

Passive Acoustic Monitoring of Anthropogenic Noise at Four Sites in the Western North Atlantic

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1 Executive Summary

Long-term passive acoustic monitoring was conducted across four U.S. Navy operational areas along the western North Atlantic margin to characterize patterns in anthropogenic acoustic activity and underwater sound exposure. Monitoring occurred near Norfolk Canyon (NFC), offshore Cape Hatteras (HAT), within Onslow Bay (OB), and off Jacksonville (JAX) using seafloor-mounted High-frequency Acoustic Recording Packages (HARPs) deployed across shelf and slope habitats between 2007 and 2021. Anthropogenic sound sources evaluated in this report included low-frequency active sonar (LFAS), mid-frequency active sonar (MFAS), high-frequency active sonar/echosounders (HFAS), impulsive sounds, and broadband ship noise. Impulsive sounds included a mixture of sources such as geophysical airguns, fishing-vessel seal bombs, military detonations, and other explosion-like acoustic events.

Broadband ship noise represented the most persistent and spatially widespread anthropogenic sound source across all monitored regions. Elevated ship detections occurred at nearly all sites during periods with recording effort, although the timing and magnitude of activity varied seasonally and interannually. Norfolk Canyon and Cape Hatteras exhibited persistent moderate-to-high ship activity throughout much of the monitoring period, while Onslow Bay and Jacksonville exhibited strong seasonal fluctuations and alternating periods of elevated and reduced detections across sites. Ship detections occurred throughout the 24-hour cycle at all regions, although strong or consistent diel patterns were generally uncommon.

LFAS detections were generally intermittent and occurred at comparatively low levels across monitored regions. Norfolk Canyon exhibited episodic LFAS activity with seasonal variability, while offshore Cape Hatteras exhibited relatively low but persistent detections at both sites. LFAS analyses were prioritized for regions and deployments where low-frequency active sonar activity was expected to be most prevalent based on prior observations and operational context. As a result, LFAS analyses were not conducted for the Onslow Bay sites or Jacksonville sites A and B. Across analyzed regions, LFAS detections occurred throughout the 24-hour cycle without strong or consistent diel structure.

MFAS detections exhibited greater variability in magnitude and temporal structure than LFAS activity. Norfolk Canyon exhibited episodic MFAS activity concentrated primarily during 2018–2019, while offshore Cape Hatteras exhibited moderate activity with higher levels at site B relative to A. Jacksonville exhibited the highest overall MFAS activity among monitored regions, with slightly higher overall activity at sites A and D and pronounced seasonal structure across sites. Across all regions, MFAS detections occurred throughout the 24-hour cycle and generally lacked strong or consistent diel patterns, although slight increases in nighttime detections were observed at some locations.

HFAS and echosounder detections varied substantially among monitored regions. Offshore Cape Hatteras exhibited the highest overall HFAS activity, including prolonged periods of

elevated detections at both sites and peak weekly totals exceeding 100 hours per week. Norfolk Canyon exhibited intermittent but recurring HFAS activity, particularly during 2016–2018, while Jacksonville sites C and D exhibited only limited HFAS detections. HFAS analyses were prioritized for regions and deployments where high-frequency active acoustic activity was expected to be most prevalent based on prior observations and operational context; therefore, HFAS analyses were not conducted for the Onslow Bay sites or Jacksonville sites A and B. Seasonal variability was evident at several locations, particularly offshore Cape Hatteras where activity was elevated during winter months.

Impulsive sounds were generally intermittent and occurred at substantially lower levels than broadband ship noise or active sonar activity. Impulsive sound detections near Norfolk Canyon were concentrated primarily during 2018–2020, with highest activity occurring during summer and fall months. Offshore Cape Hatteras exhibited relatively low but persistent impulsive sound detections, while Jacksonville exhibited localized activity primarily at site A. Impulsive sounds generally occurred throughout the 24-hour cycle and did not exhibit strong diel structure.

