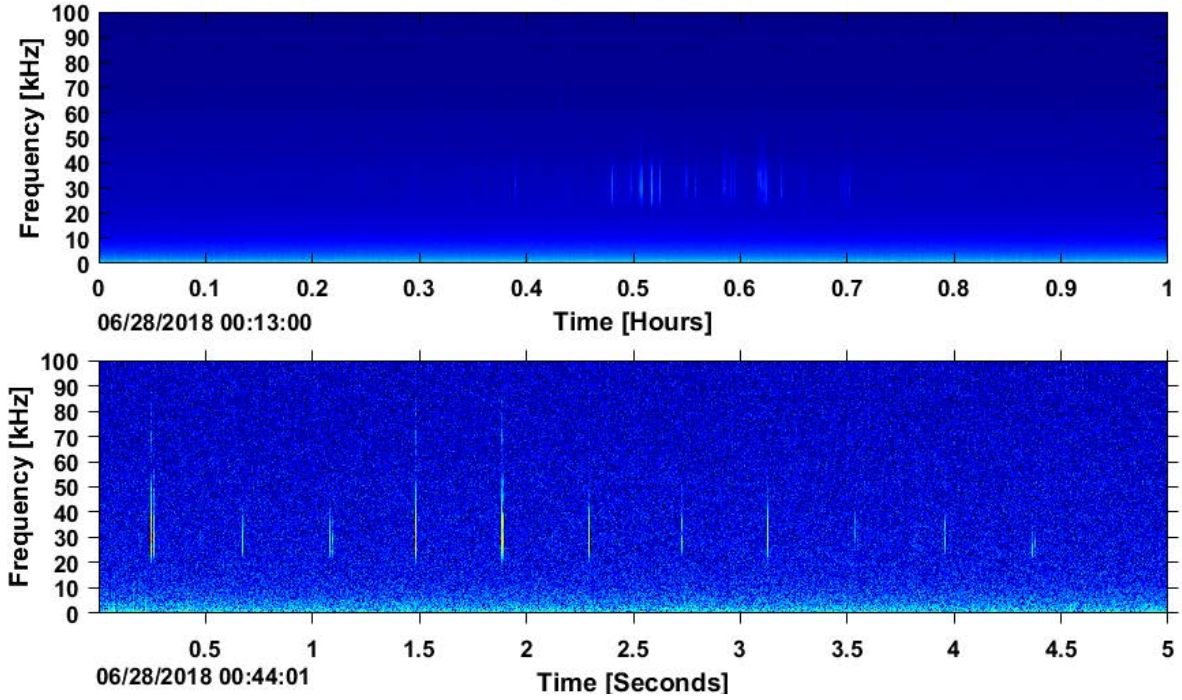

Figure 8: Blainville's beaked whale signal in LTSA (top) and spectrogram (bottom).

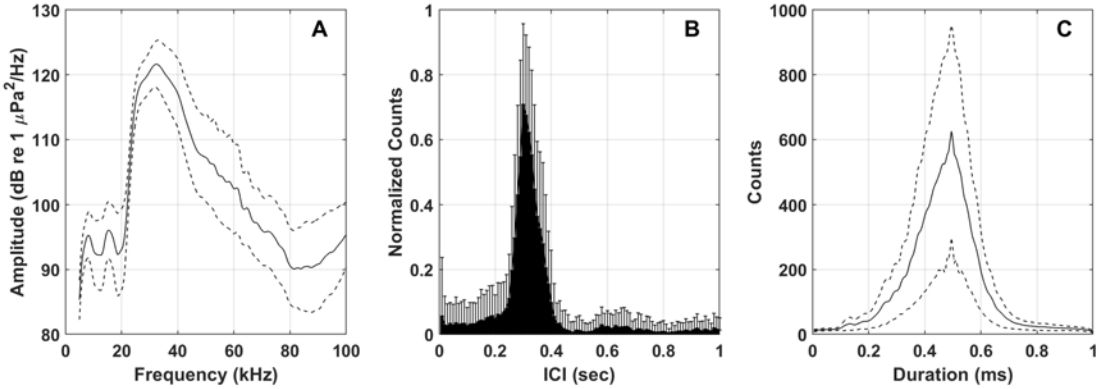

Figure 9: Left: Mean frequency spectrum of Blainville's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.3 s; Right: Mean waveform envelope of representative clicks.

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 hotspot for this species within the U.S. EEZ (Haver et al. 2025; Cohen et al. 2023; DeAngelis et al. 2025).

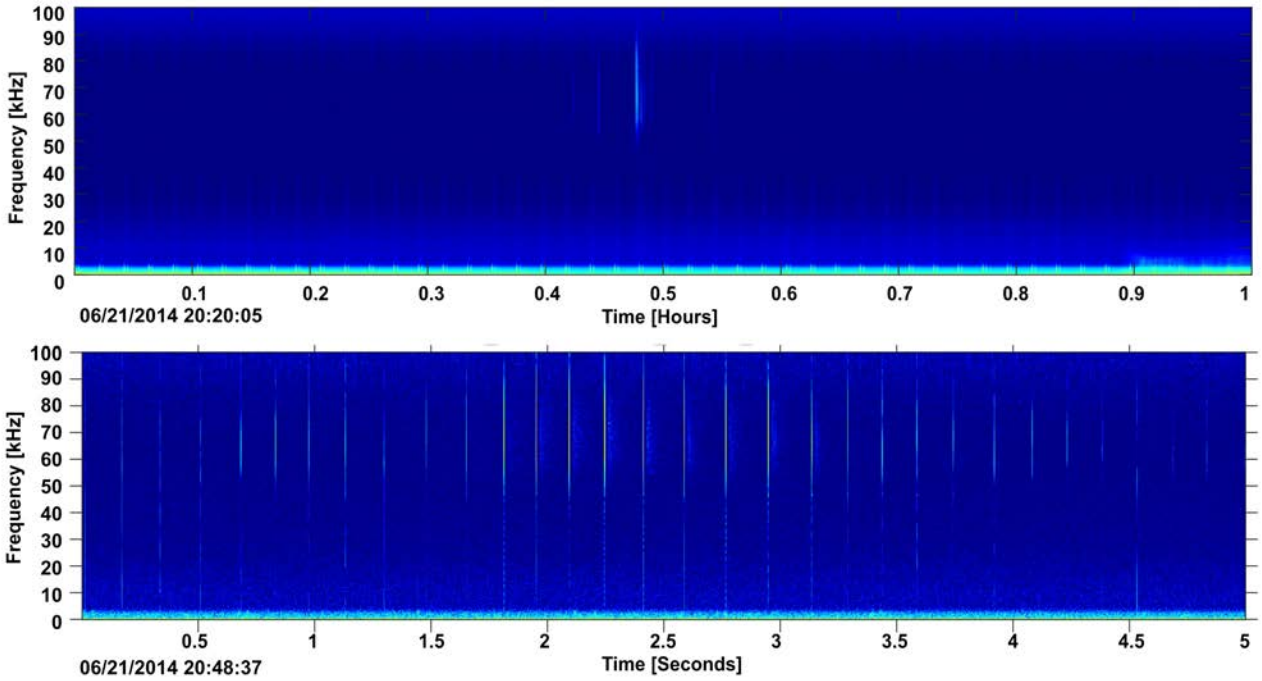

Figure 10: Sowerby's beaked whale signal in LTSA (top) and spectrogram (bottom).

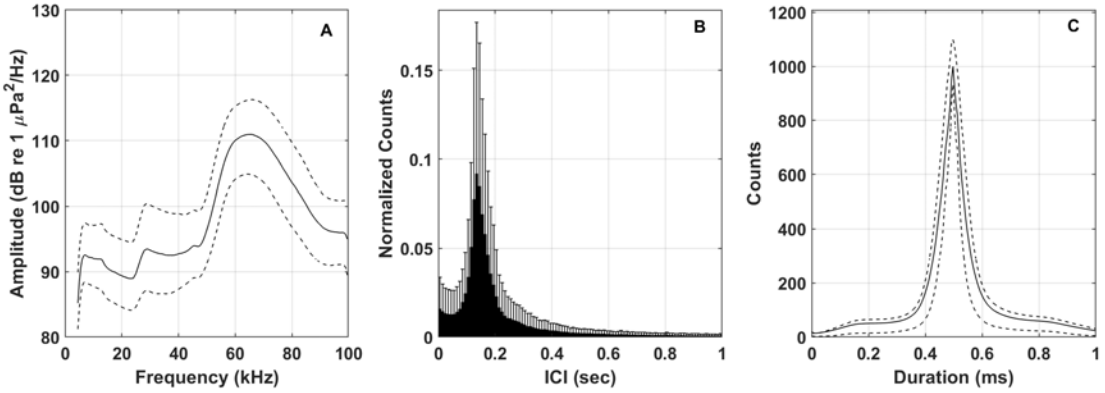

Figure 11: Left: Mean frequency spectrum of Sowerby's beaked whale echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.15 s; Right: Mean waveform envelope of representative clicks.

4.2.6 BWG

BWG ("Beaked Whale Gulf") is a signal believed to be produced by a beaked whale but currently of an unidentified speices. 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.

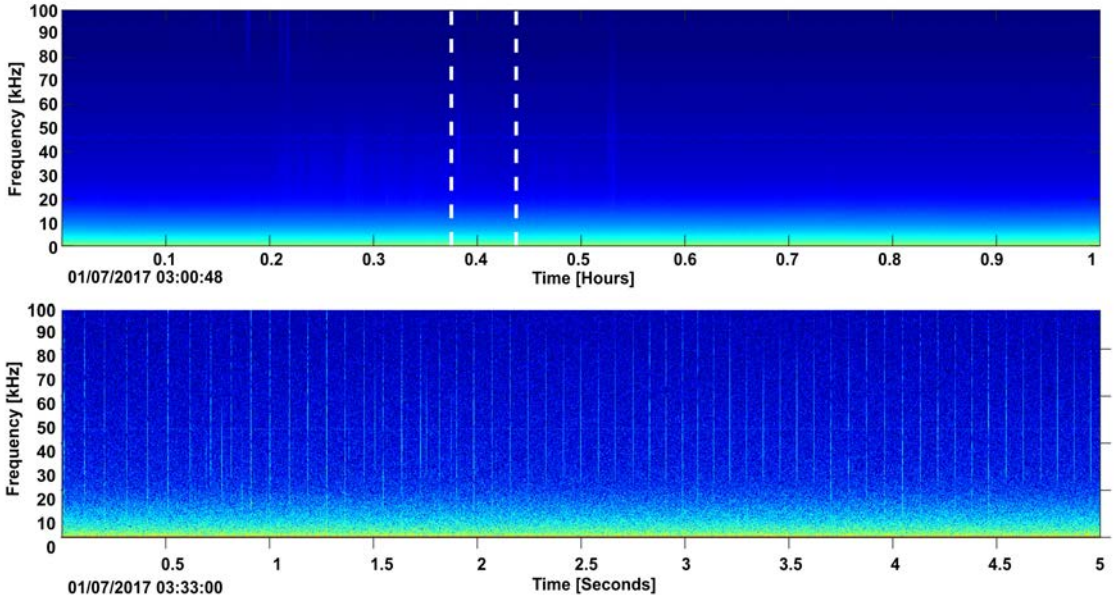

Figure 12: BWG signal in LTSA (top) and spectrogram (bottom).

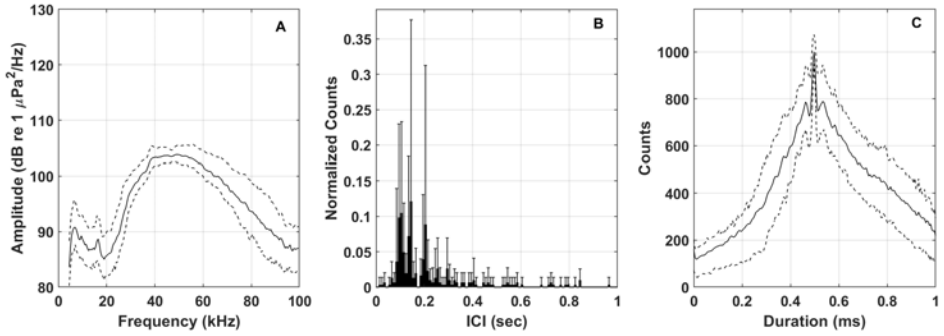

Figure 13: Left: Mean frequency spectrum of BWG echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.18 s; Right: Mean waveform envelope of representative clicks.

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).

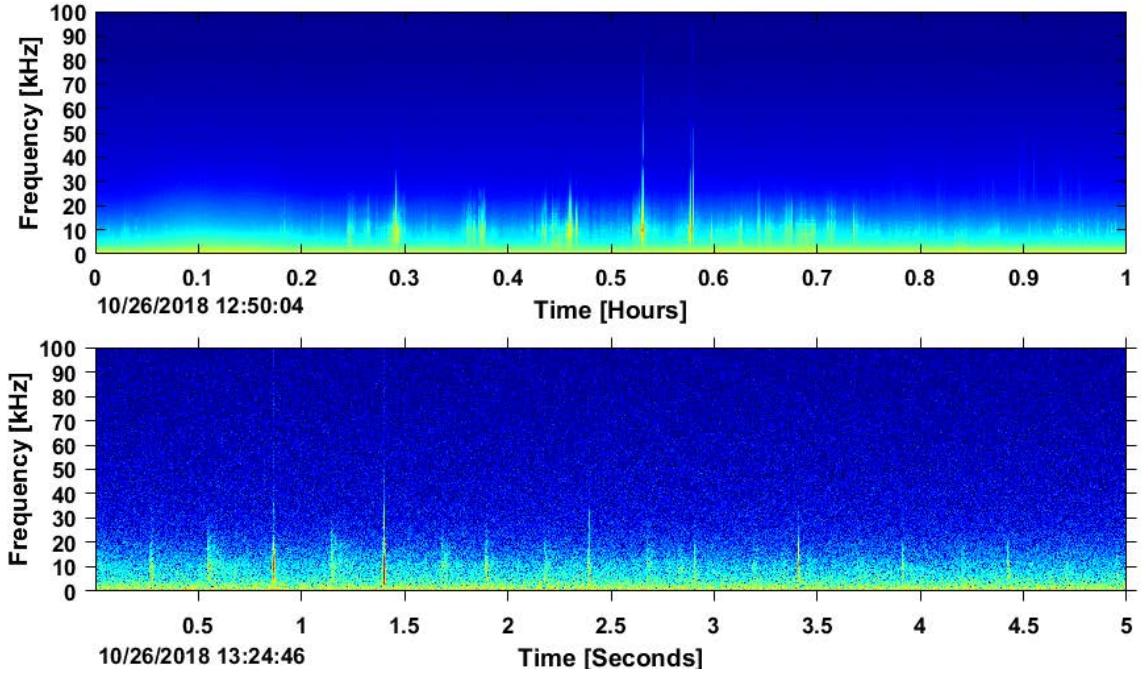

Figure 14: Sperm whale signals in LTSA (top) and spectrogram (bottom).

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).

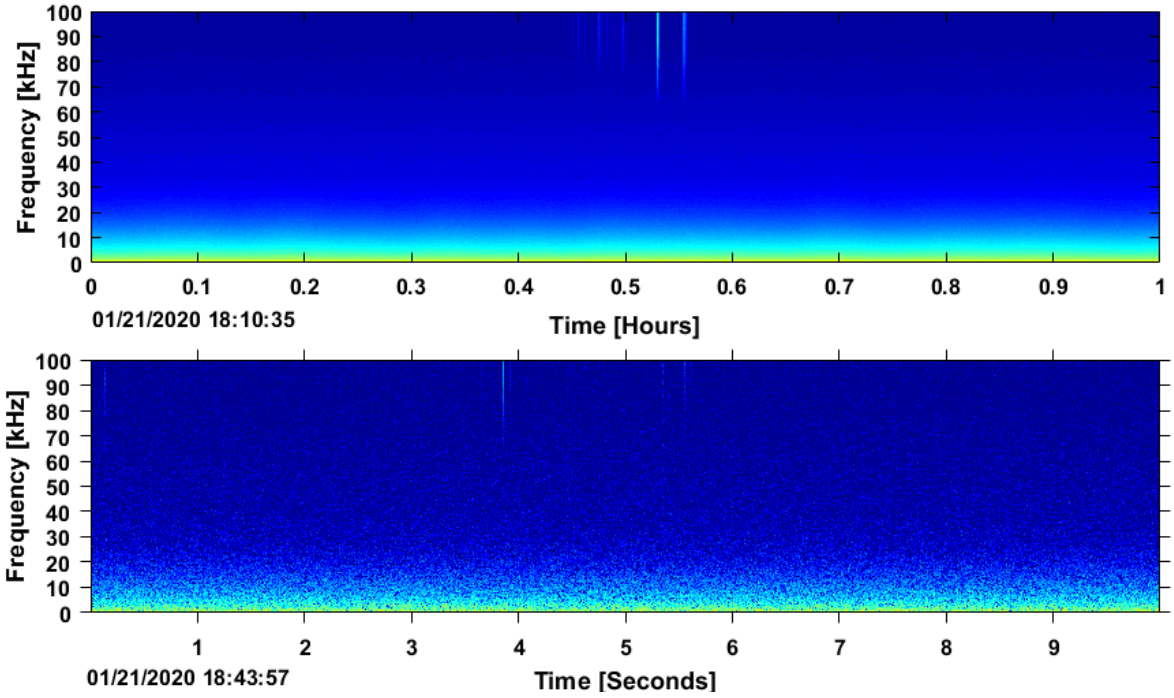

Figure 15: *Kogia* spp. signals in LTSA (top) and spectrogram (bottom).

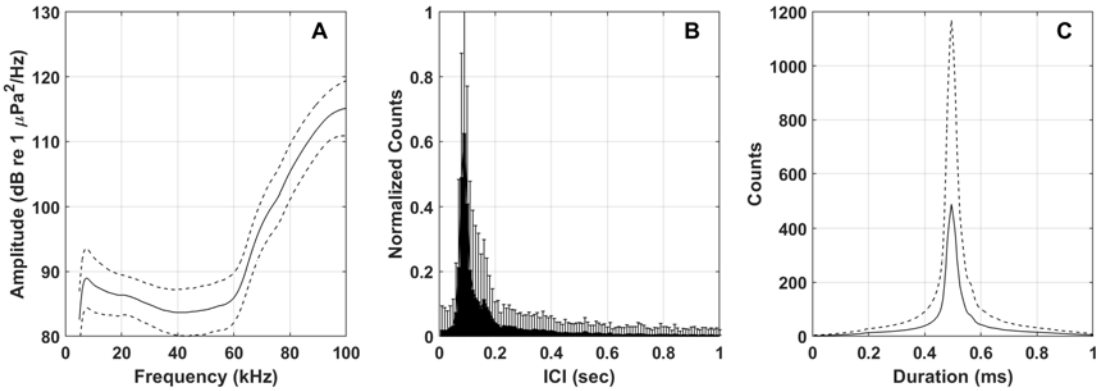

Figure 16: Left: Mean frequency spectrum of *Kogia* spp. echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.1 s; Right: Mean waveform envelope of representative clicks.

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).

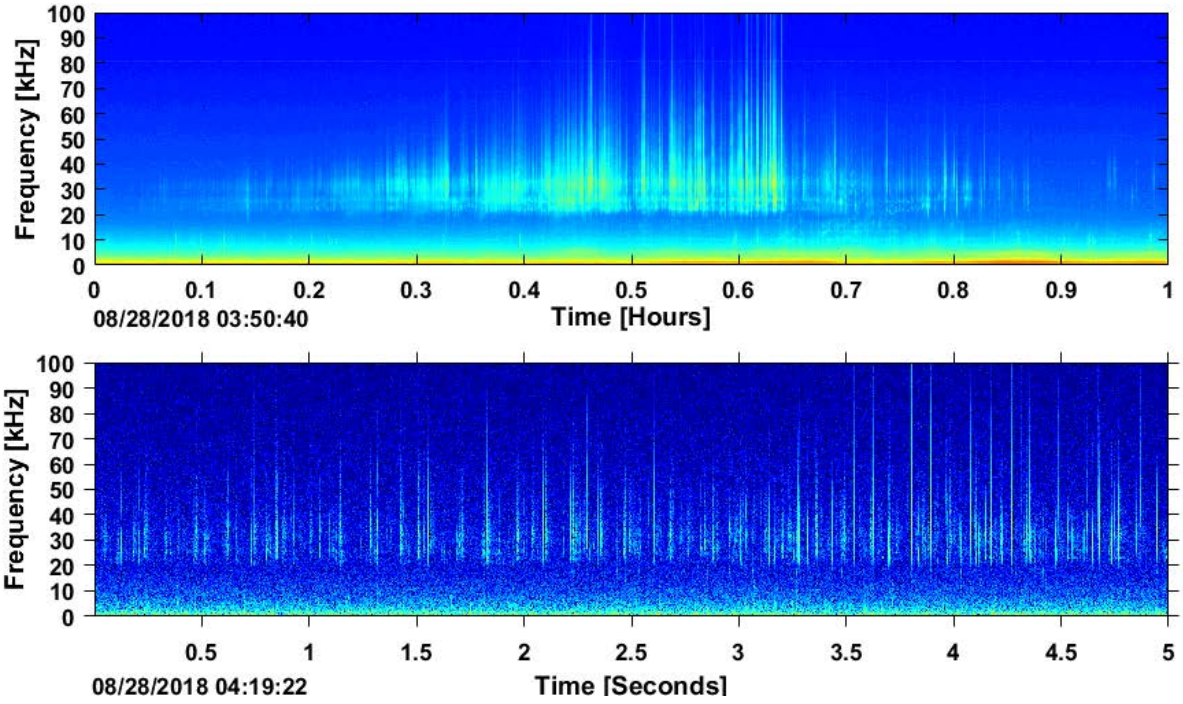

Figure 17: Risso's dolphins signals in LTSA (top) and spectrogram (bottom).

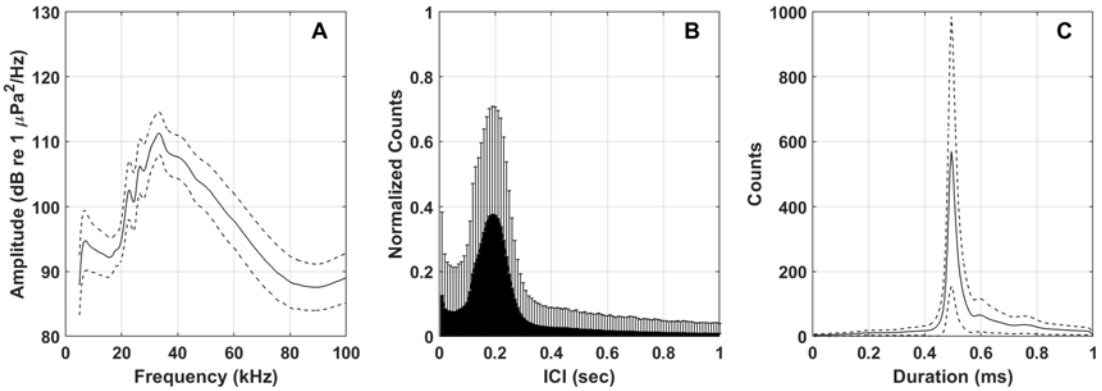

Figure 18: Left: Mean frequency spectrum of Risso's dolphins echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.2 s; Right: Mean waveform envelope of representative clicks.

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 Cape Hatteras 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). These patterns indicate that Cape Hatteras and adjacent slope habitats represent important foraging areas for smaller-bodied delphinids producing UD HF clicks (Haver et al. 2025; Cohen et al. 2023).