Collectively, these results demonstrate that anthropogenic acoustic activity across the western North Atlantic was highly variable in space and time, with substantial differences among regions, signal types, and individual monitoring sites. Seasonal and interannual variability represented the dominant temporal structure across most anthropogenic sound sources, while strong diel patterns were generally uncommon. These long-term passive acoustic datasets provide an important baseline for understanding regional soundscape dynamics and for evaluating future changes in anthropogenic acoustic exposure across shelf and slope ecosystems of the western North Atlantic.

2 Introduction

2.1 Project Background

Long-term passive acoustic monitoring has been conducted across four U.S. Navy operational areas along the western North Atlantic margin to characterize ambient sound levels and anthropogenic acoustic activity. Arranged geographically from north to south, these include Norfolk Canyon within the Virginia Capes Range Complex, Cape Hatteras within the Virginia Capes Range Complex, Onslow Bay within the Cherry Point Operating Area, and the Jacksonville Range Complex in the South Atlantic Bight (Figure 1).

Acoustic data were collected using High-frequency Acoustic Recording Packages (HARPs; Wiggins & Hildebrand 2007), seafloor-mounted autonomous recorders designed to continuously sample the underwater acoustic environment over extended periods. Across all four regions, HARPs were deployed across shelf and slope habitats to capture multi-year records of ambient and anthropogenic sound sources.

2.2 Norfolk Canyon

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. Monitoring sites were deployed near Norfolk Canyon within this range complex (Figure 2).

From 2014 to 2021, six HARPs were deployed in this region to conduct long-term passive acoustic monitoring. Deployment dates, locations, and recording durations are summarized in Table 1.

2.3 Cape Hatteras

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. Monitoring sites were deployed offshore from Cape Hatteras within the southern portion of the Virginia Capes Range Complex (Figure 3).

From 2012 to 2020, twelve HARPs were deployed offshore of Cape Hatteras to conduct passive acoustic monitoring. Deployment dates, locations, and recording durations are

summarized in Table 2.

2.4 Onslow Bay

The U.S. Navy's Cherry Point Operating Area (OPAREA) is situated in the coastal and offshore waters of Onslow Bay, North Carolina, within the South Atlantic Bight. This area encompasses a broad continental shelf, ranging from 40 to 140 km in width, with an inner zone of less than 200 meters in depth and an outer zone extending across the slope to depths approaching 2,000 meters. Monitoring sites were strategically deployed across a shelf-to-slope gradient (Figure 4).

From 2007 to 2013, HARPes were deployed across five sites (sites A–E) within Onslow Bay to conduct long-term passive acoustic monitoring. Deployment dates, locations, and recording durations are summarized in Table 3.

2.5 Jacksonville

The U.S. Navy's Jacksonville Range Complex (JAX) is situated within the South Atlantic Bight that extends from Cape Hatteras, North Carolina to the Florida Straits. The seafloor is relatively smooth and features a broad continental shelf, with an inner zone of less than 200 m water depth, and an outer zone extending to depths of 2000 m. Monitoring sites were deployed across a shelf-to-slope gradient within this range complex (Figure 5).

From 2009 to 2019, HARPes were deployed across four sites (sites A–D) within the Jacksonville study area to conduct long-term passive acoustic monitoring. Deployment dates, locations, and recording durations are summarized in Table 4.

Table 1: Recording effort for deployments at the Norfolk Canyon (NFC) study area.

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

Table 2: Recording effort for deployments at the Cape Hatteras (HAT) study area.

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

Table 3: Recording effort for deployments at the Onslow Bay (OB) study area.

Site	Deployment	Start Date	End Date	Depth (m)	Recording Duration (Days)	Duty Cycle (Min)
A	01	10/10/2007	01/16/2008	160	99	5/10
	03	04/24/2009	08/09/2009	170	108	5/10
	04	11/08/2009	02/24/2010	170	109	5/15
	05	07/30/2010	03/03/2011	170	217	5/10
B	02	05/20/2008	09/10/2008	230	114	5/10
C	04	11/08/2009	04/20/2010	330	164	5/15
D	05	07/30/2010	02/04/2011	340	190	5/10
E	06	08/19/2011	12/01/2011	950	105	5/10
	07	07/14/2012	10/02/2012	900	81	5/10
	08	10/24/2012	06/30/2013	850	250	5/10

Table 4: Recording effort for deployments at the Jacksonville (JAX) study area.