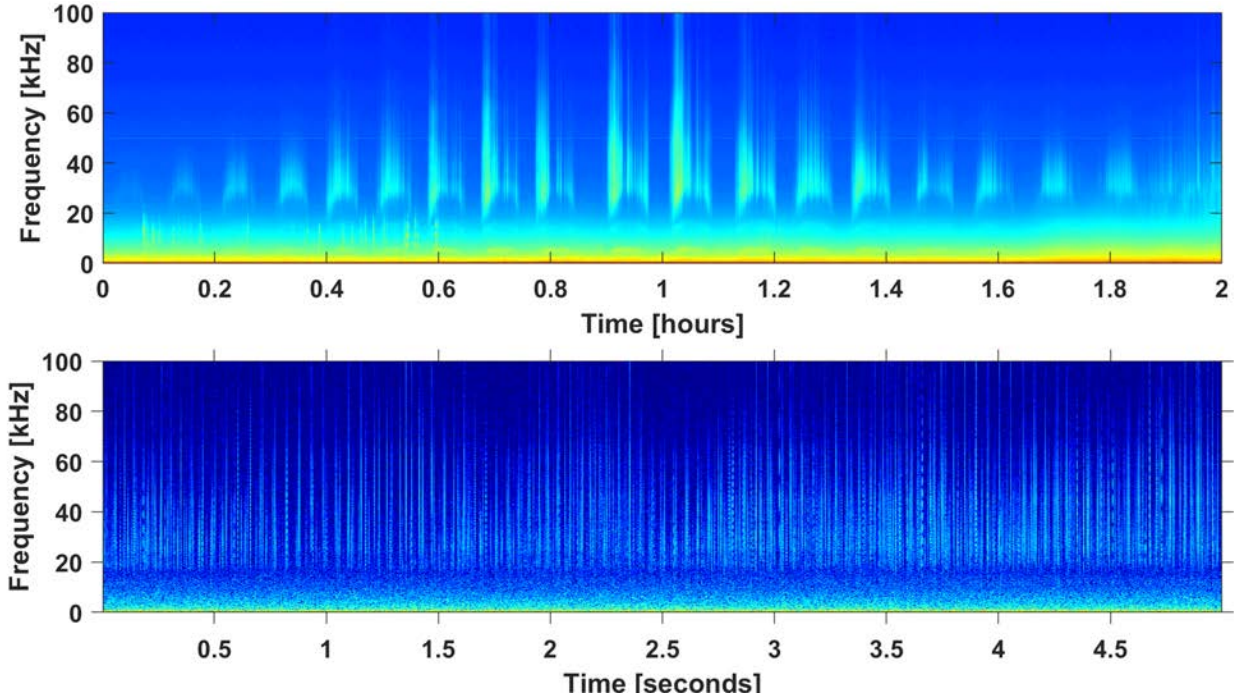

Figure 19: Unidentified dolphin high-frequency (UD HF) echolocation signals in LTSA (top) and spectrogram (bottom).

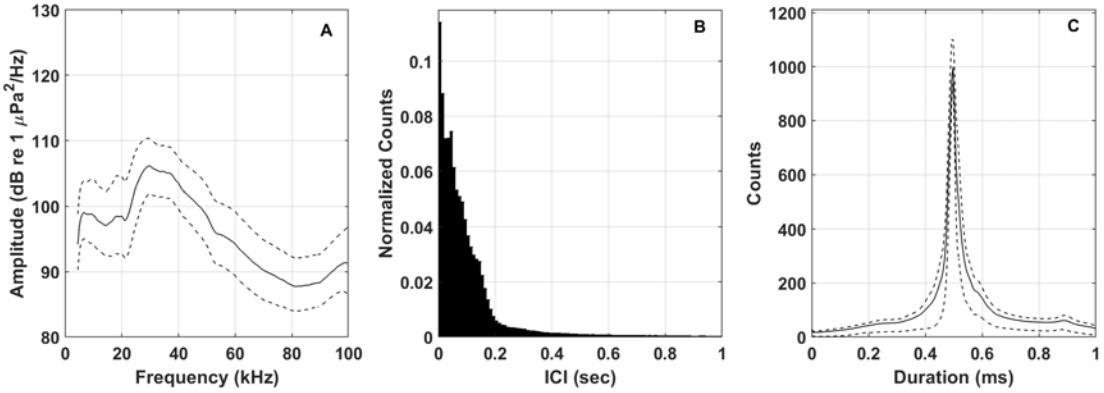

Figure 20: Left: Mean frequency spectrum of unidentified dolphin mid-frequency (UD HF) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.065 s and 0.1 s; Right: Mean waveform envelope of representative clicks.

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 seperately 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 Cape Hatteras and mid-Atlantic slope habitats represent important foraging areas for smaller-bodied delphinids producing UD47 clicks (Haver et al. 2025; Cohen et al. 2023).

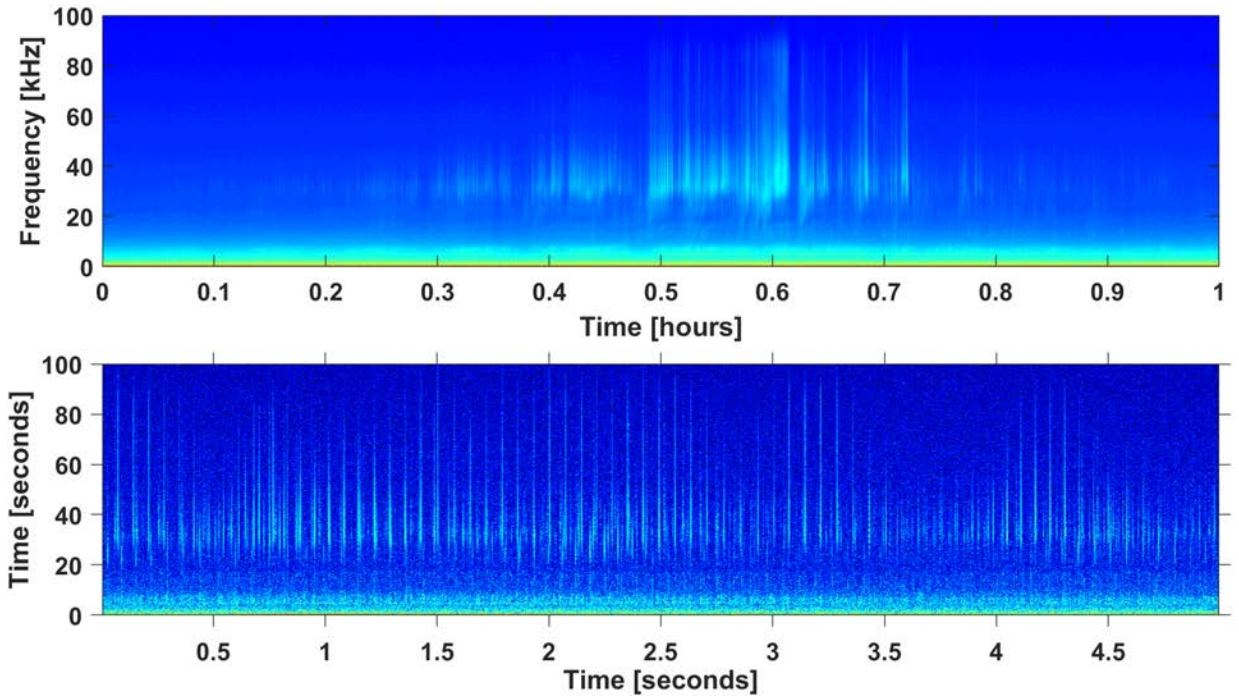

Figure 21: Unidentified dolphin 47 (UD47) echolocation signals in LTSA (top) and spectrogram (bottom).

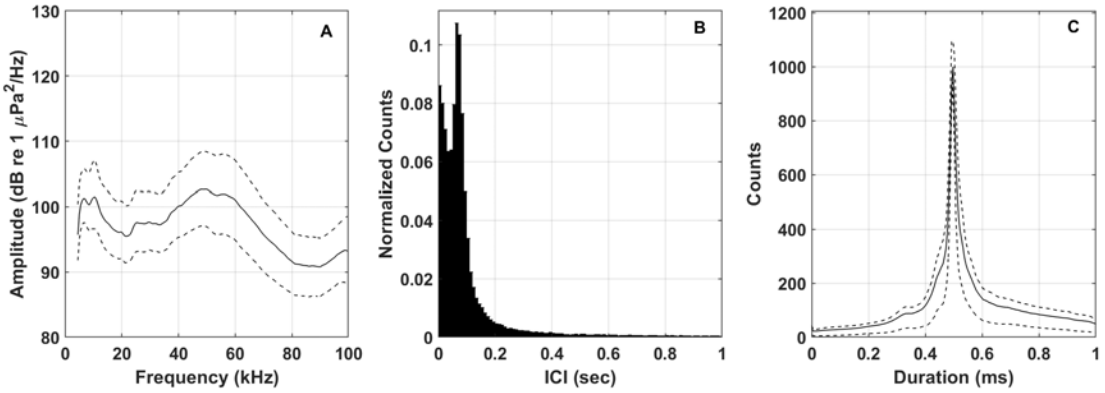

Figure 22: Left: Mean frequency spectrum of unidentified dolphin 47 (UD47) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.1 s; Right: Mean waveform envelope of representative clicks.

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 Cape Hatteras and the mid-Atlantic slope represent important foraging areas for larger-bodied delphinids producing UD LF clicks (Cohen et al. 2023).

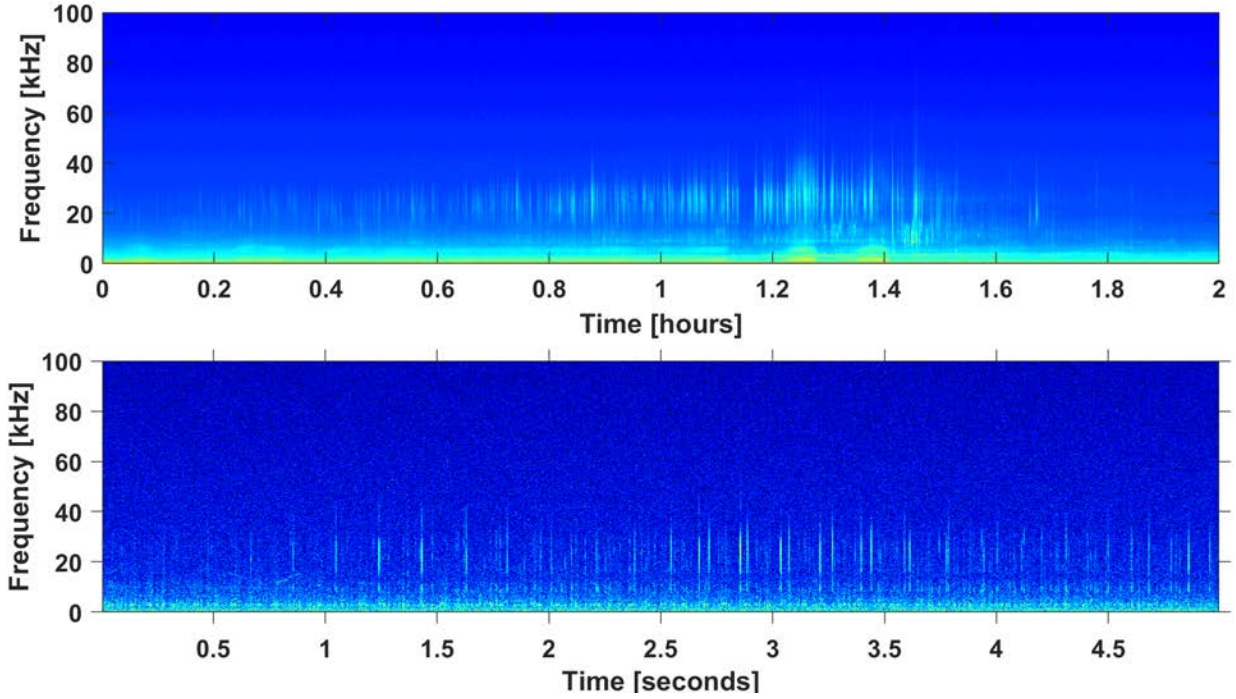

Figure 23: Unidentified dolphin low-frequency (UD LF) echolocation signals in LTSA (top) and spectrogram (bottom).

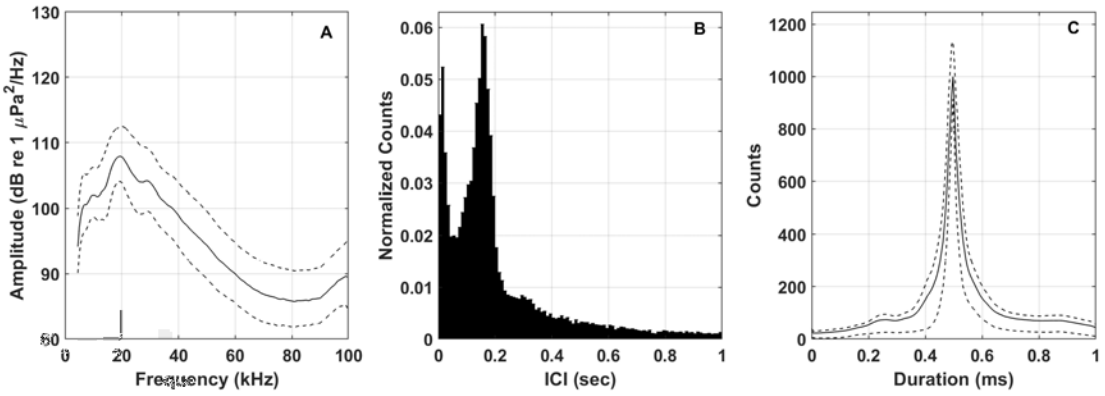

Figure 24: Left: Mean frequency spectrum unidentified dolphin low-frequency (UD LF) echolocation clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Inter-click interval distribution with peak near 0.2 s; Right: Mean waveform envelope of representative clicks.

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).

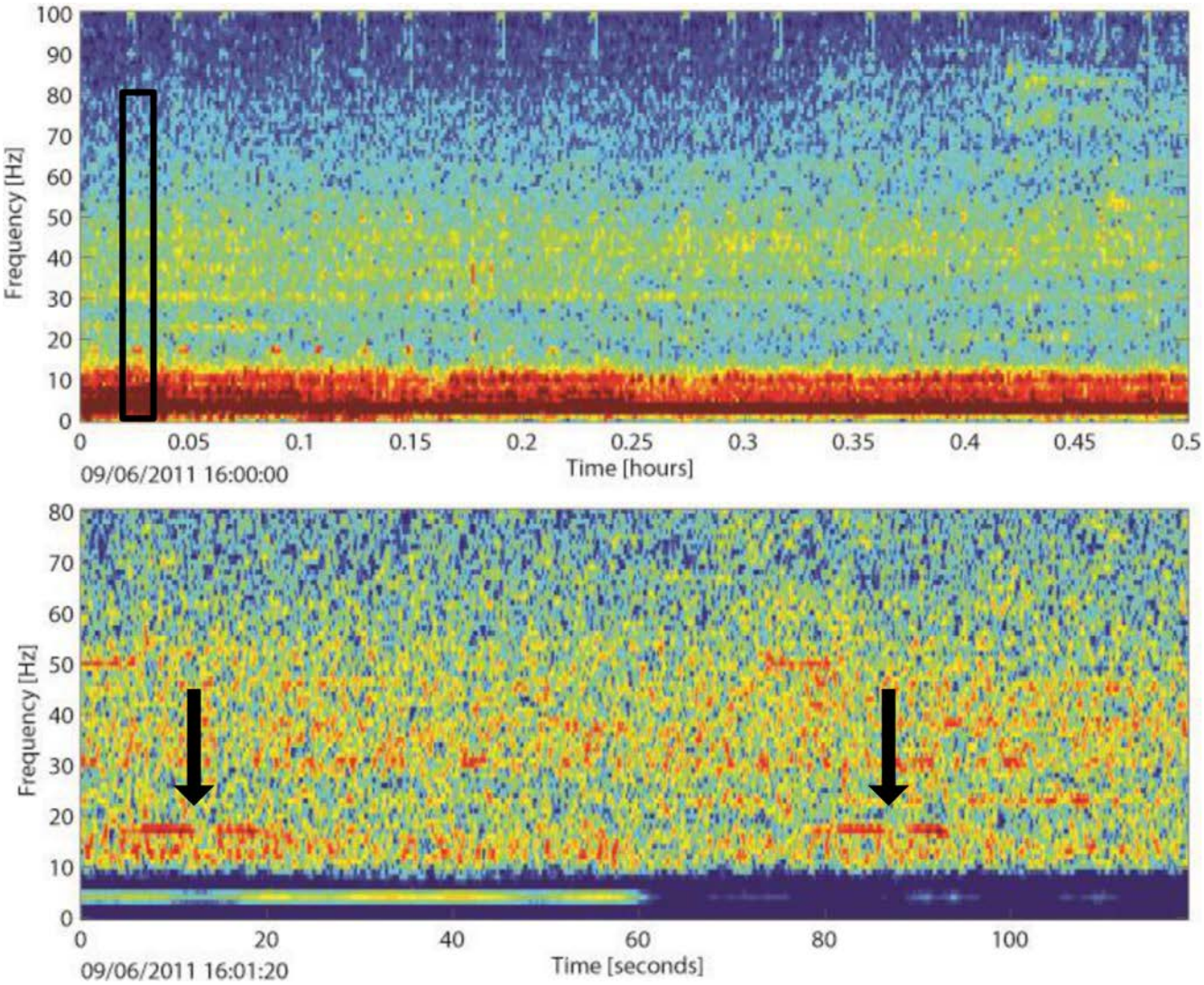

Figure 25: North Atlantic blue whale calls in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by black arrows.

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.

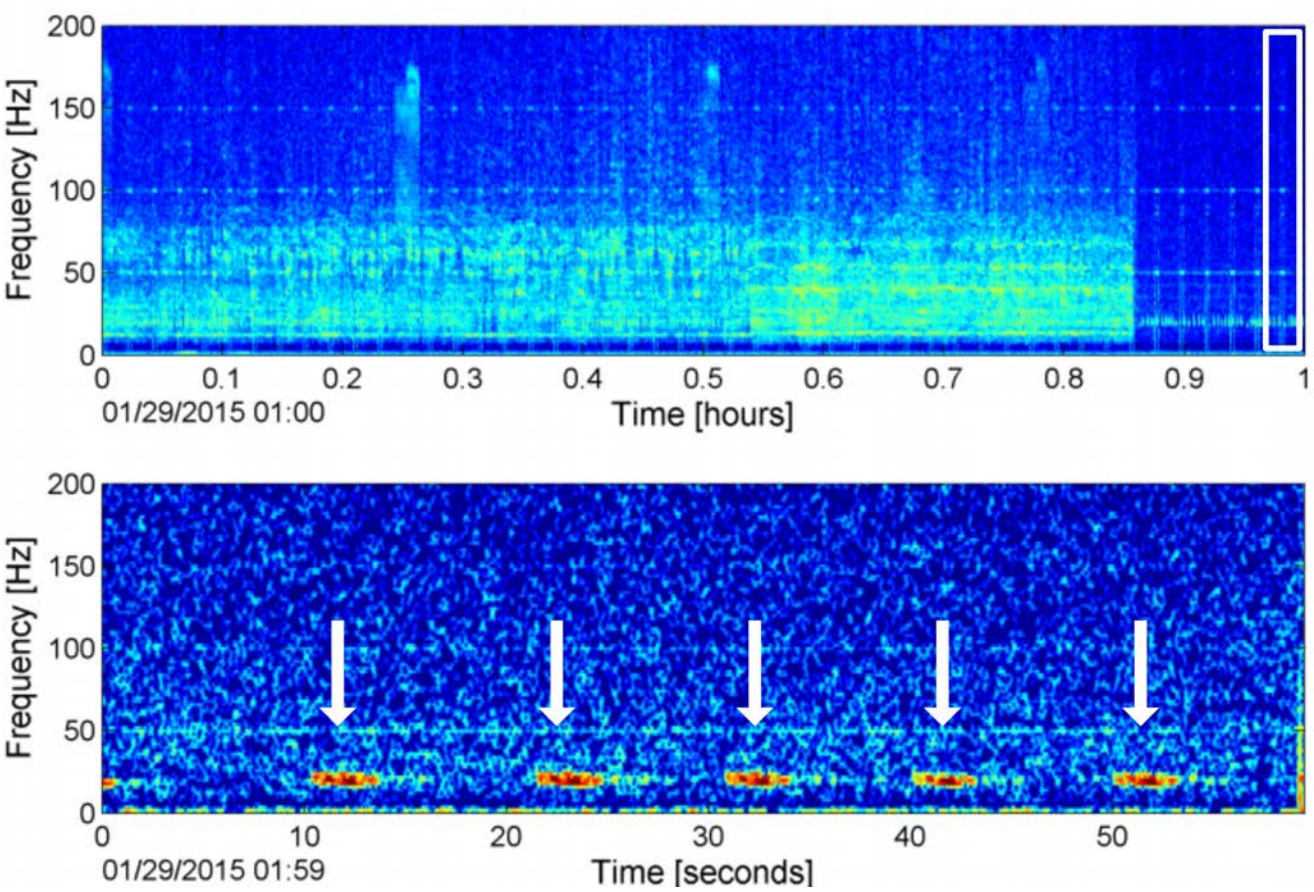

Figure 26: Fin whale 20 Hz calls in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

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).

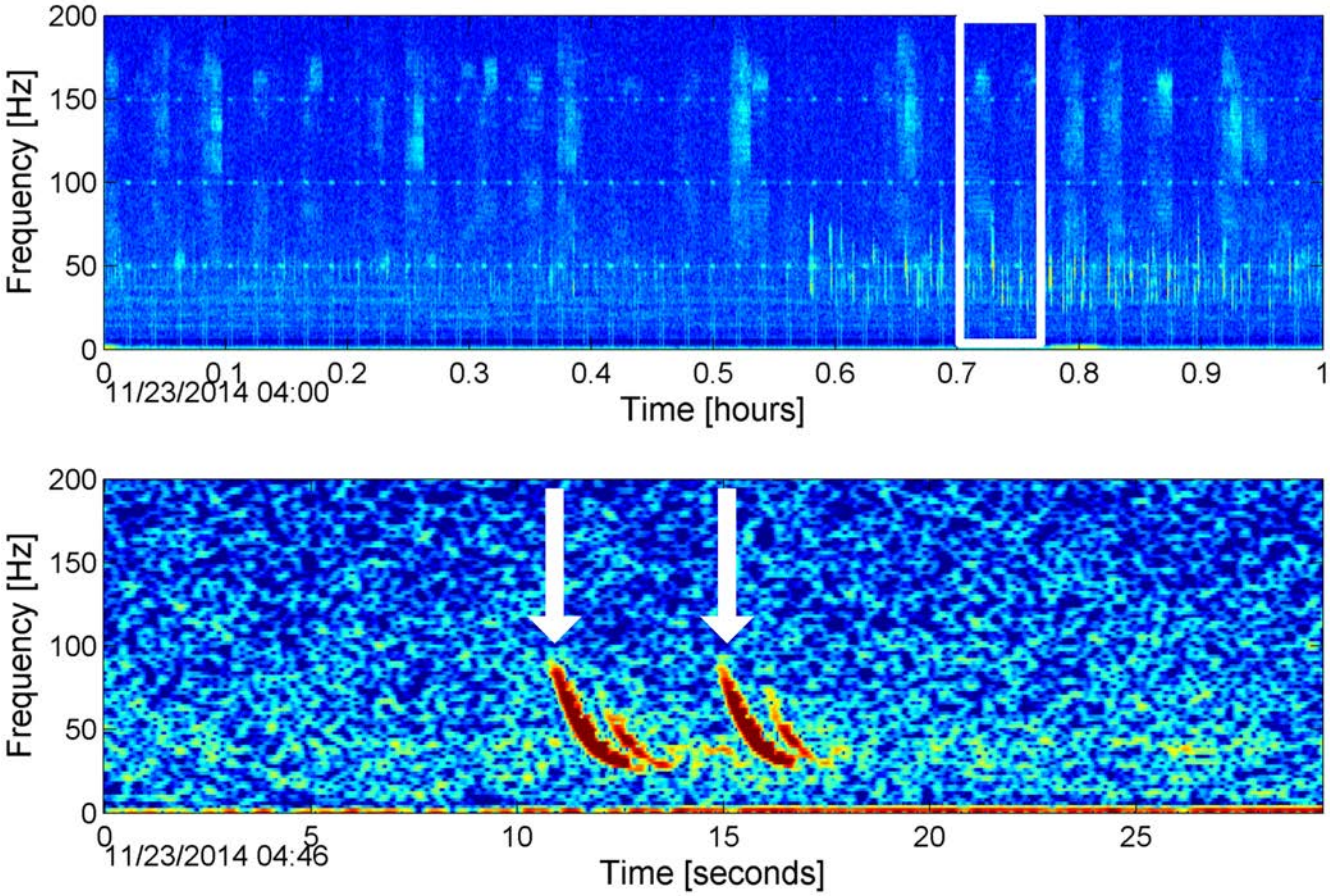

Figure 27: Sei whale downseep call in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

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).

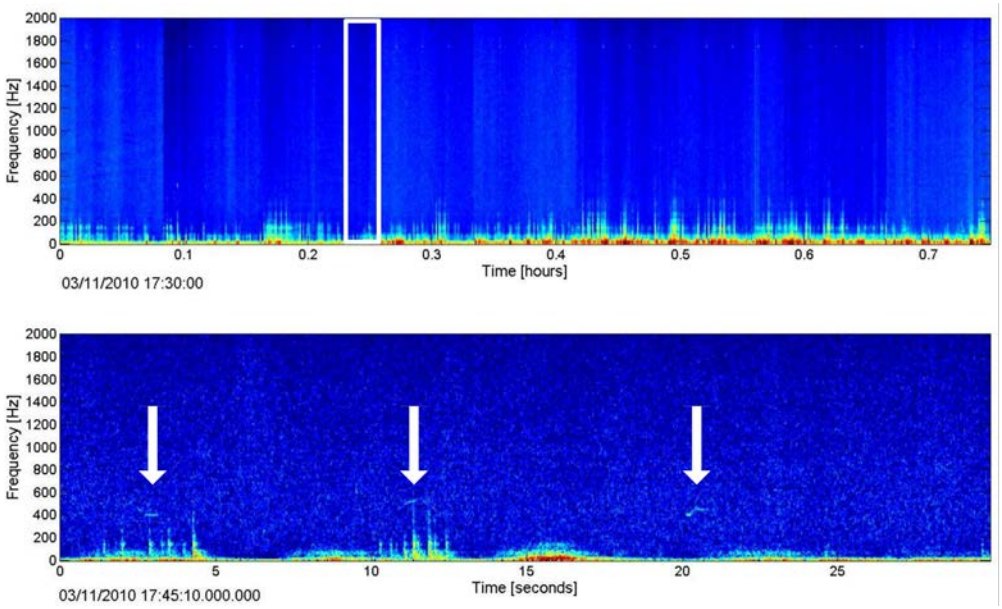

Figure 28: Humpback whale call in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the black arrows.