Site	Deployment	Start Date	End Date	Depth (m)	Recording Duration (Days)	Duty Cycle (Min)
A	01	04/02/2009	05/25/2009	82	57	5/15
	02	09/16/2009	12/27/2009	83	102	5/15
	03	02/22/2010	07/30/2010	89	158	5/15
	05	08/26/2010	01/25/2011	91	152	5/15
	06	02/01/2011	07/14/2011	91	163	5/15
B	01	04/02/2009	09/05/2009	37	156	5/15
	04	03/09/2010	08/19/2010	38	163	5/15
	05	08/27/2010	02/01/2011	37	158	5/15
	06	02/02/2011	07/14/2011	37	162	5/15
C	09	05/13/2013	06/20/2013	94	38	Continuous
	10	02/17/2014	08/23/2014	88	187	Continuous
D	11	08/23/2014	05/29/2015	800	279	Continuous
	12	07/03/2015	11/04/2015	750	125	Continuous
	13	04/26/2016	06/25/2017	736	425	Continuous
	14	06/25/2017	10/28/2017	740	125	Continuous
	15	06/27/2018	06/15/2019	740	354	Continuous
	16	06/15/2019	05/31/2020	735	351	Continuous

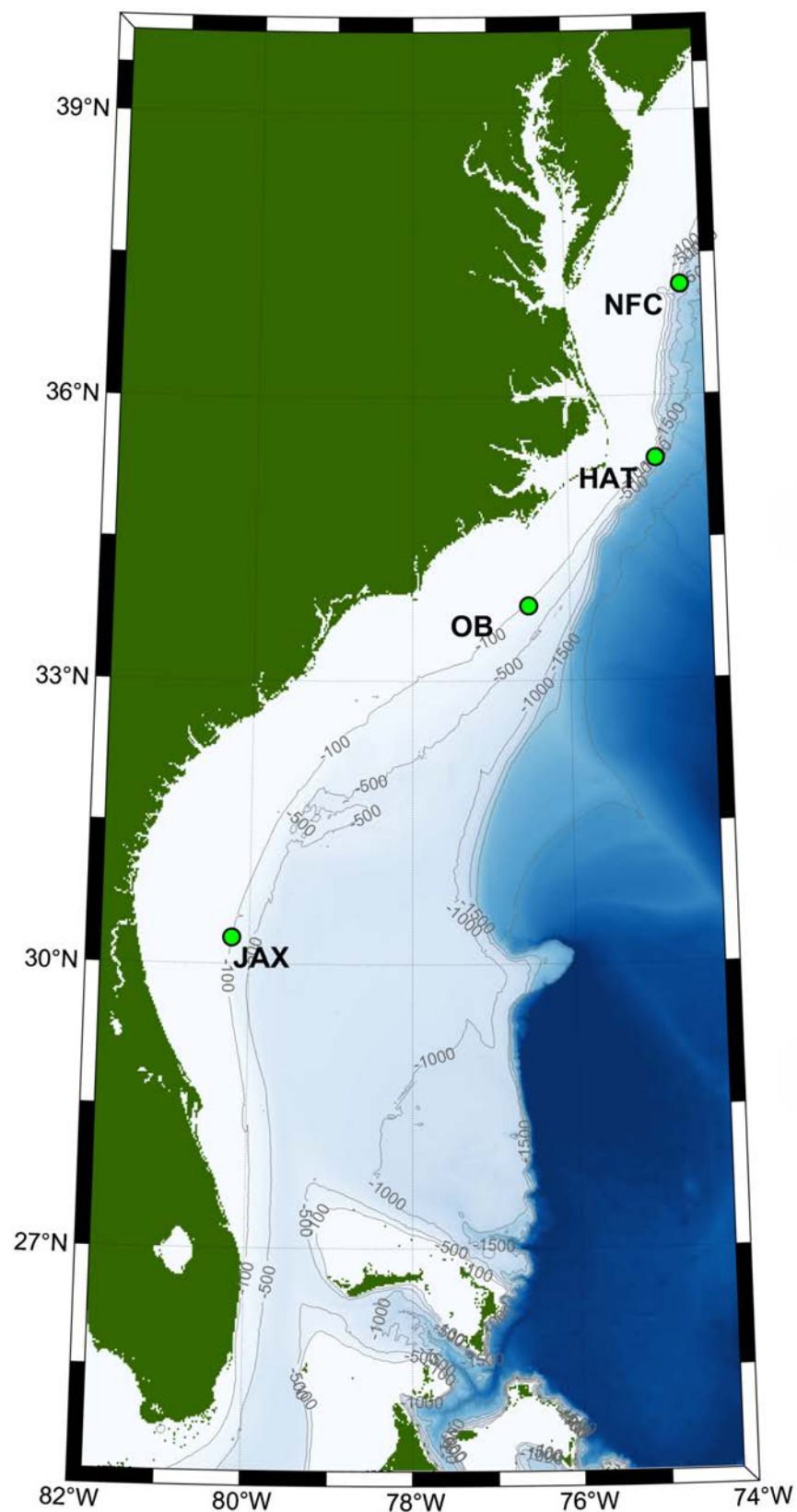


Figure 1: Large-scale view of the locations of the High-frequency Acoustic Recording Packages (HARPs) at the four study sites along the U.S. East Coast. Norfolk Canyon (NFC), Cape Hatteras (HAT), Onslow Bay (OB), and Jacksonville (JAX).