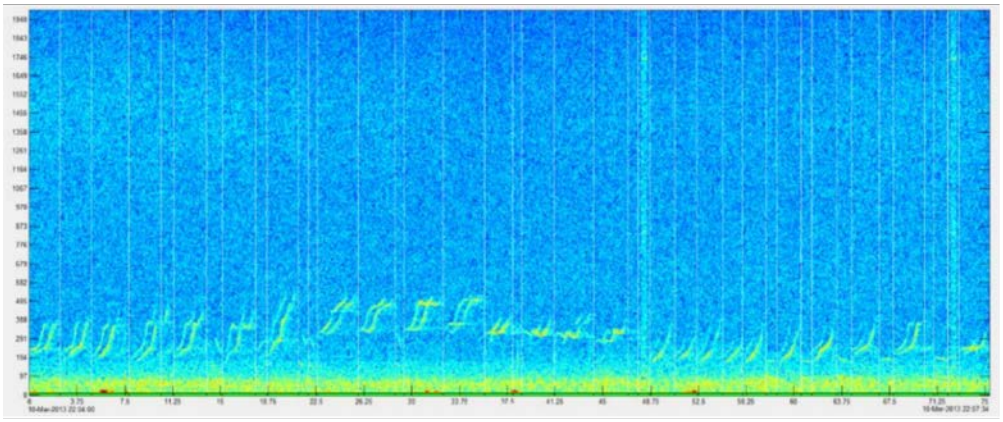

Figure 29: Concatenated humpback whale songs viewed in the software GPL review (Helble et al. 2012).

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).

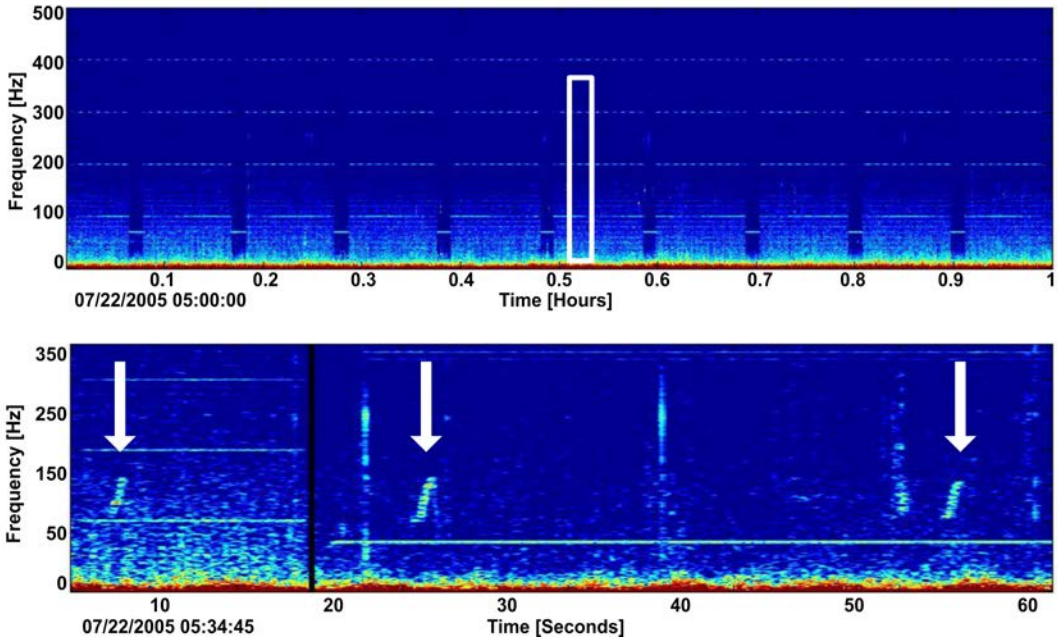

Figure 30: North Atlantic right whale upcall in LTSA (top), with white box indicating the region shown in the corresponding spectrogram (bottom); individual calls noted by the white arrows.

4.3.6 Minke Whales

For HAT A 02 -06 and HAT B 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 HATA01 HAT B 04-07, 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).

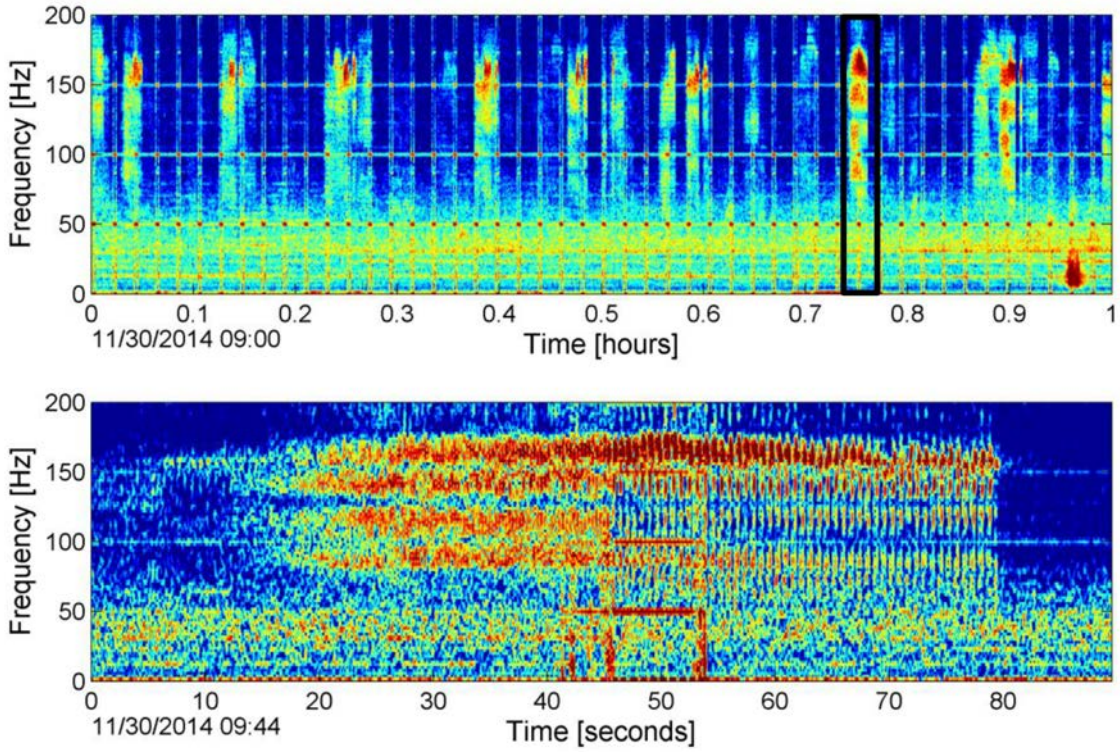

Figure 31: Minke whale pulse train in LTSA (top), with black box indicating the region shown in the corresponding spectrogram (bottom).

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 in the Cape Hatteras study area between 2012 and 2020 (Figure 32). The following results describe site-specific temporal patterns at HAT A and B; we do not infer spatial gradients across the western North Atlantic, and references to other studies are provided only for context.

Goose-beaked and sperm whales were among the most frequently occurring species. Other beaked whales showed more variable presence across years and between sites, with some occurring more often at HAT A and others at HAT B. Mysticete occurrence followed a seasonal pattern, present from fall through spring and not detected in summer, consistent with the use of the Cape Hatteras study area as a migratory passage with opportunities for foraging. Differences between HAT A, located in warmer Gulf Stream waters, and HAT B, just north in cooler slope waters, highlight how small spatial shifts in monitoring location can influence the species composition.

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, wintertime spectral levels increased due to elevated sea states. The relocation of the hydrophone to a position north of the Gulf Stream revealed differences in ambient noise levels and species presence, highlighting the importance of spatial oceanographic context in interpreting passive acoustic data.

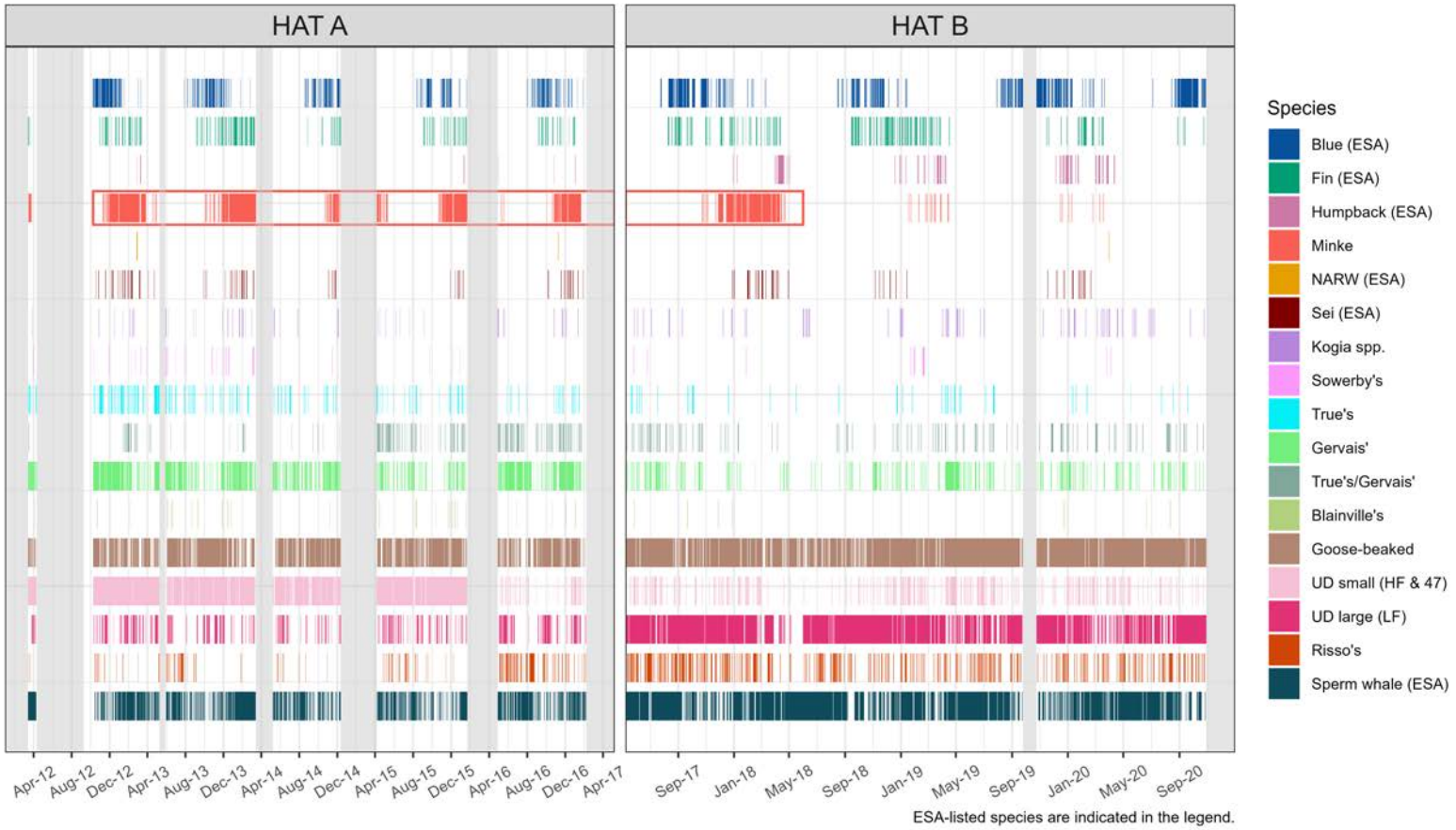

Figure 32: Daily presence of odontocetes and mysticetes at sites HAT A and HAT B from 2012 to 2020. Colored bars indicate days with confirmed acoustic presence for each species or species group. For goose-beaked whales, UD small (HF & 47), and UD large (LF), a 25% daily-occurrence threshold was used 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. In 2017, the instrument was relocated from site A (left) to B (right), leading to changes in species occurrence. The two time series are plotted separately to clearly delineate the two locations. 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 Cape Hatteras sites between 2012 and 2020, with patterns of occurrence varying by species, season, and site (Figure 32). Sperm whales and goose-beaked whales were the most frequently occurring species across the monitoring period, while other beaked whale species, Kogia spp., Risso's dolphins, and several presumed delphinid groups contributed additional layers of variability. The BWG signal was included in the neural network classifier, but no encounters were identified during the analysis period.

Sperm whales were acoustically present year-round at both sites, with occurrence tending to increase in winter and early spring. Goose-beaked whales were also consistently acoustically present throughout the year, with higher occurrence during late fall and winter months. Among the other beaked whales, Gervais' whales showed greater acoustic presence in winter and spring, while True's, Blainville's, and Sowerby's whales were only intermittently present at lower levels. Across most beaked whale species, acoustic presence was higher at HAT A than at HAT B, a difference that likely reflects contrasting oceanographic conditions between the Gulf Stream–influenced southern site and the cooler slope waters to the north.

Kogia spp. were intermittently acoustically present, with variability across years and seasons. Occurrence appeared somewhat higher during transitional seasons such as spring and fall, and diel patterns suggested greater nighttime activity. Risso's dolphins were acoustically present at low to moderate levels throughout the study, with presence spanning nearly the entire monitoring period. Following the relocation to HAT B, their occurrence became more consistent across years, though generally lower in intensity compared to earlier years at HAT A.

Unidentified smaller-bodied delphinids (UD HF & 47) were frequently acoustically present throughout the study period, with sustained occurrence at both sites but generally higher presence at HAT A than at HAT B. In contrast, unidentified larger-bodied delphinids (UD LF) showed greater acoustic presence at HAT B, indicating spatial variability in habitat use among delphinid groups. Across most odontocete taxa and signal-based groups, diel patterns were weak or inconsistent, although Gervais' beaked whales and presumed larger-bodied delphinids (UD LF) exhibited higher acoustic occurrence during nighttime hours.

Together, these results illustrate the species-specific and site-specific nature of odontocete occurrence at Cape Hatteras. The proximity of HAT A and HAT B (40 km apart) yet differing presence patterns emphasize how oceanographic context, in this case, the influence of Gulf Stream waters at HAT A versus cooler slope waters at HAT B, can shape the acoustic community composition in this highly dynamic region.

5.1.1 Goose-Beaked Whale

Goose-beaked whales were the most consistently and frequently occurring beaked whale species at Cape Hatteras from 2012 to 2020. Acoustic presence occurred throughout the year, with weekly acoustic presence regularly exceeding 40-60 hours (Figure 33). An increase in acoustic presence following the hydrophone relocation approximately 17 nm north from site HAT A to HAT B may reflect a preference for cooler waters, as HAT B is typically located north of the Gulf Stream. A seasonal increase in presence was observed in the fall and winter at site HAT A, while HAT B exhibited more consistent presence throughout the year, with an increase of presence in the spring and summer (Figure 34). No consistent diel pattern was evident in goose-beaked whale acoustic presence, suggesting relatively uniform acoustic activity throughout the day (Figure 35).

These results are consistent with previous studies showing that goose-beaked whales occur year-round at high levels from Cape Hatteras northward, with increased prevalence in winter and spring and limited presence south of Hatteras, as well as with satellite-tagging and photo-identification studies demonstrating a resident population of Cuvier's beaked whales off Cape Hatteras (Haver et al. 2025; Cohen et al. 2022; Stanistreet et al. 2022; Cohen et al. 2023; DeAngelis et al. 2025; Foley et al. 2021).

Summary of Results – Goose-beaked whale

- Goose-beaked whales were the most frequently detected beaked whale species.
- Seasonal increases in acoustic presence were observed in the fall and winter at site HAT A, while HAT B showed relatively consistent presence across all months, with a small increase in presence in the spring and summer.
- No clear diel pattern was observed.
- Acoustic presence increased after the hydrophone was moved north from HAT A to HAT B.

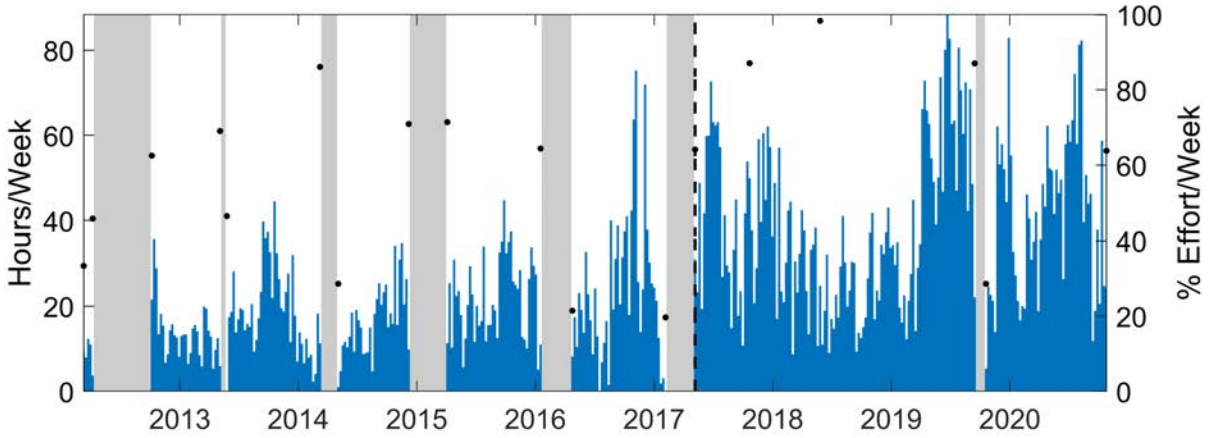

Figure 33: Cumulative hours/week of goose-beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

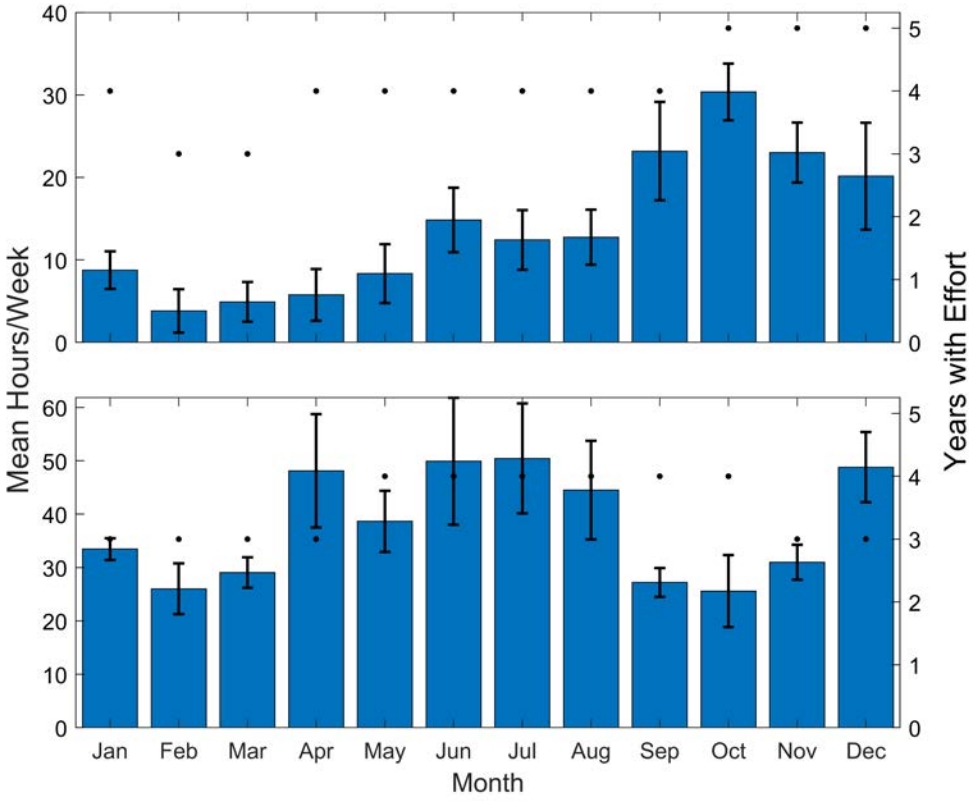

Figure 34: Monthly mean hours per week of goose-beaked whale acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black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

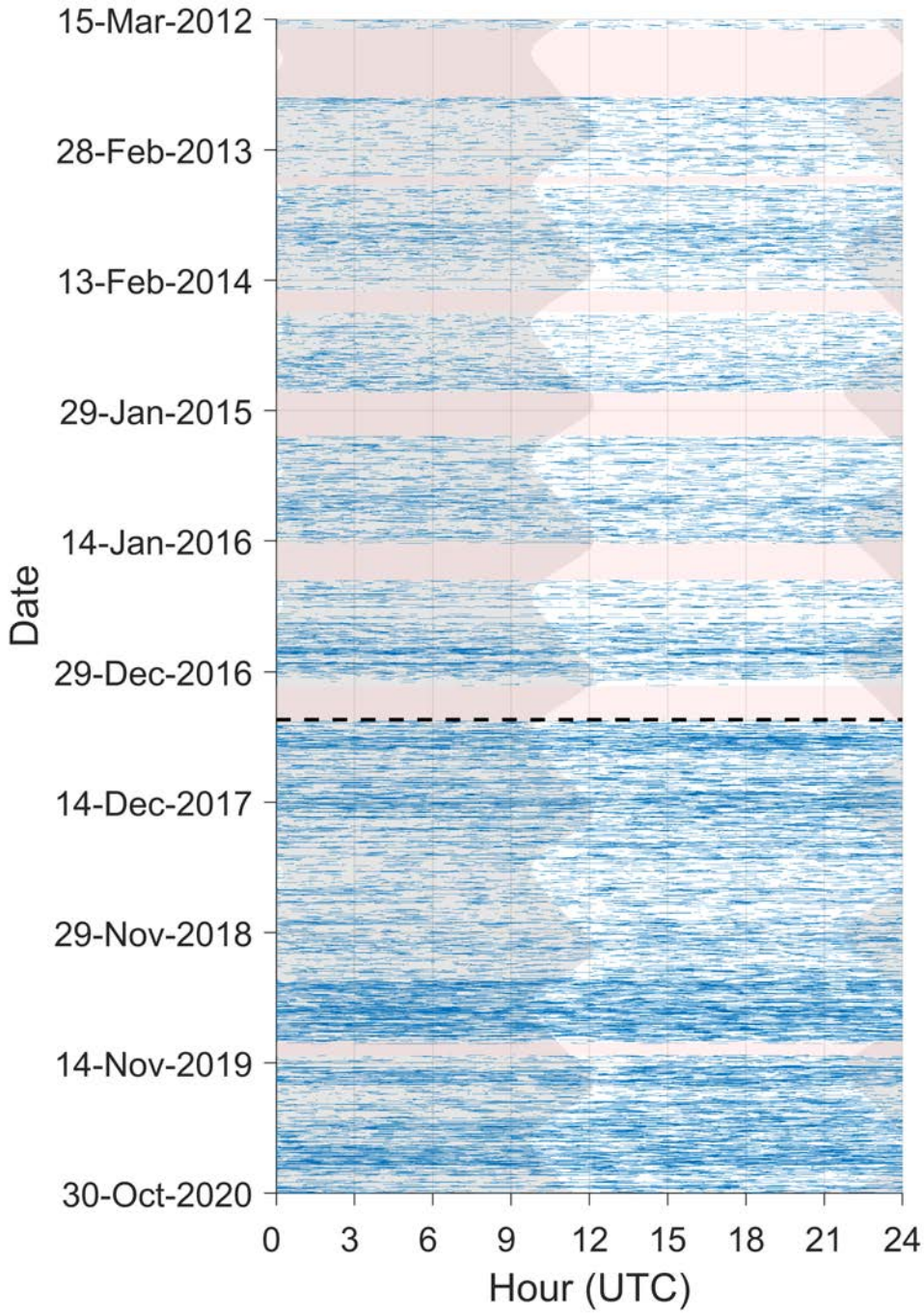

Figure 35: Goose-beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.2 Gervais' and True's Beaked Whales

Gervais' and True's beaked whales both occurred at Cape Hatteras between 2012 and 2020, with Gervais' whales exhibiting higher levels of acoustic presence compared to True's. 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. Gervais' and True's acoustic presence occurred across all months, with no clear seasonal pattern at either HAT site (Figure 37).