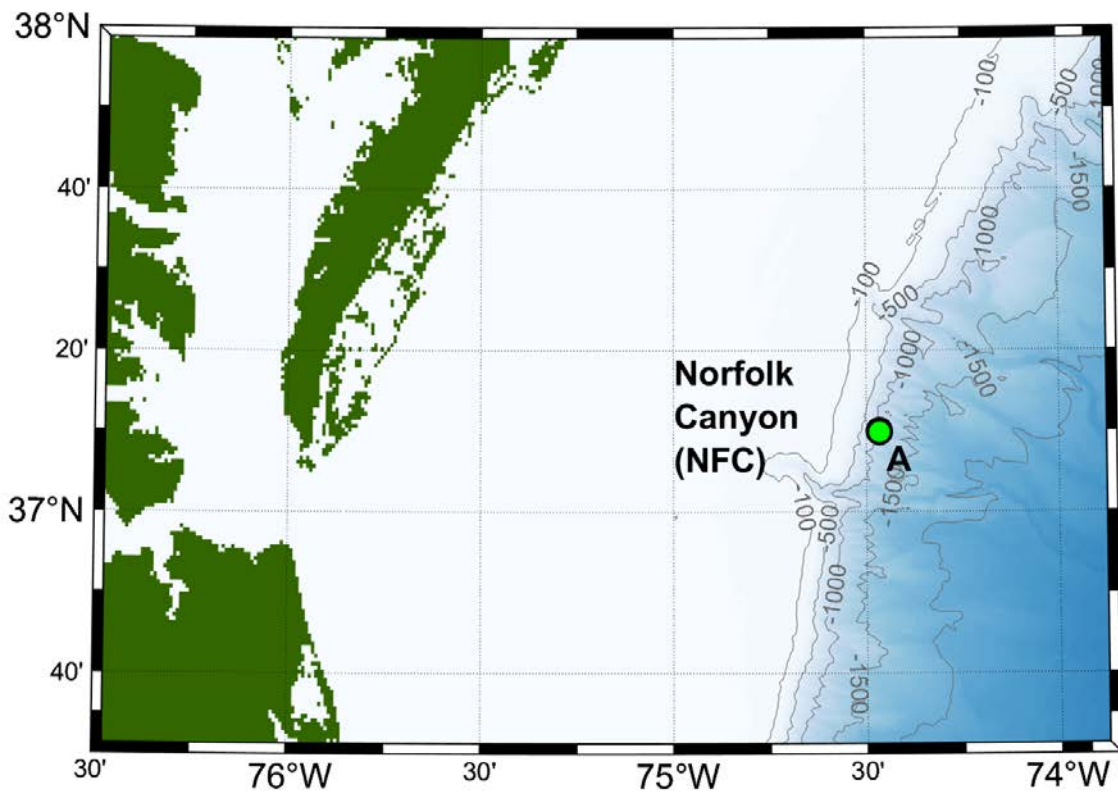


Figure 2: Zoomed-in view of the positions of the individual High-frequency Acoustic Recording Packages (HARPs) deployments at the Norfolk Canyon (NFC).