Gervais' beaked whales generally occurred at low to moderate levels across the 2012–2020 period, with weekly acoustic presence ranging from 5 to 10 hours on average (Figure 36). Occurrence appeared lower following the hydrophone relocation to site HAT B, which may reflect differences in site conditions or a preference for warmer waters or prey more commonly found within or south of the Gulf Stream. A weak nocturnal diel pattern was evident, with slightly higher acoustic presence during nighttime (Figure 38).

True's beaked whales occurred less frequently during the recording period, with an average presence of less than an hour per week (Figure 36). Acoustic presence decreased following the transition from site HAT A to HAT B, possibly due to a preference for warmer waters or prey types found further south. No consistent diel pattern was observed, likely due to the limited number of detections (Figure 38).

These results are consistent with previous studies that found Gervais' beaked whales are much more common than True's at Cape Hatteras, with Gervais' detections peaking from late summer through winter, while True's occur less frequently and are primarily present from winter through 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

- Gervais' beaked whales generally occurred at low to moderate levels throughout the study period, while True's beaked whales occurred less frequently.
- Both species occurred across all months with no clear seasonal pattern at either HAT site.
- A weak nocturnal diel pattern was observed for Gervais' beaked whales; no consistent diel pattern was evident for True's beaked whales.
- Reduced acoustic presence was observed for both species after the hydrophone relocation from HAT A to HAT B.

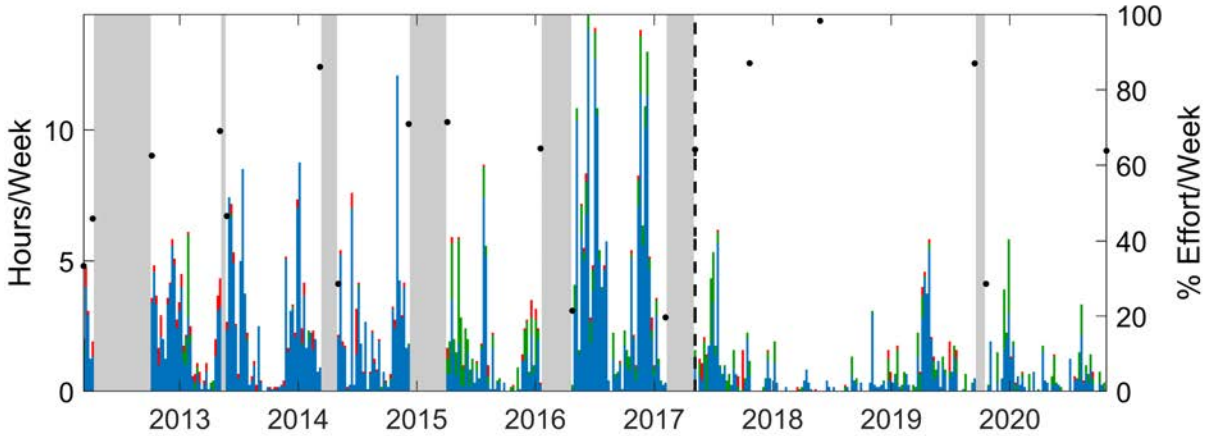

Figure 36: Cumulative hours/week of Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

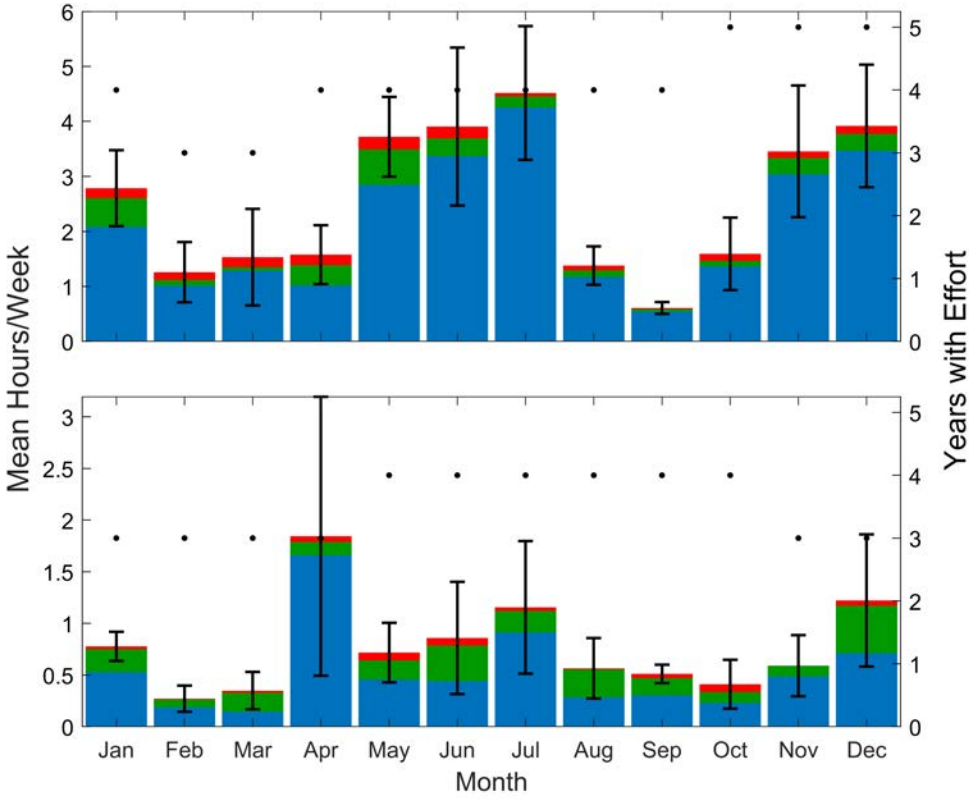

Figure 37: Monthly mean hours per week of Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with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

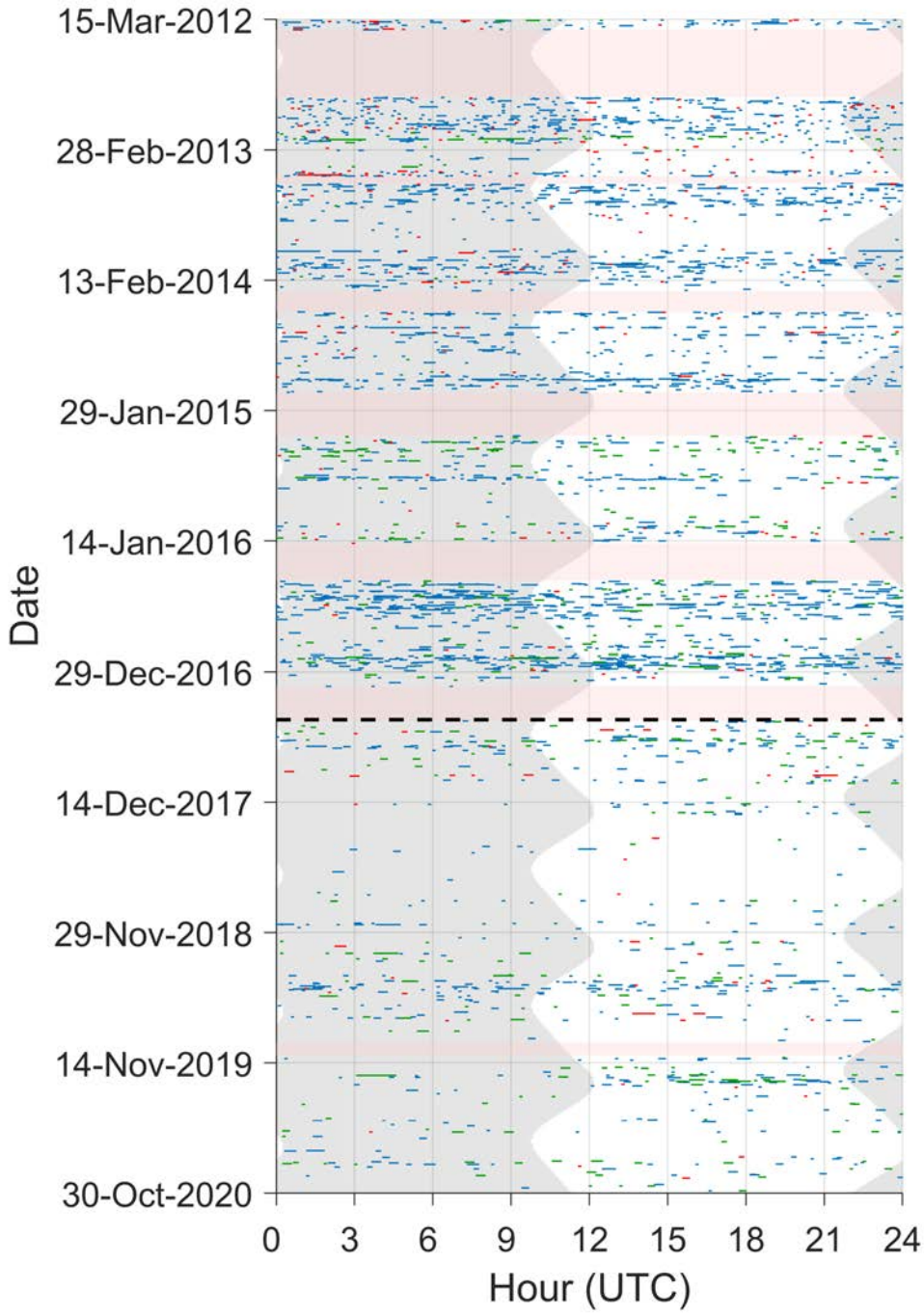

Figure 38: Gervais' (blue), True's (red), and unclassified Gervais'/True's (green) beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.3 Blainville's Beaked Whale

Blainville's beaked whales sporadically occurred throughout the 2012–2020 recording period at Cape Hatteras, never exceeding more than 30 minutes in a single week (Figure 39). There appeared to be a slight increase in the fall and winter, particularly at site HAT A (Figure 40). Reduced acoustic presence was observed following the hydrophone move from site HAT A to site HAT B, which may reflect a lower occurrence of suitable habitat or prey in the cooler waters north of the Gulf Stream. Due to less frequent acoustic presence, no consistent diel pattern was observed (Figure 41).

These results are consistent with previous studies that found Blainville's beaked whales are infrequently detected in the region and not associated with a major foraging hotspot (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 sporadically occurred, with low average weekly presence across the recording period.
- A slight seasonal increase in presence was observed in the fall and winter, particularly at site HAT A.
- No consistent diel pattern was observed due to infrequent acoustic presence.
- Reduced acoustic presence was observed following the hydrophone relocation from site HAT A to site HAT B.

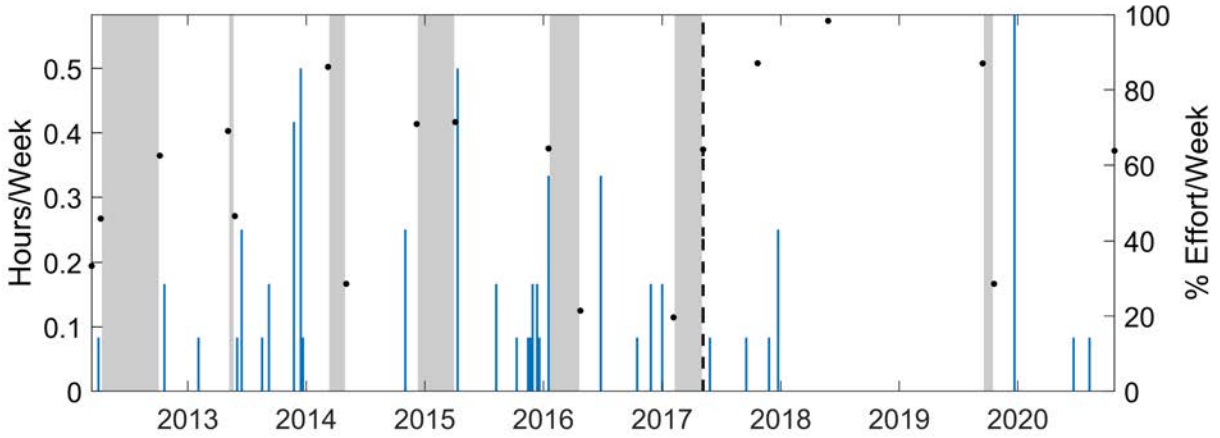

Figure 39: Cumulative hours/week of Blainville's beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

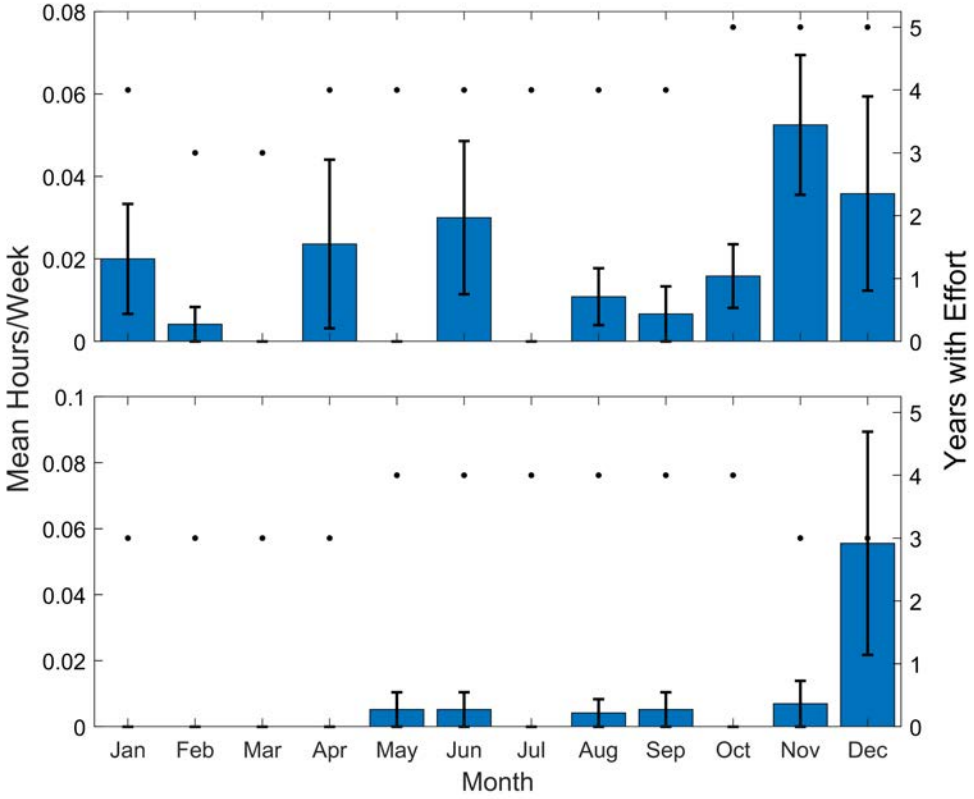

Figure 40: Monthly mean hours per week of Blainville's beaked whale acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by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

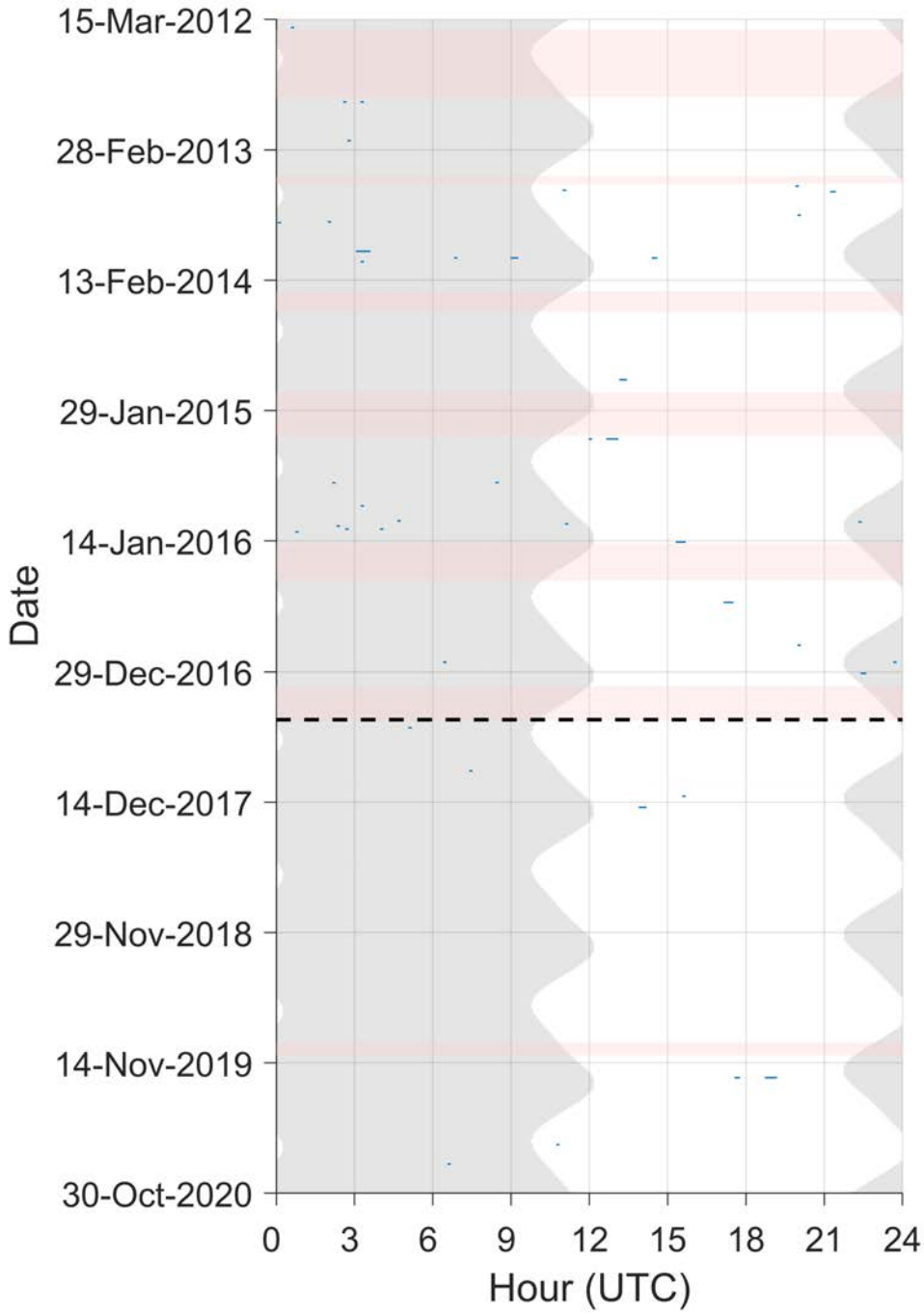

Figure 41: Blainville's beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.4 Sowerby's Beaked Whale

Sowerby's beaked whales exhibited the lowest overall acoustic presence among the five species recorded at Cape Hatteras between 2012 and 2020. Weekly acoustic presence was low, typically under 30 minutes per week, and long stretches of weeks to months passed without any acoustic presence (Figure 42). Acoustic presence peaked in the winter and early spring, with very limited presence during the rest of the year (Figure 43). Presence remained limited following the relocation of the hydrophone to site HAT B. This continued low presence may reflect sparse regional occurrence or limited prey availability in the cooler waters north of the Gulf Stream. No consistent diel pattern was observed for this species, likely due to the low number of encounters (Figure 44).

These results are consistent with previous studies that found Sowerby's beaked whales are uncommon at Cape Hatteras, with their main foraging hotspots occurring farther north, particularly north of Norfolk Canyon (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 the lowest overall acoustic presence among the five species recorded, with less frequent acoustic presence across the study period.
- Acoustic presence peaked in the winter and early spring, with limited presence during the remainder of the year.
- No consistent diel pattern was observed, likely due to the low number of encounters.
- Presence remained low following the hydrophone relocation from site HAT A to site HAT B.

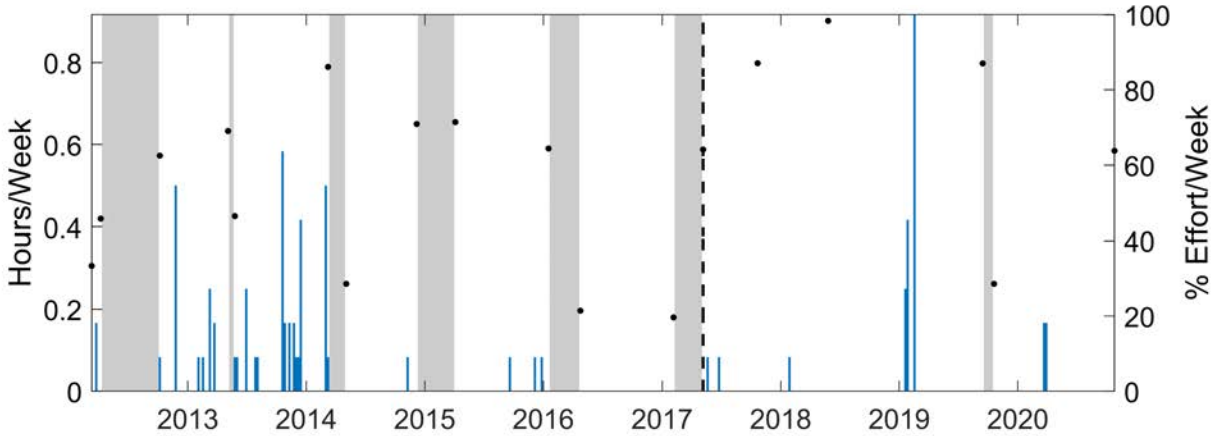

Figure 42: Cumulative hours/week of Sowerby's beaked whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

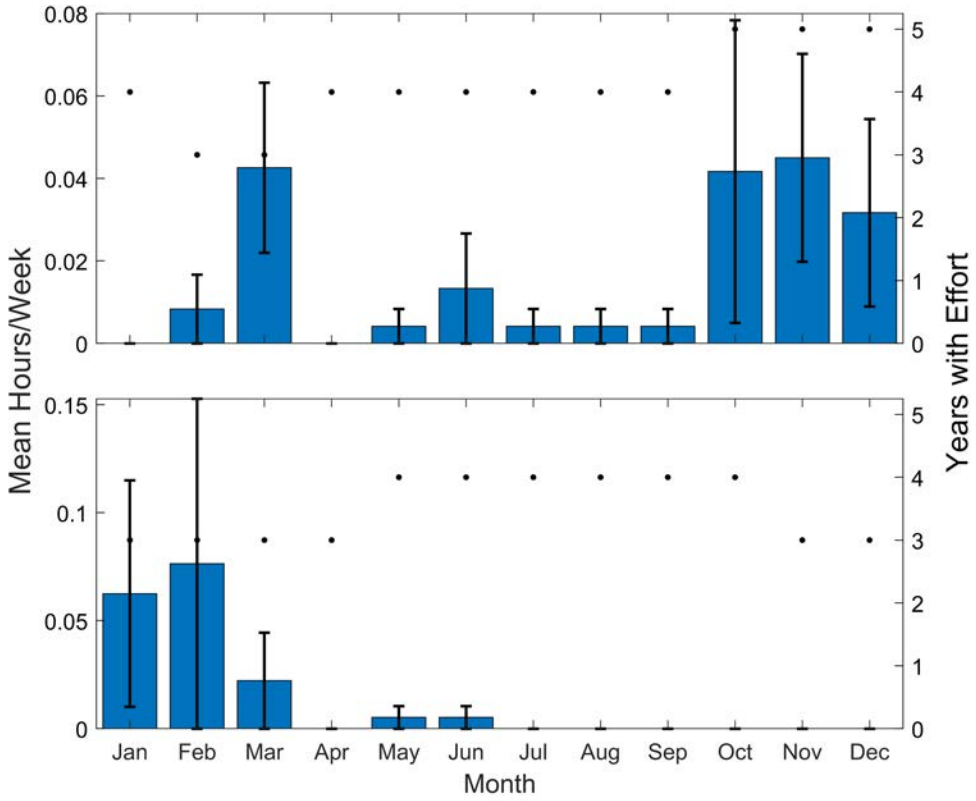

Figure 43: Monthly mean hours per week of Sowerby's beaked whale acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the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

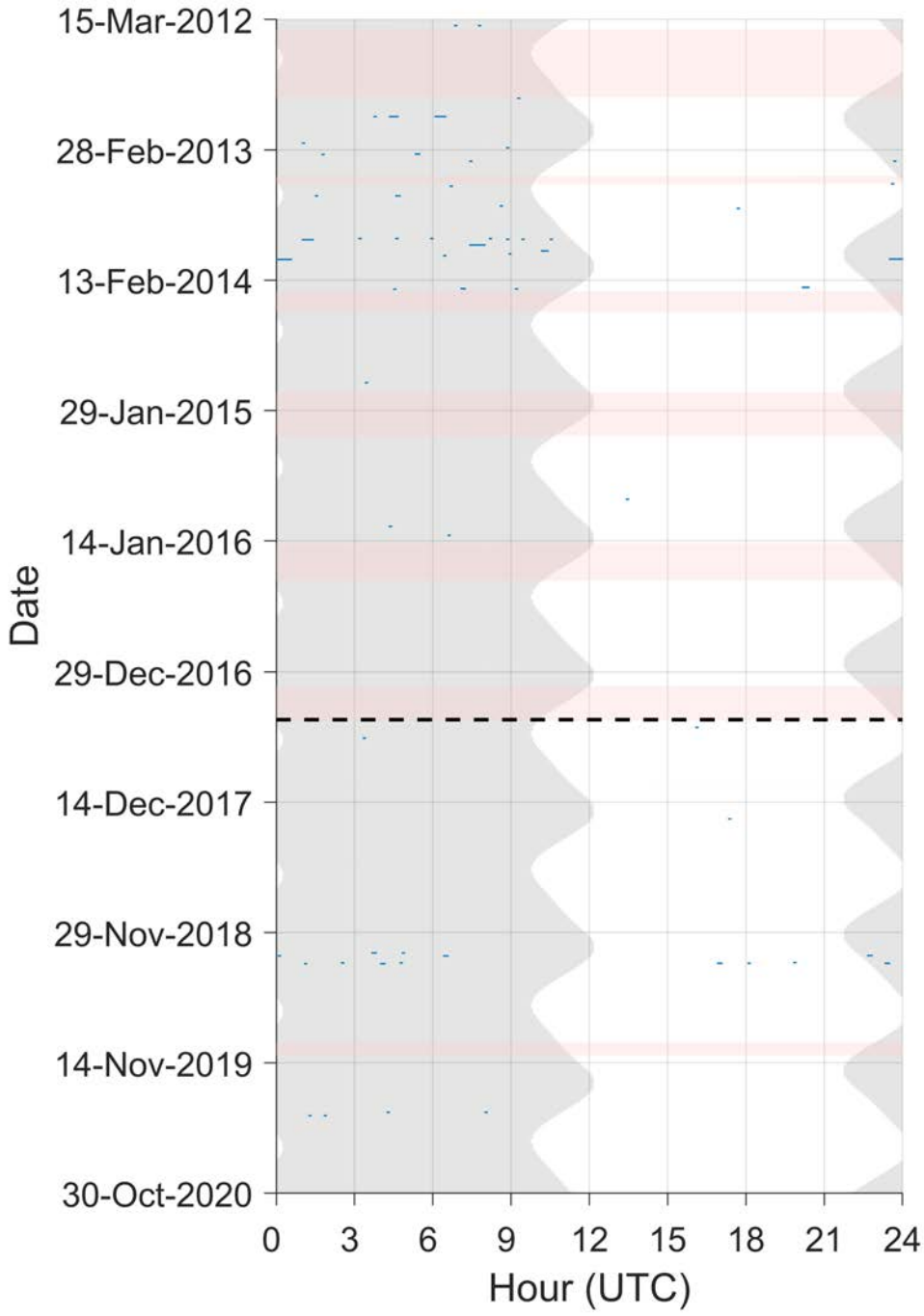

Figure 44: Sowerby's beaked whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.5 Sperm Whale

Sperm whales consistently occurred at Cape Hatteras from 2012 to 2020, exhibiting sustained acoustic presence with moderate seasonal variability. Weekly cumulative acoustic presence ranged between 40–100 hours, with several weeks surpassing 120 hours (Figure 45). Sperm whales showed distinct seasonal and spatial differences, with peak presence in winter at site HAT A and in late spring and summer at HAT B (Figure 46). Following the relocation of the hydrophone array from site HAT A to HAT B, there was a noticeable increase in sperm whale presence, potentially due to increased prey that prefer the cooler waters north of the Gulf Stream. No consistent 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 that found sperm whales are regularly detected along the slope at Cape Hatteras, with year-round presence and higher prevalence in winter, identifying the region as an important foraging area (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.
- Peak presence occurred in winter at site HAT A and in late spring and summer at site HAT B, indicating seasonal and spatial variation.
- No consistent diel pattern was observed; sperm whales were vocally active during both day and night.
- Acoustic presence increased following the relocation of the hydrophone from site HAT A to site HAT B.

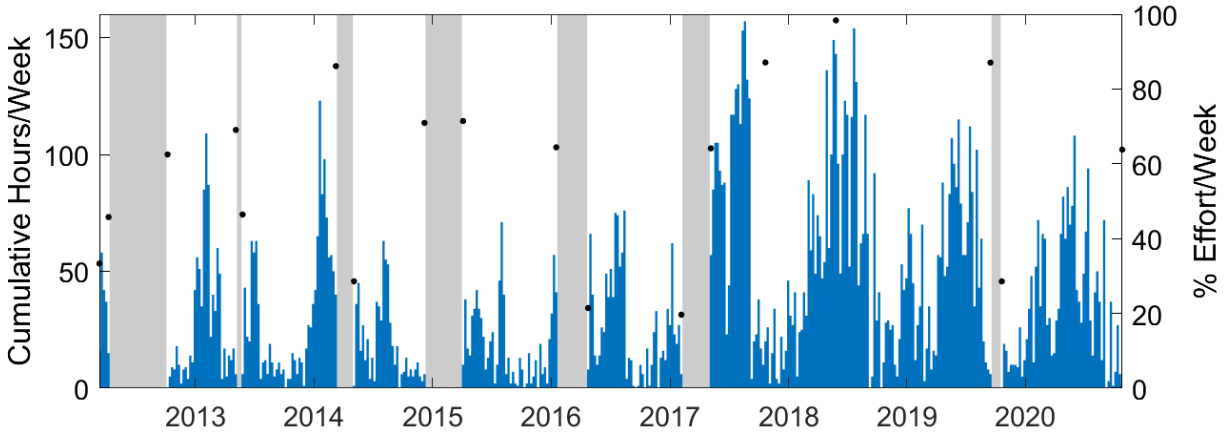

Figure 45: Cumulative hours/week of sperm whale presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

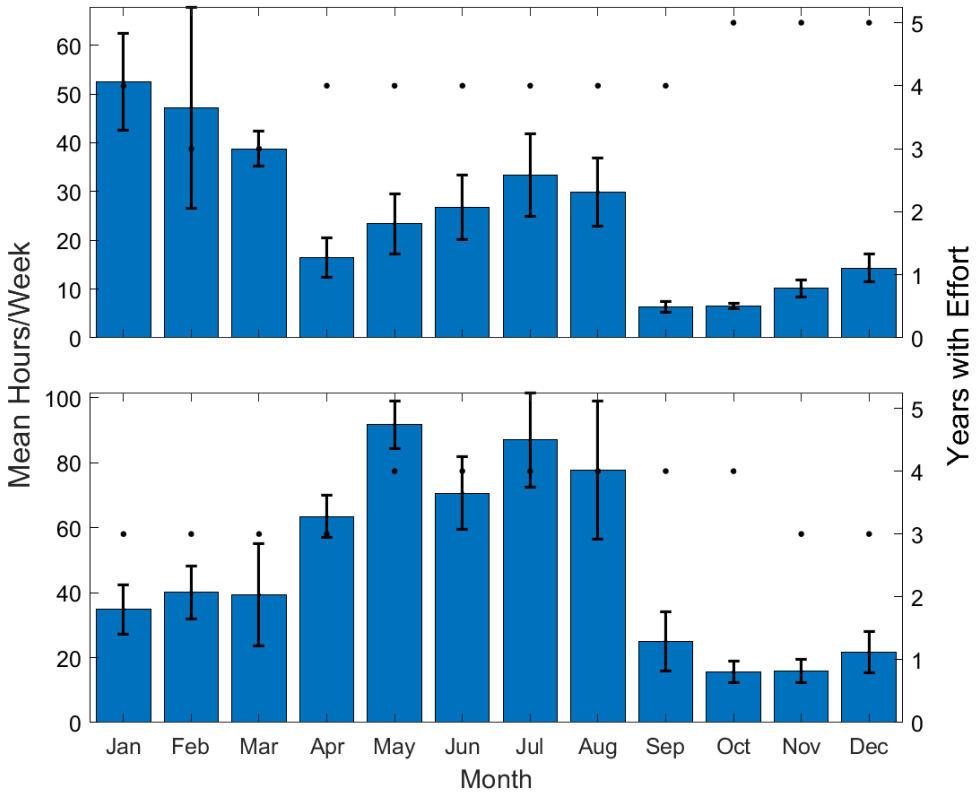

Figure 46: Monthly mean hours per week of sperm whale acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

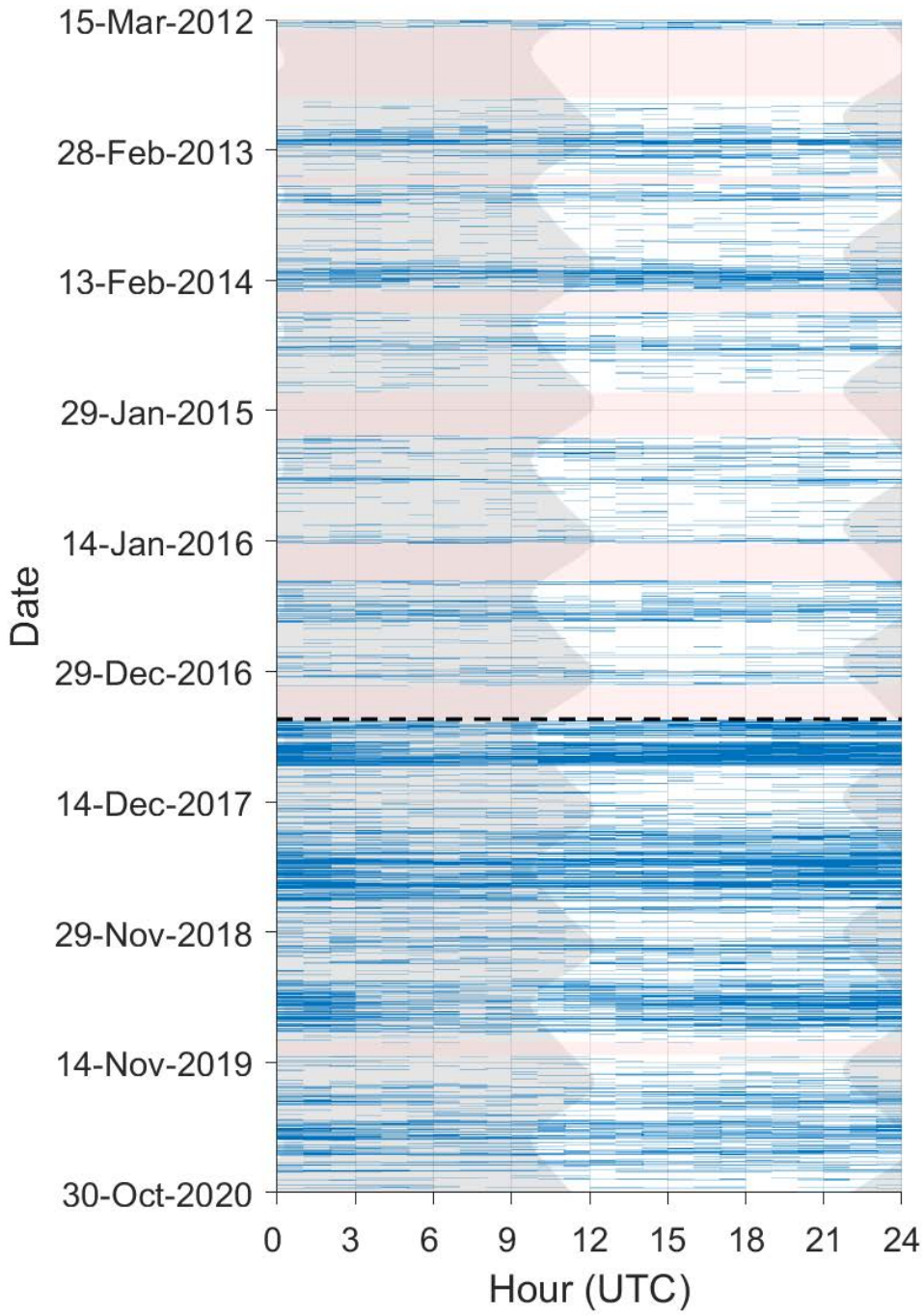

Figure 47: Sperm whale acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.6 *Kogia* spp.

Kogia spp. exhibited low acoustic presence at Cape Hatteras from 2012 to 2020, with sporadic presence across all years of the study period never exceeding a weekly presence of 1-hour (Figure 48). A weak seasonal trend was observed, with less presence in the late summer and fall months (Figure 49). Presence remained relatively consistent following the hydrophone relocation to site HAT B. A weak diel pattern was observed, with more acoustic presence occurring during nighttime and early morning hours (Figure 50), consistent with nocturnal foraging behavior reported for this genus.

These results are consistent with previous studies that found Kogia spp. occur year-round at relatively low levels at Cape Hatteras, with higher occurrence in southern slope waters, indicating that Hatteras represents the northern edge of their main distribution (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023).

Summary of Results – *Kogia* spp.

- *Kogia* spp. showed low acoustic presence at Cape Hatteras across all years of the study.
- Acoustic presence decreased in the late summer and fall.
- Acoustic presence remained consistent after the hydrophone relocation from site HAT A to site HAT B.
- A diel pattern was evident, with increased presence at night and in early morning hours.

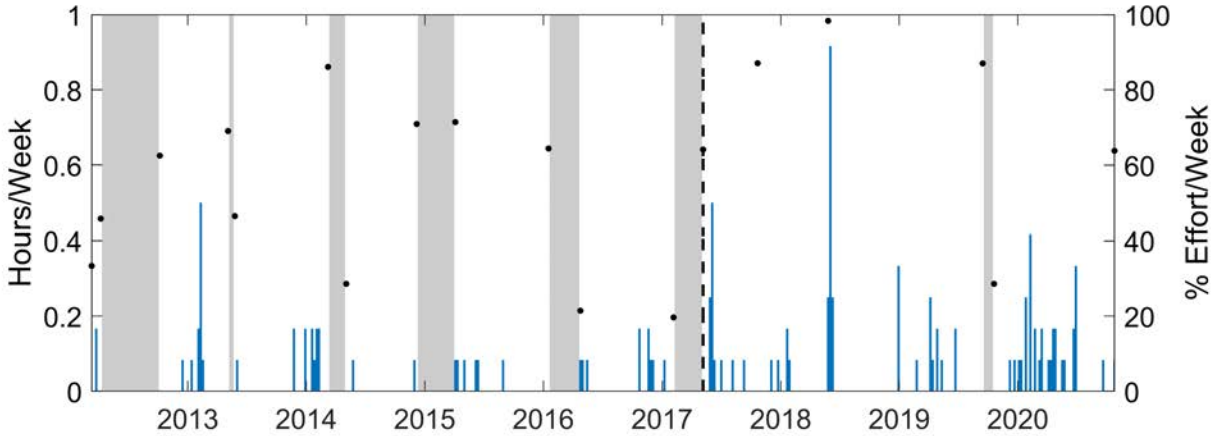

Figure 48: Cumulative hours/week of *Kogia* spp. presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

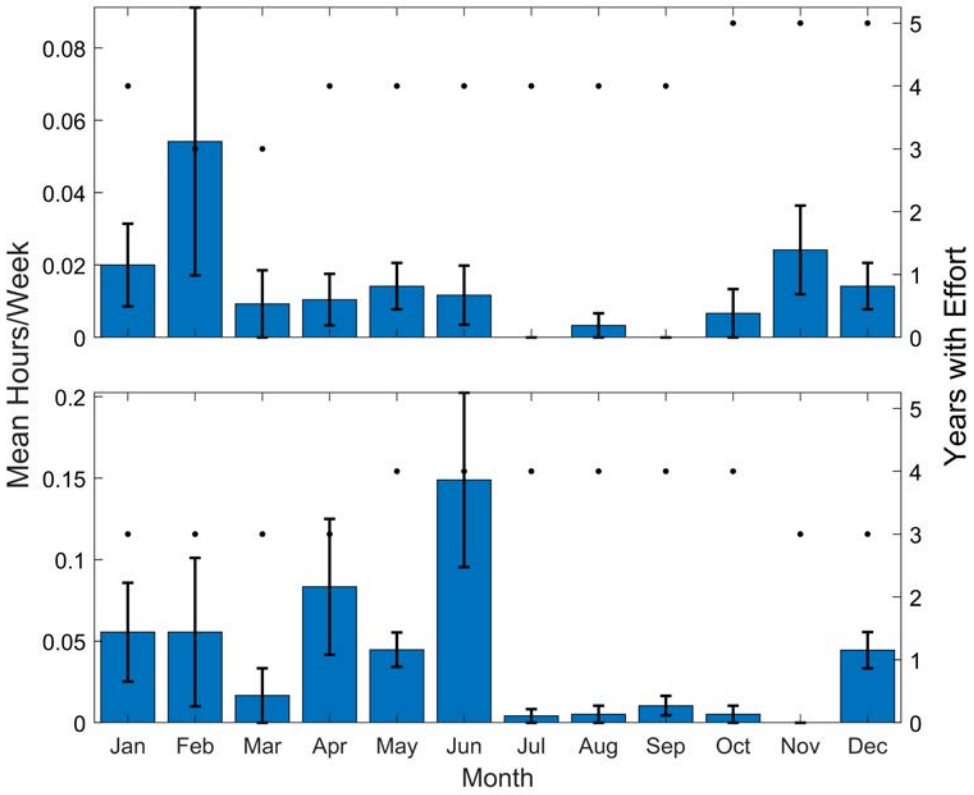

Figure 49: Monthly mean hours per week of *Kogia* spp. acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

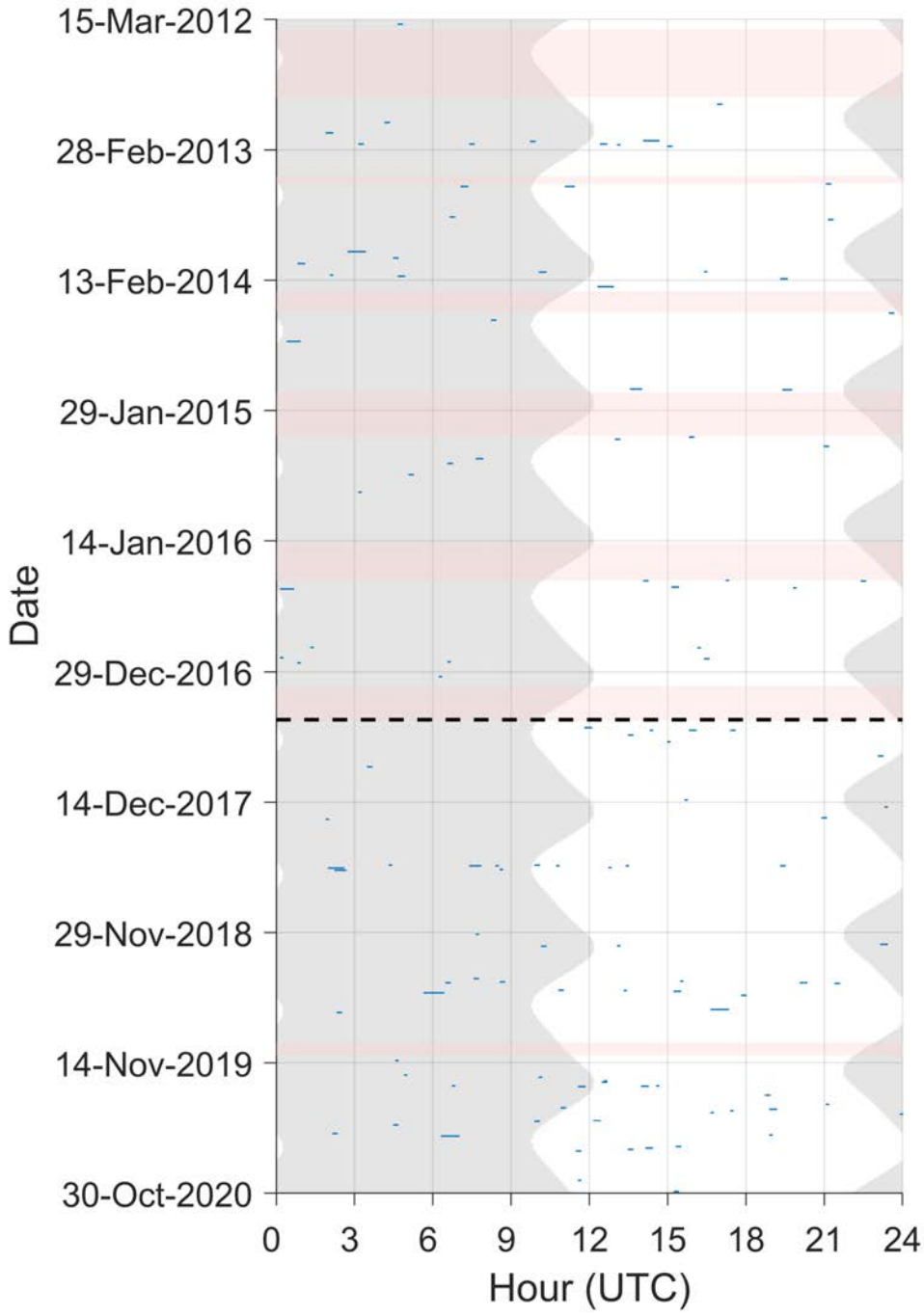

Figure 50: *Kogia* spp. acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

5.1.7 Risso's Dolphin

Risso's dolphins were present at low to moderate levels at Cape Hatteras between 2012 and 2020, spanning nearly the entire study period (Figure 51). Weekly acoustic presence was typically under 5 hours, with a brief period of elevated presence in 2016–2017. Prior to the hydrophone relocation from site HAT A to HAT B, presence was less consistent but occasionally included weeks with higher levels of acoustic activity. Following the move to HAT B, presence appeared more evenly distributed across years, although individual weeks typically showed lower intensity. Seasonally, Risso's dolphins showed a clear increase in presence during the summer months at both HAT A and HAT B (Figure 52). Presence was lowest from January through April and rose steadily through late summer, peaking in July and August. These patterns suggest seasonal habitat use, potentially linked to shifts in prey availability or oceanographic conditions. The diel pattern was relatively uniform, with presence throughout all hours of the day and night and no clear preference for specific time periods (Figure 53).

These results are consistent with previous studies that found Risso's dolphins were commonly detected year-round but most prevalent in summer and fall, identifying the region as important foraging habitat (Baumgartner & Mussoline 2011; Haver et al. 2025; Cohen et al. 2023).

Summary of Results – Risso's Dolphin

- Risso's dolphins consistently occurred throughout the study period at low to moderate levels with an anomalously high presence in 2016-2017.
- Presence peaked during summer months, particularly in July and August.
- Occurrence was higher at HAT B, reflecting a potential preference for cooler waters above the gulf stream.
- No consistent diel trend was observed, with presence distributed throughout the day.

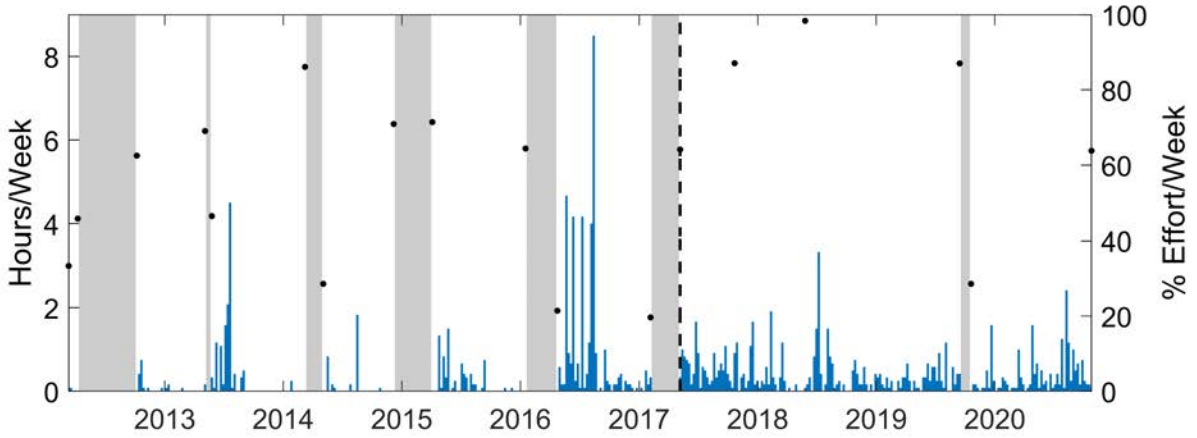

Figure 51: Cumulative hours/week of Risso's dolphin presence. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The black dashed line delineates the location change from site HAT A to HAT B.

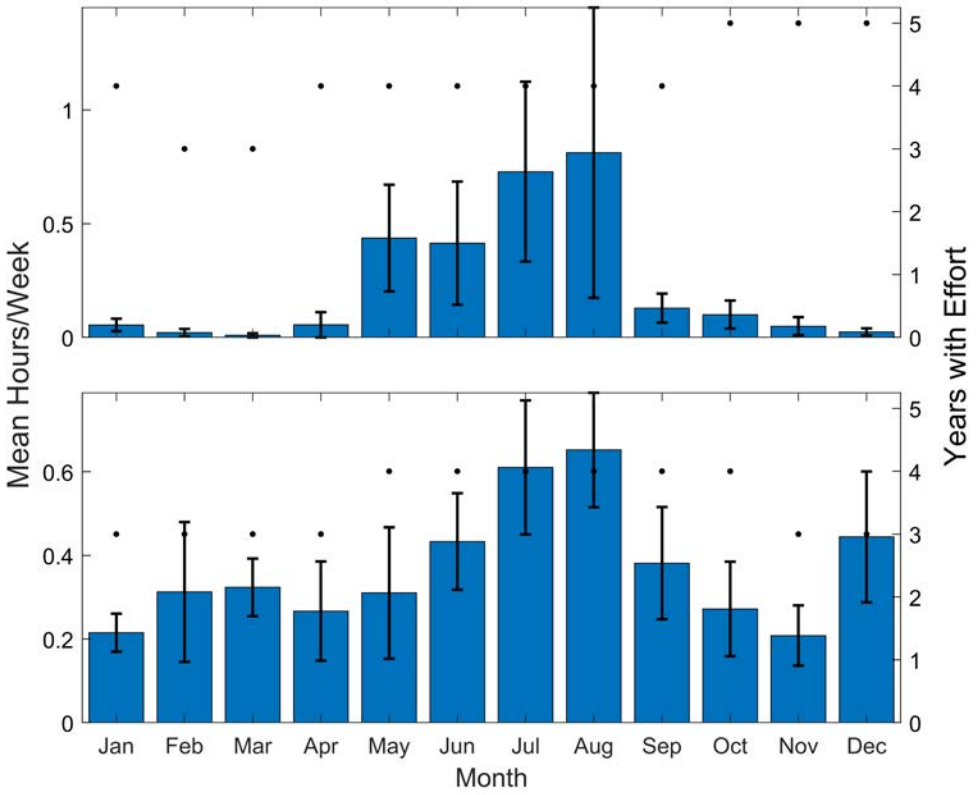

Figure 52: Monthly mean hours per week of Risso's dolphin acoustic presence at sites HAT A (top) and B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black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

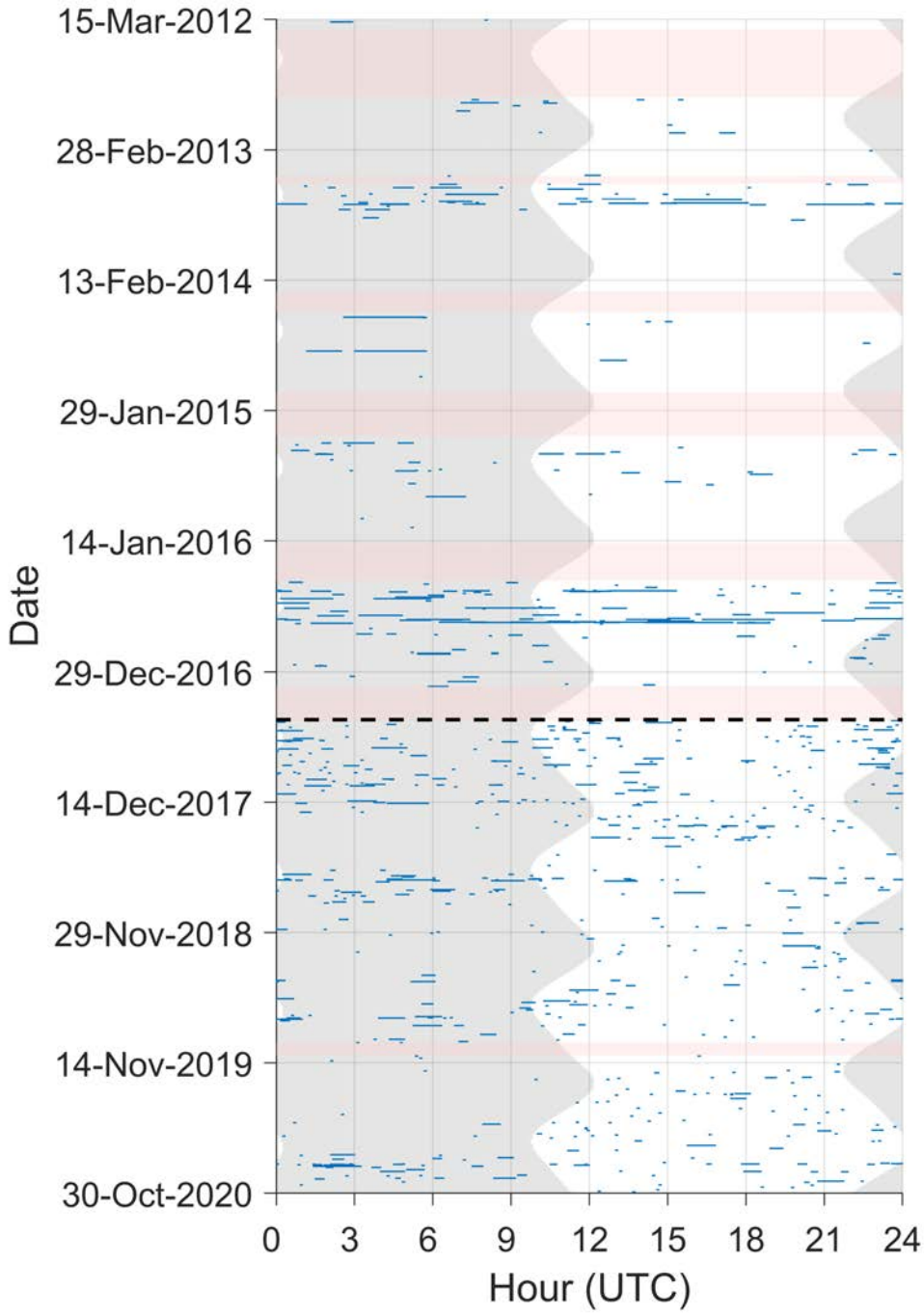

Figure 53: Risso's dolphin acoustic presence in 5-min bins. Gray vertical shading denotes nighttime and light red horizontal shading indicate times of no effort. The black dashed line delineates the location change from site HAT A to HAT B.

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 consistently acoustically present at Cape Hatteras from 2012 to 2020. Acoustic presence was generally high, frequently exceeding 50 hours per week (Figure 54). A reduction in acoustic presence was observed beginning in 2016, prior to the formal relocation of the hydrophone. This decrease coincided with a subtle shift in the hydrophone position during the final deployment at site HAT A, suggesting that even small spatial changes may influence detection rates in this highly dynamic region. Following relocation to site HAT B in late 2016, acoustic presence remained consistently lower, indicating spatial variability in the distribution or habitat use of smaller-bodied delphinids across the two sites.

No consistent seasonal pattern was evident for this group (Figure 55). In contrast, diel patterns were apparent across years, with acoustic presence most common during early morning hours (Figure 56), indicating persistent nocturnal or crepuscular activity.

These results are consistent with previous studies showing that smaller-bodied delphinids producing UD HF & 47 clicks are detected year-round along the western North Atlantic slope, with higher prevalence during summer and fall and strong nocturnal detection patterns consistent with nighttime foraging behavior (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023).

Summary of Results – Smaller-Bodied Delphinids (UD HF & 47)

- Smaller-bodied delphinids were consistently present throughout the monitoring period, with generally high levels of acoustic presence.
- Weekly acoustic presence frequently exceeded 50 hours.
- No clear seasonal trends were observed.
- Diel patterns were evident, with peak acoustic activity during early morning hours.

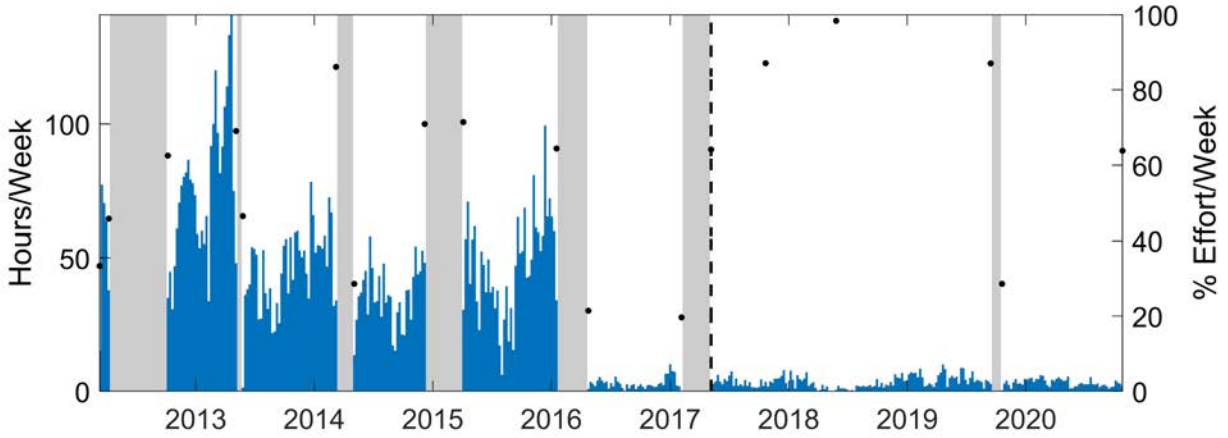

Figure 54: Cumulative hours/week of smaller-bodied delphinid (UD HF & 47) presence. Gray bars indicate periods of no recording effort, and black dots represent weeks with partial effort. The black dashed line denotes the relocation of the hydrophone from site HAT A to site HAT B.

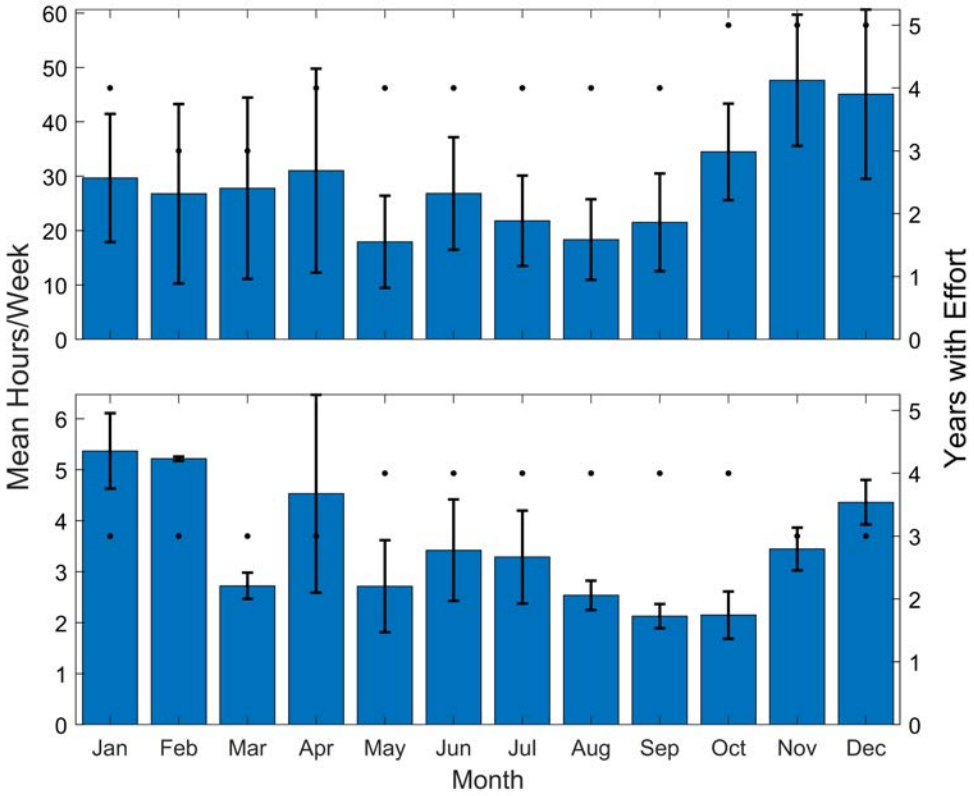

Figure 55: Monthly mean hours per week of smaller-bodied delphinid (UD HF & 47) acoustic presence at sites HAT A (top) and HAT B (bottom). Bars indicate monthly means (left y-axis), error bars represent standard error across years, and black dots denote years with recording effort for each month (right y-axis).

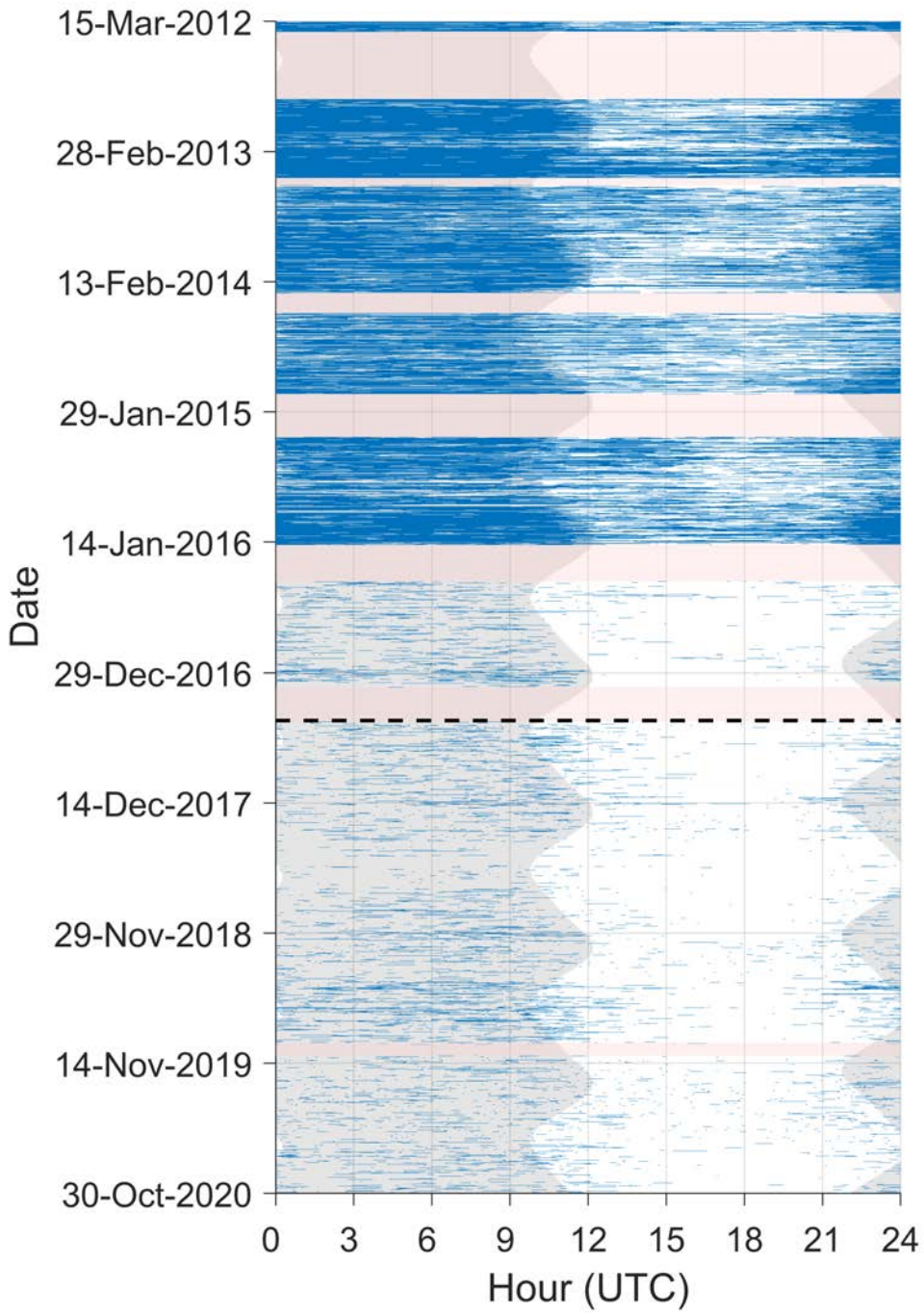

Figure 56: Smaller-bodied delphinid (UD HF & 47) acoustic presence in 5-min bins. Gray vertical shading denotes nighttime hours, and light red horizontal shading indicates periods of no recording effort. The black dashed line denotes the relocation of the hydrophone from site HAT A to site HAT B.

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 regularly acoustically present at Cape Hatteras from 2012 to 2020, with moderate to high levels of occurrence throughout the monitoring period. At site HAT A, weekly acoustic presence averaged approximately 20 hours. Following relocation of the hydrophone to site HAT B in 2017, acoustic presence increased substantially, with weekly values typically ranging between 50 and 100 hours and several weeks exceeding 100 hours (Figure 57).

A modest seasonal decrease in acoustic presence was observed during spring months at site HAT B, although presence remained relatively high throughout the remainder of the year (Figure 58). No consistent diel pattern was evident for this group (Figure 59), suggesting relatively uniform acoustic activity throughout the day.

These results are consistent with previous studies demonstrating year-round occurrence of larger-bodied delphinids producing UD LF clicks along the western North Atlantic slope, with higher prevalence during summer and fall and identifying Cape Hatteras as an important foraging area for large delphinids (Haver et al. 2025; Cohen et al. 2022; Cohen et al. 2023; Leu et al. 2022).

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

- Larger-bodied delphinids were consistently present from 2012 to 2020.
- Acoustic presence increased substantially following relocation to site HAT B.
- A seasonal dip in presence was observed during spring months at site HAT B.
- No consistent diel pattern was evident.

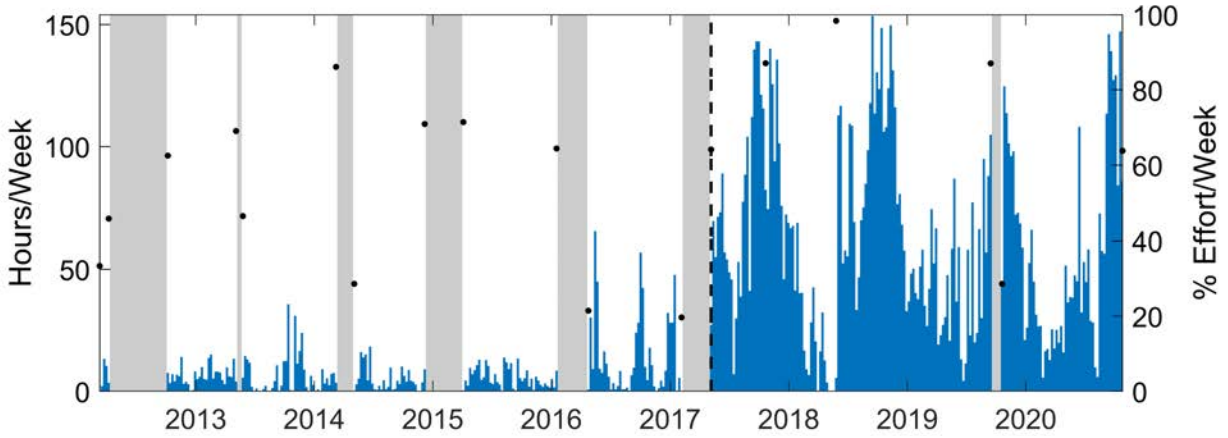

Figure 57: Cumulative hours/week for larger-bodied delphinid (UD LF) presence. Gray bars indicate periods of no recording effort, and black dots represent weeks with partial effort. The black dashed line denotes the relocation of the hydrophone from site HAT A to site HAT B.

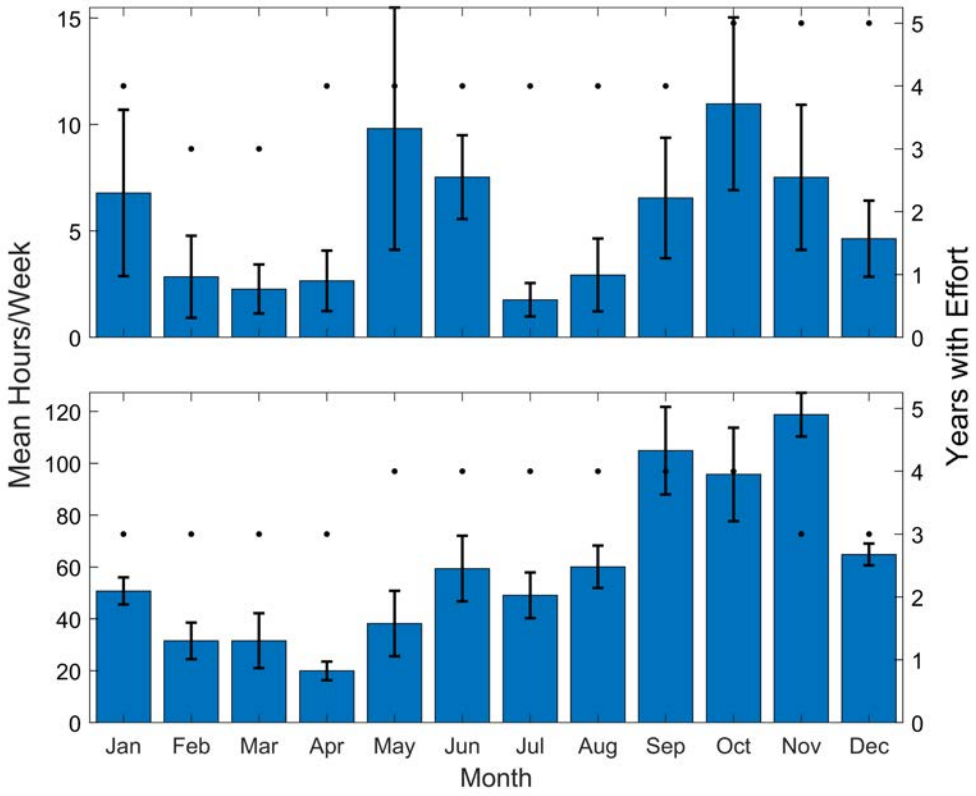

Figure 58: Monthly mean hours per week of larger-bodied delphinid (UD LF) acoustic presence at sites HAT A (top) and HAT B (bottom). Bars indicate monthly means (left y-axis), error bars represent standard error across years, and black dots denote years with recording effort for each month (right y-axis).

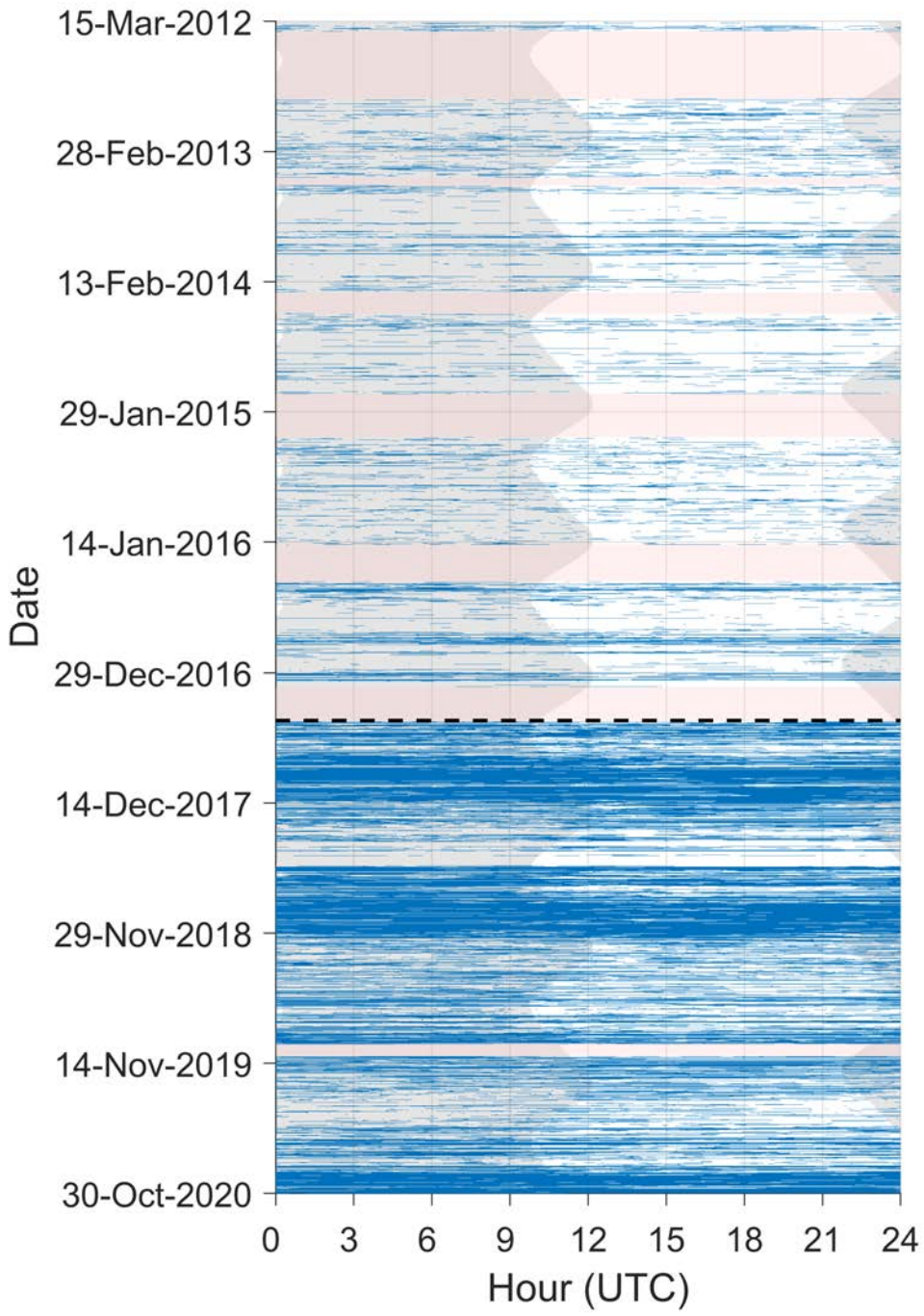

Figure 59: Larger-bodied delphinid (UD LF) acoustic presence in 5-min bins. Gray vertical shading denotes nighttime hours, and light red horizontal shading indicates periods of no recording effort. The black dashed line denotes the relocation of the hydrophone from site HAT A to site HAT B.

5.2 Mysticetes

Mysticetes at Cape Hatteras exhibited distinct seasonal and interannual variation in acoustic presence (Figure 60 & 61). Most species were acoustically present from fall through spring and not detected in summer, consistent with the role of Cape Hatteras as a migratory passage with seasonal foraging opportunities.

Fin, minke, and sei whales showed the most consistent presence within this seasonal window, particularly at the southern site (HAT A), where Gulf Stream–influenced waters may support enhanced foraging conditions. Minke whales were frequently present in winter and spring, with additional calling in late fall. Fin whales were broadly present from fall through spring, while sei whales were also more commonly acoustically present at HAT A during late fall and winter months.

Blue whales differed somewhat from this pattern, with acoustic presence extending from late summer through early winter. Their occurrence was more pronounced at HAT B, suggesting stronger use of the cooler slope waters north of the Gulf Stream. Humpback whale acoustic presence increased notably in the latter part of the study at HAT B, particularly during late winter and early spring, after being limited in earlier years. North Atlantic right whales were only occasionally acoustically present, generally during spring and fall, consistent with migratory passage through the region rather than sustained foraging use.

These results highlight both the shared seasonal patterns of mysticetes at Cape Hatteras and the site-specific differences between HAT A and HAT B. The contrast between higher occurrence of minke, fin, and sei whales at HAT A and the stronger presence of blue and humpback whales at HAT B underscores how species composition can shift across relatively small spatial scales in this dynamic oceanographic setting.

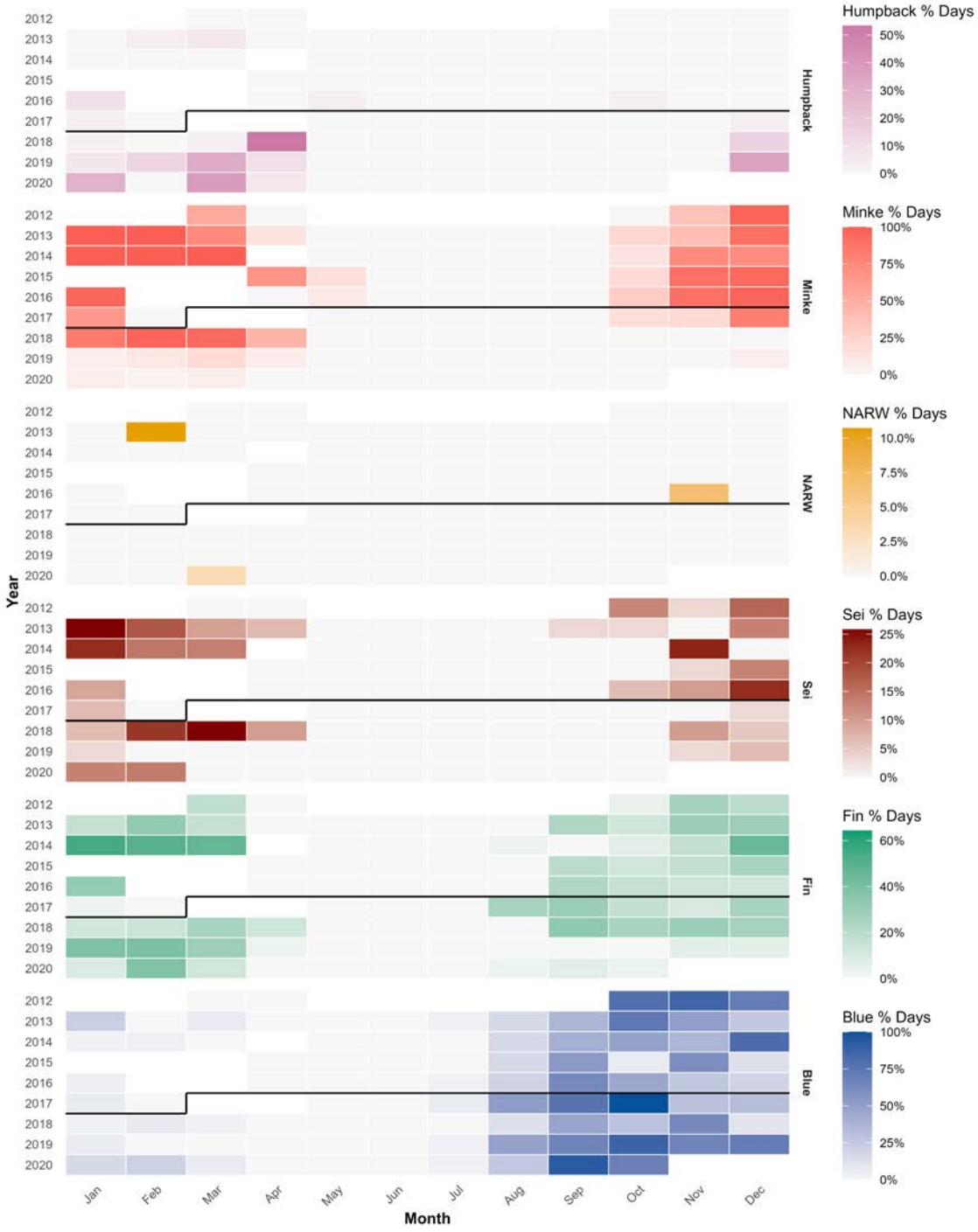

Figure 60: Annual monthly acoustic presence by species, represented as the percentage of days each species was detected per month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site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

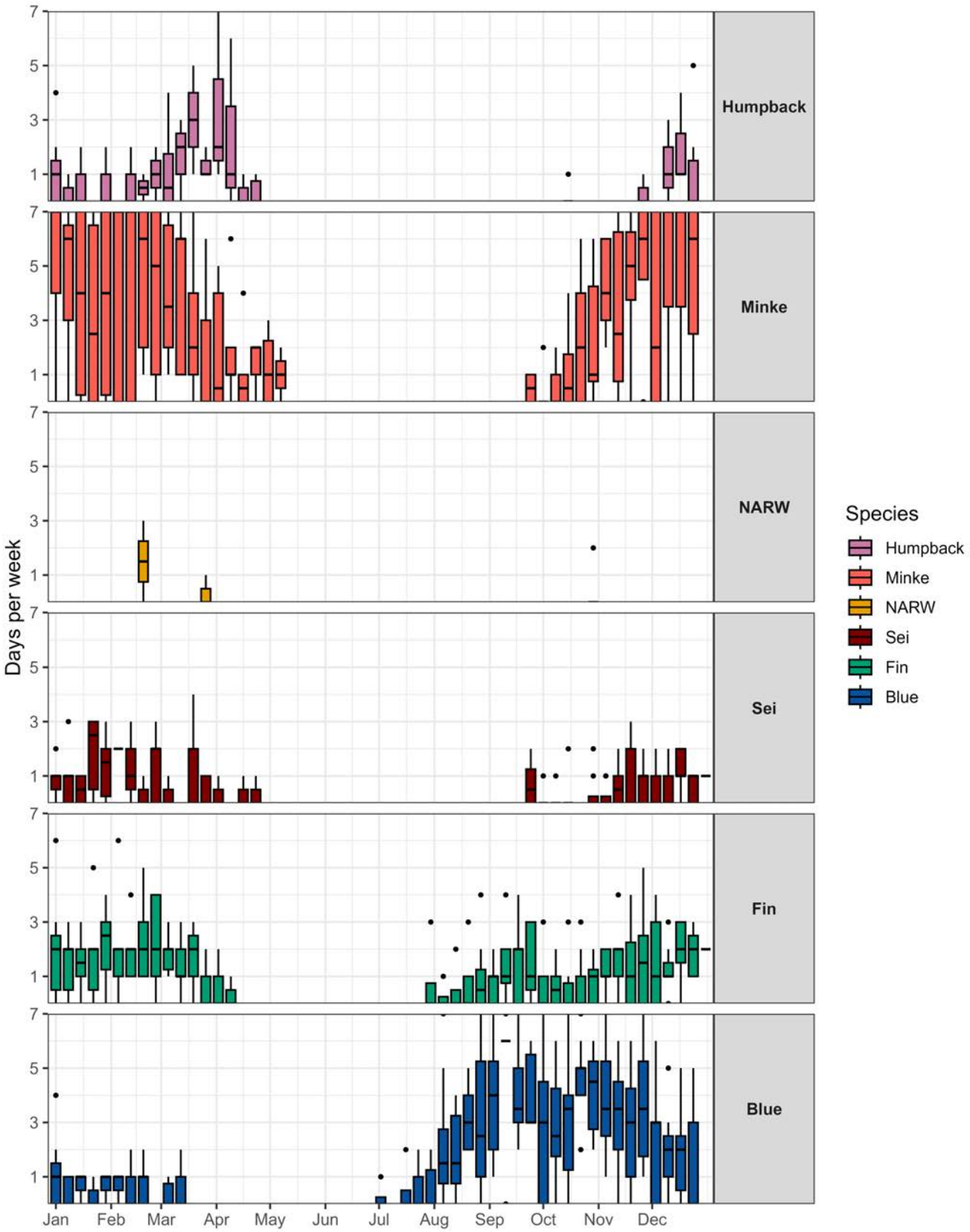

Figure 61: Average weekly acoustic presence (days per week) by species at HAT A and HAT B sites from 2012–2020. The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.1 Humpback Whales

Humpback whale occurrence was limited at site HAT A, with only sporadic low-level presence during late winter and early spring months (Figure 62). Acoustic presence increased following the relocation of the hydrophone array to site HAT B in 2017. At HAT B, humpback whales were regularly occurring between December and April.

Weekly presence during the core spring season often exceeded 3 and occasionally approached near-daily presence (Figure 63), indicating a consistent seasonal use of the region. The increase in presence post-relocation may reflect greater proximity of the HAT B site to their migratory corridor.

Summary of Results – Humpback Whale

- Sparse presence at HAT A; increased seasonal presence at HAT B which may reflect greater proximity of the site to their migratory corridor.
- Regular presence at HAT B from December through April.
- Weekly presence during peak season exceeded 3 days per week.

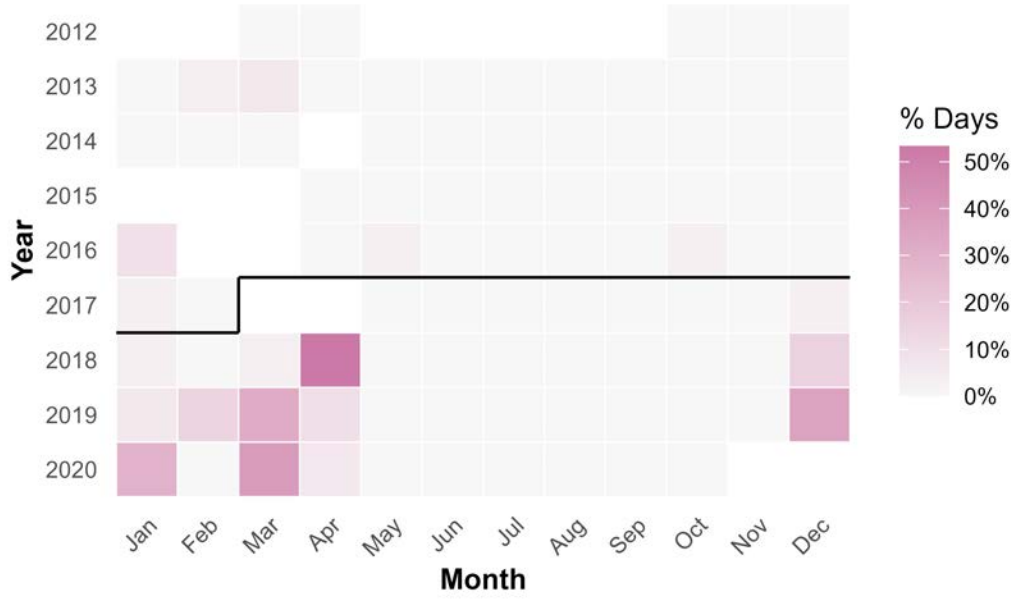

Figure 62: Annual monthly humpback whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. White spaces represent months with no effort.

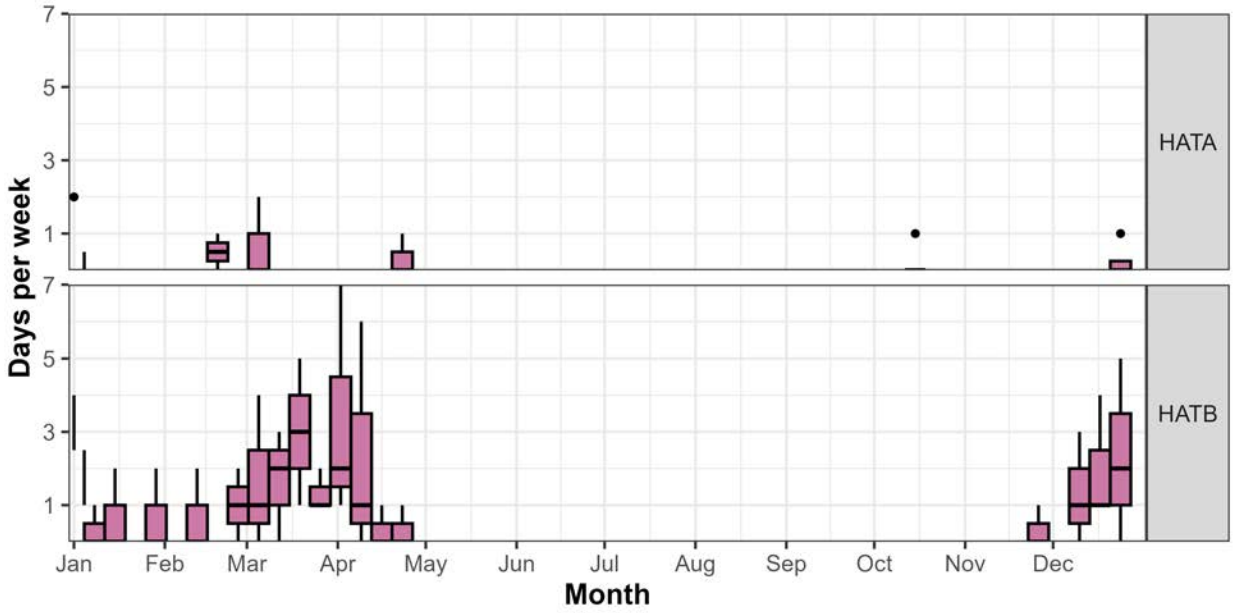

Figure 63: Average weekly acoustic presence of humpback whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.2 Minke Whales

Minke whales consistently occurred throughout the study period, exhibiting clear seasonal patterns and distinct temporal differences between the two sites (Figure 64). At HAT A, presence increased from November through May. Following the transition to HAT B in 2017, a similar pattern was observed, though the timing of peak presence shifted earlier in the year and the overall magnitude of presence appeared lower.

Weekly presence at HAT B peaked from November to March but were more variable (Figure 65), suggesting a slightly less consistent presence. It is important to note that the observed decrease in detection magnitude and consistency at HAT B may reflect, in part, the methodological shift from manual data review to an automated detector, as manual and automated detections are not directly comparable. Despite this consideration, the persistent winter-spring presence at both sites suggests regular use of the region as a migratory corridor.

Summary of Results – Minke Whale

- Strong seasonal presence at both sites, with a peak from October through May.
- Overall magnitude of presence was lower at HAT B.
- Regular use of the site as a migratory corridor.

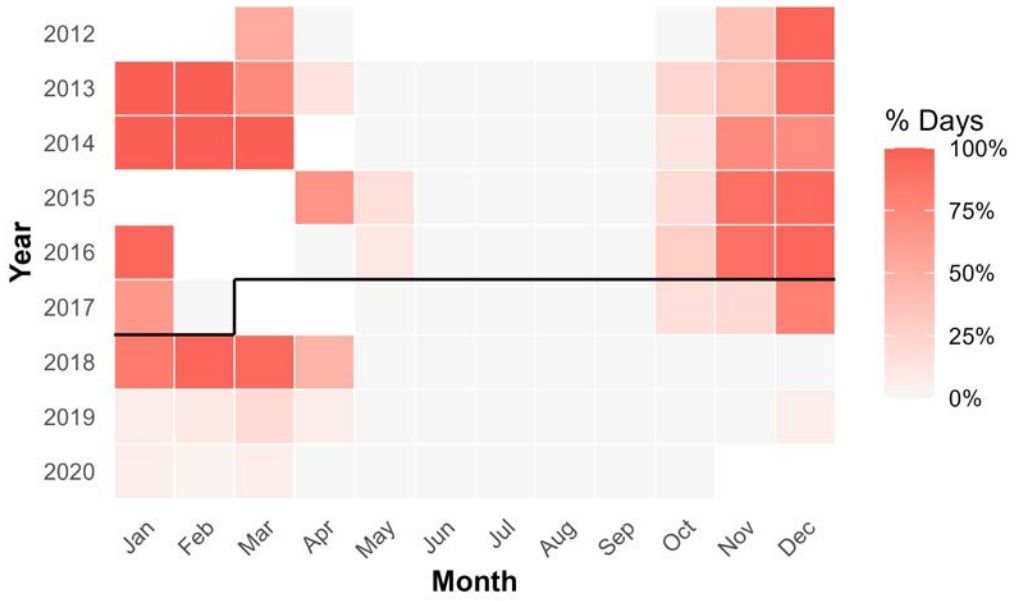

Figure 64: Annual monthly minke whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. 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.

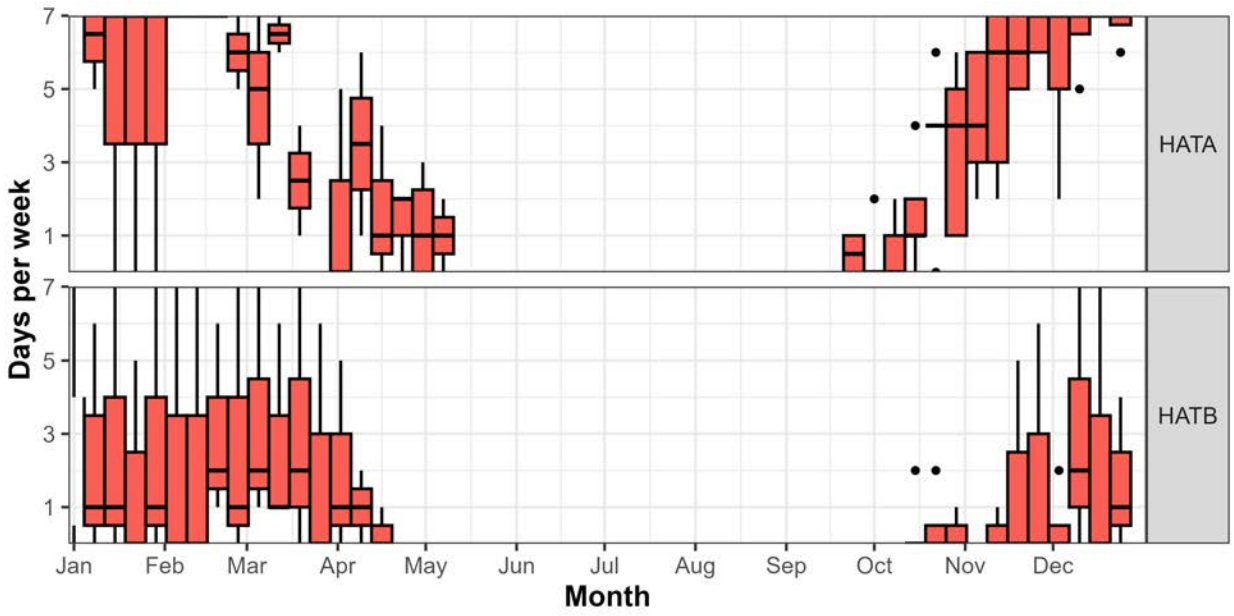

Figure 65: Average weekly acoustic presence of minke whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots). Differences between sites should be interpreted with consideration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

5.2.3 Blue Whales

Blue whale acoustic presence was strongly seasonal, with consistent presence across both sites during fall and early winter months (Figure 66). At HAT A, presence began in late summer and increased steadily from August through December. This seasonal pattern persisted following the move to HAT B, though presence at the new site appeared slightly more variable in timing and magnitude. Blue whale presence at HAT B also extended into January and February in some years.

Weekly presence often exceeded 4 days during the peak period of September through November (Figure 67). These findings are consistent with previous reports of seasonal migration and foraging activity along the U.S. East Coast (Davis et al. 2020) and suggest regular use of the Cape Hatteras region as a migratory corridor during fall and early winter months.

Summary of Results – Blue Whale

- Presence was strongly seasonal, with a peak from September through December.
- Weekly presence during the fall often exceeded 4 days per week.
- Similar seasonal trends were observed at both HAT A and HAT B.
- Regular use of the site as a migratory corridor.

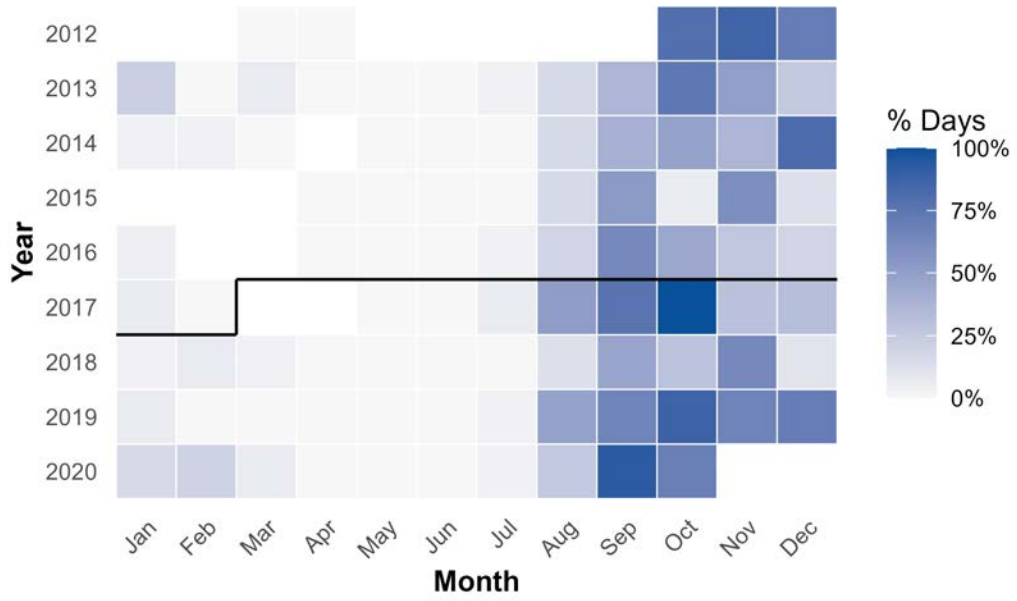

Figure 66: Annual monthly blue whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. White spaces represent months with no effort.

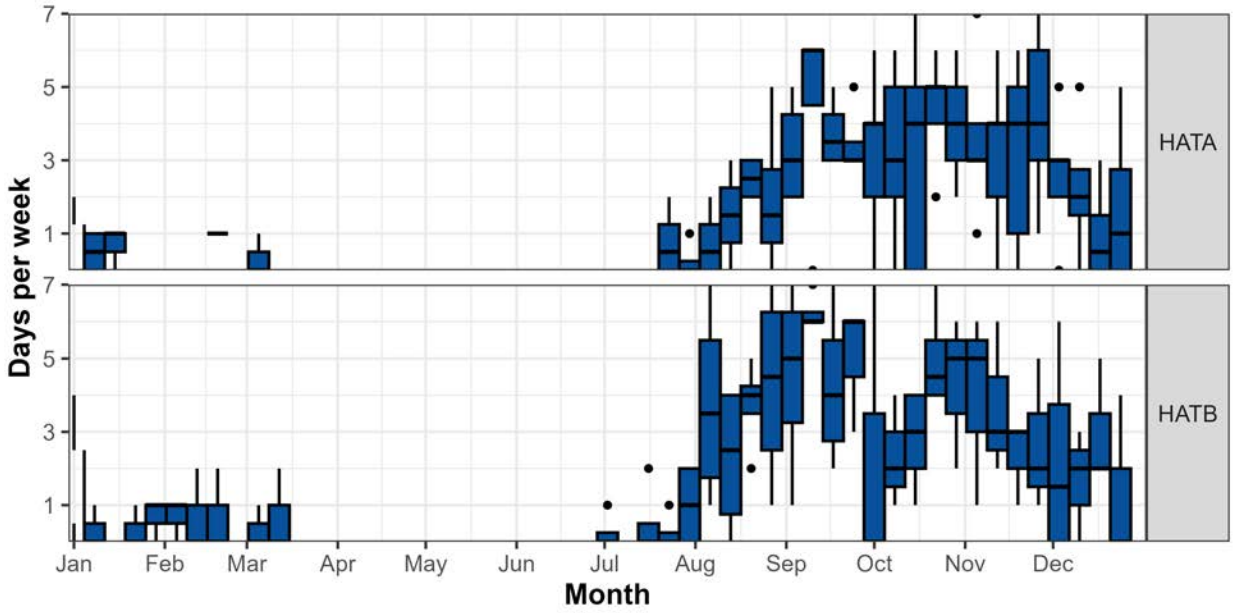

Figure 67: Average weekly acoustic presence of blue whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.4 Fin Whales

Fin whales were acoustically present throughout the recording period with calling activity concentrated in late summer through early winter (Figure 68). This pattern suggests repeated seasonal use of the area, most likely used as a migratory corridor and seasonal overwintering habitat for some animals (Davis et al. 2020).

Boxplot comparisons showed weekly presence peaking at 3–5 days per week during both periods (Figure 69). Following the relocation to HAT B, fin whale presence persisted but was more variable. Presence remained strongest in winter and spring, with January through March showing consistent weekly presence.

Summary of Results – Fin Whale

- Present nearly year-round with consistent peaks in winter and early spring.
- Weekly presence commonly exceeded 3 days during peak periods.
- Regular use of this site as a migratory corridor and seasonal overwintering habitat.

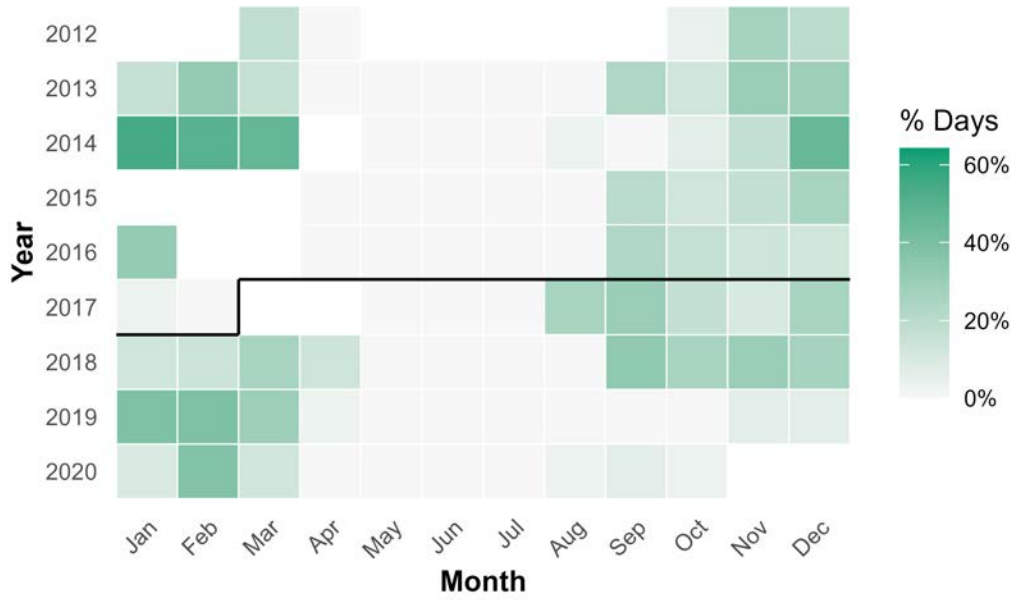

Figure 68: Annual monthly fin whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. White spaces represent months with no effort.

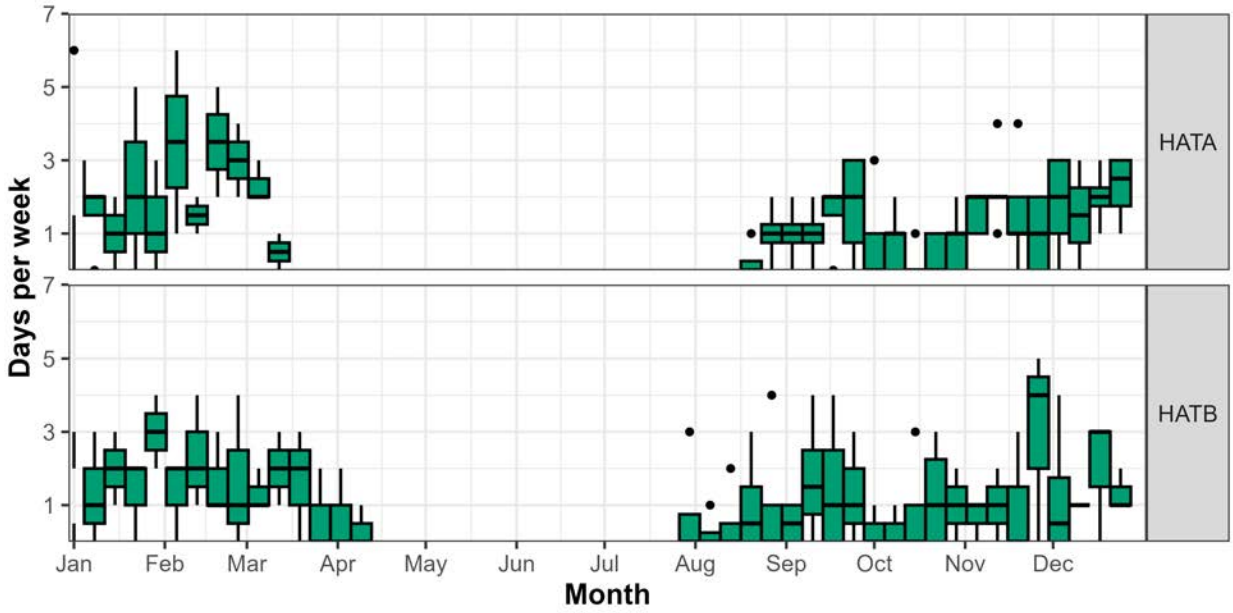

Figure 69: Average weekly acoustic presence of fin whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.5 Sei Whales

Sei whales sporadically occurred across the study period, with two main seasonal periods of presence (Figure 70). At HAT A, presence occurred primarily in late winter (January to March) and again in late fall (October to December). Presence was not consistent across years, but when present, the seasonal pattern was relatively stable.

At HAT B, sei whale occurrence followed a similar pattern but was lower overall (Figure 71). Presence mostly occurred in November and December, rarely exceeding 1–2 days per week. This pattern supports the idea that the area functions as a migratory corridor for sei whales (Davis et al. 2020).

Summary of Results – Sei Whale

- Intermittent presence with two seasonal peaks: late winter and late fall.
- More frequently present at HAT A compared to HAT B.
- When present, detections rarely exceeded 2–3 days per week.
- Regular use of this site as a migratory corridor.

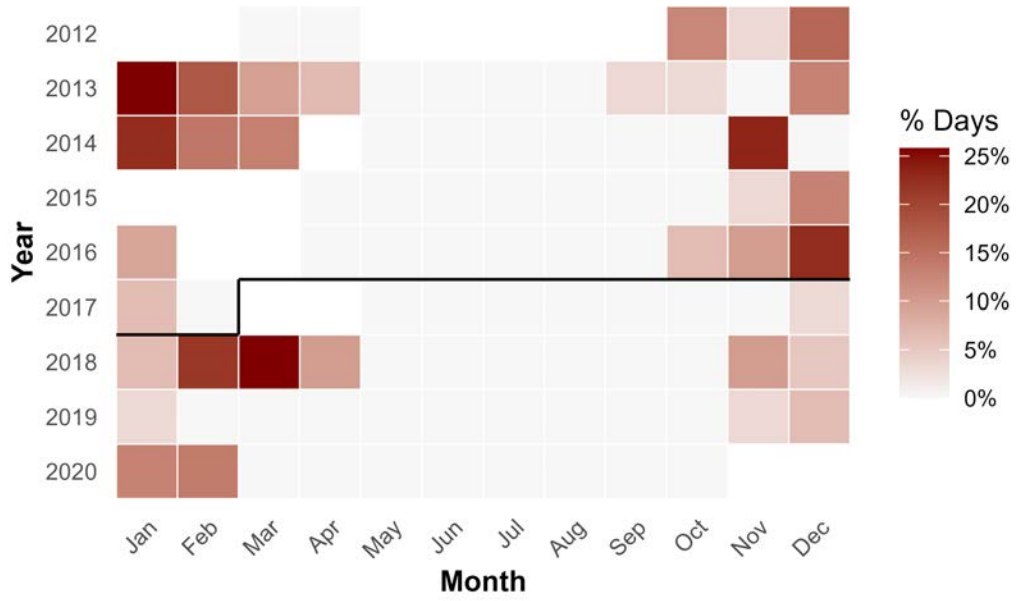

Figure 70: Annual monthly sei whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. White spaces represent months with no effort.

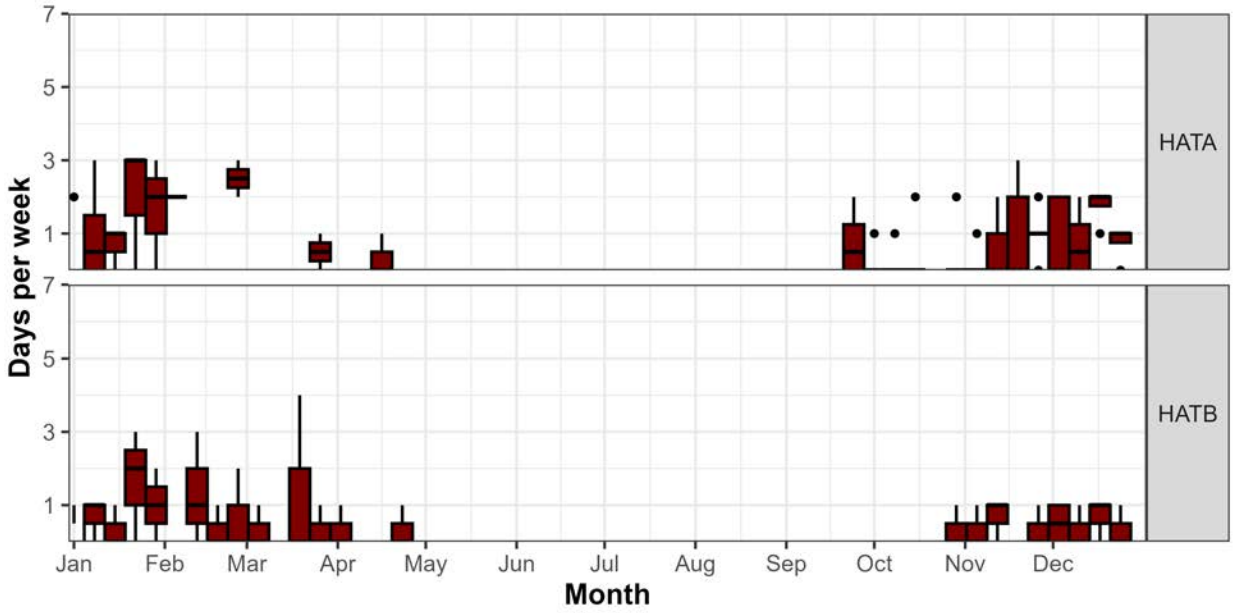

Figure 71: Average weekly acoustic presence of sei whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.2.6 North Atlantic Right Whales

North Atlantic right whales occurred less frequently throughout the study period, with sparse and isolated acoustic occurrences at both sites (Figure 72). At HAT A, presence was limited to a few weeks in March 2013 and again in November 2016. This indicates presence was highly intermittent and did not reflect consistent seasonal or interannual trends.

Boxplots revealed that presence rarely exceeded 2 days per week (Figure 73). At HAT B, only a single detection occurred in April 2017. The low frequency and irregularity of right whale presence suggests the region is not a core habitat for the species, but may represent a migratory corridor (Davis et al. 2020).

Summary of Results – North Atlantic Right Whale

- Infrequent presence, limited to a few weeks across the 8-year period.
- Present more often at HAT A than HAT B.
- A weak seasonal and interannual pattern was observed.

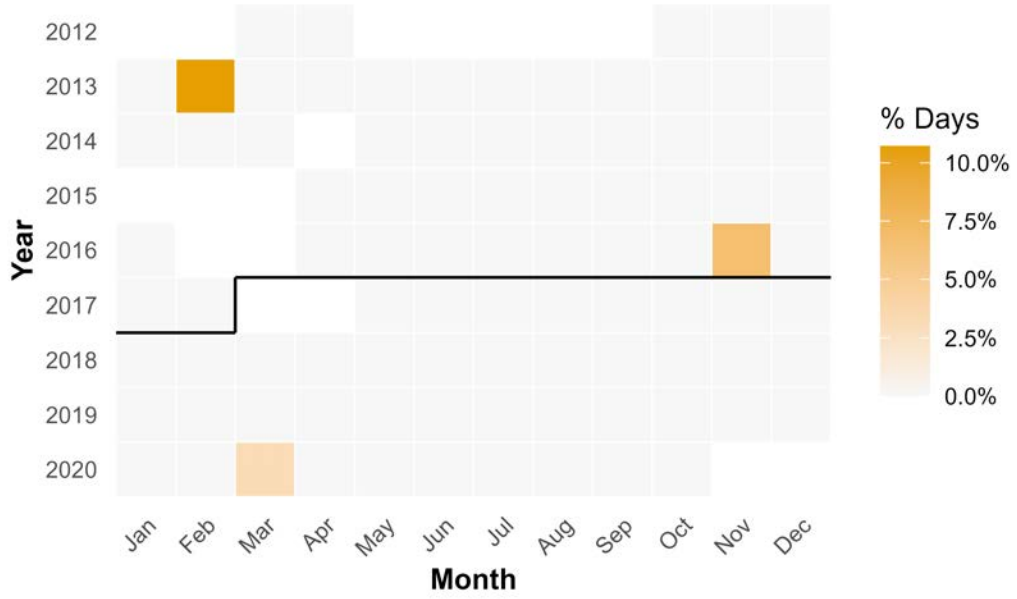

Figure 72: Annual monthly North Atlantic right whale acoustic presence, represented as percentage of days with detections by month and year, corrected for effort by dividing the number of days with detections by the number of days with recordings. The black line delineates the location change from site HAT A to HAT B. White spaces represent months with no effort.

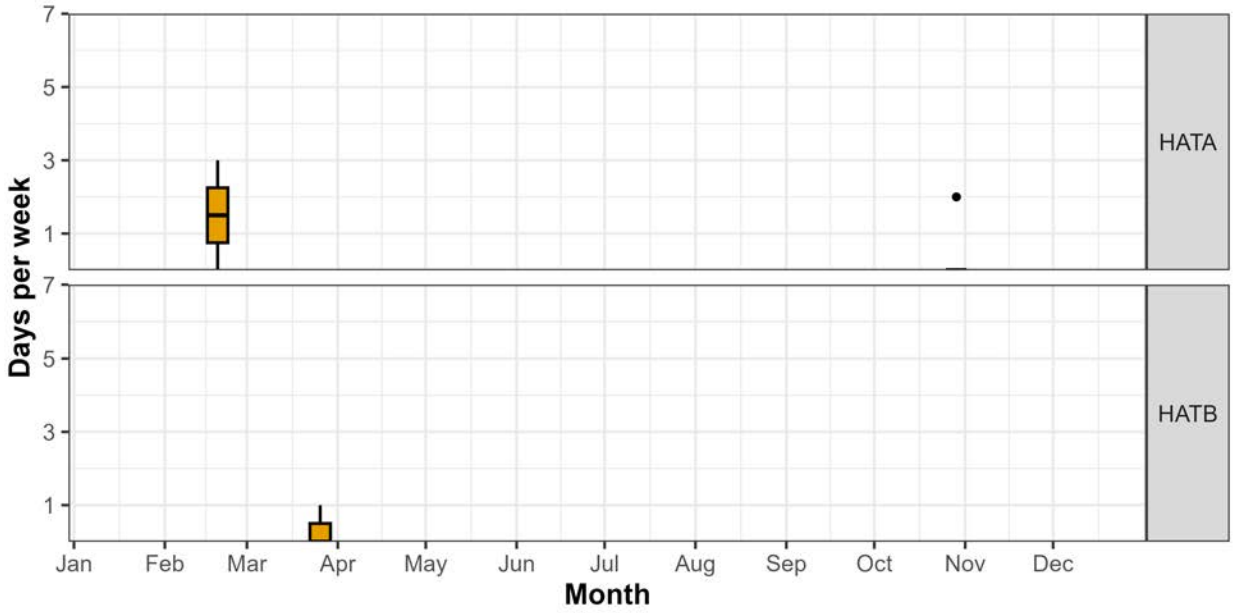

Figure 73: Average weekly acoustic presence of North Atlantic right whales (days per week) at HAT A (top) and HAT B (bottom). The boxplots show the interquartile range (box), median (line), data spread up to 1.5×IQR (whiskers), and outliers (dots).

5.3 Ambient Noise

Ambient sound levels at Cape Hatteras between 2012 and 2020 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 summer, 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 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 months were attributed to increased surface wind and wave action.

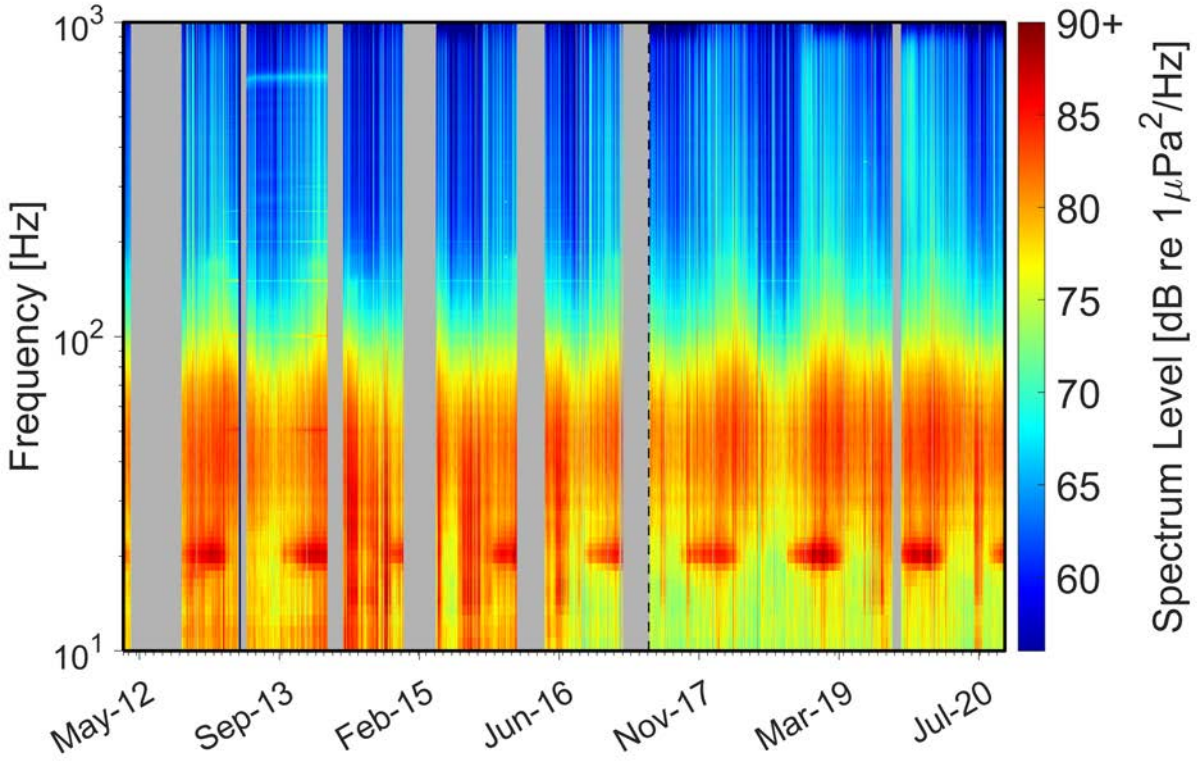

Figure 74: Long spectrograms using daily-averaged spectra for the Cape Hatteras monitoring site from 2012 to 2020. The dashed black line represents when the instrument was moved. Gray blocks represent periods with no effort.

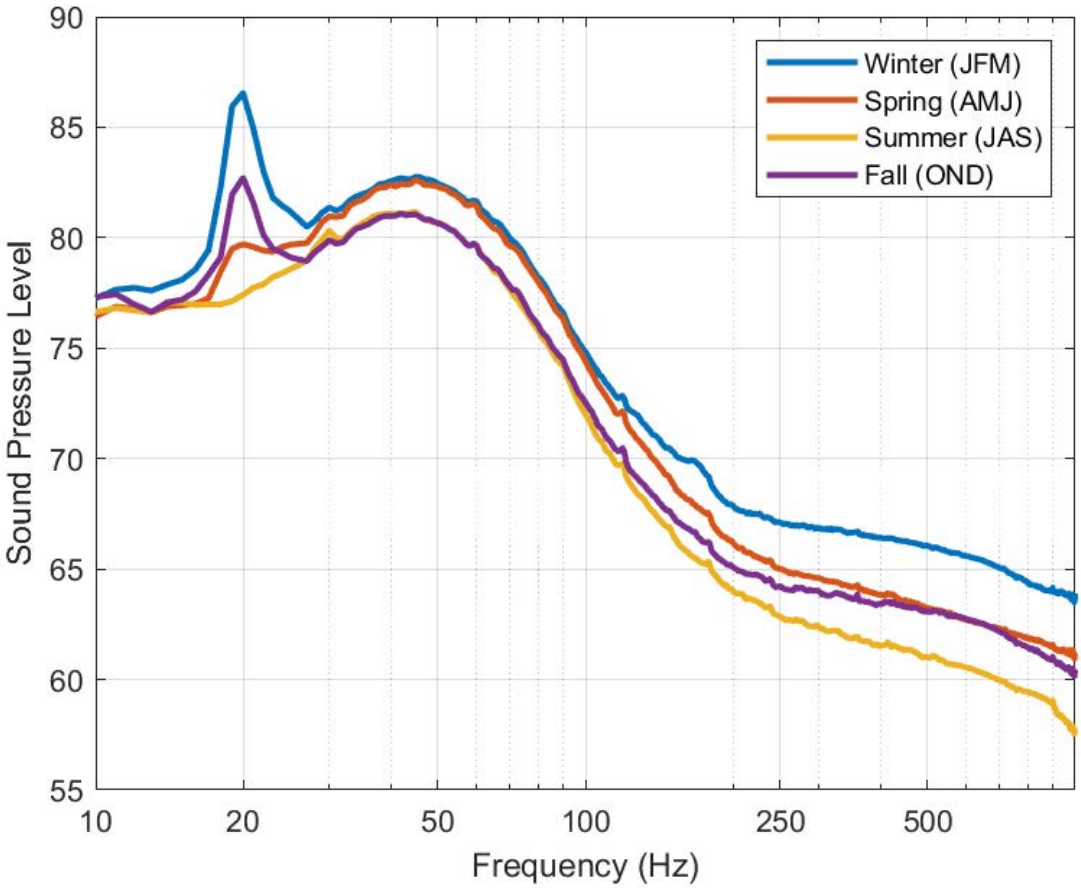

Figure 75: Full spectra averaged over each season for the Cape Hatteras monitoring site from 2012 to 2020. Winter is represented by January, February March; spring as April, May, June; summer as July, August, September; and fall as October, November, and December.

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.

Foley, Heather J., Krishna Pacifici, Robin W. Baird, David L. Webster, Zachary T. Swaim, and Andrew J. Read (2021). “Residency and movement patterns of Cuvier’s beaked whales Ziphius cavirostris off Cape Hatteras, North Carolina, USA”. In: *Marine Ecology Progress Series* 660, pp. 203–216. DOI: 10.3354/meps13593.

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, David Claridge, Clare Embling, and Ian Boyd (2009a). “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.

Gillespie, Douglas, Charlotte Dunn, Jonathan Gordon, Diane Claridge, Clare Embling, and Ian Boyd (2009b). “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.