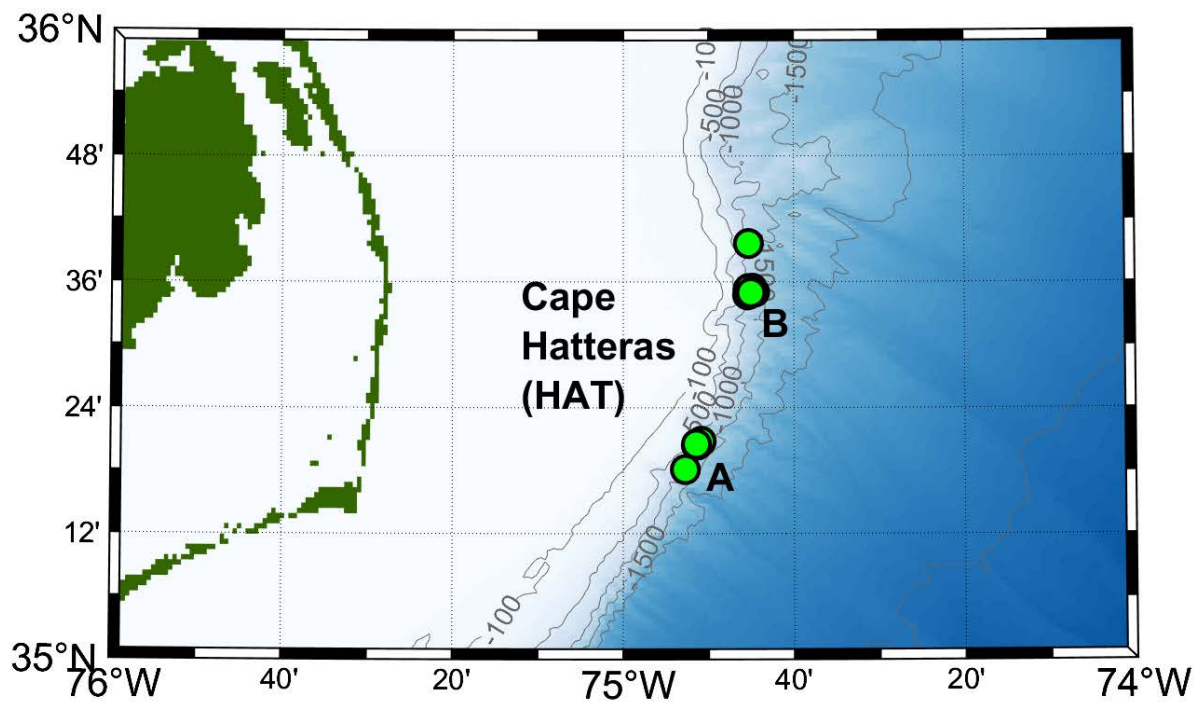


Figure 3: Zoomed-in view of the positions of the individual High-frequency Acoustic Recording Packages (HARPs) deployments at the Cape Hatteras (HAT) A and B sites.

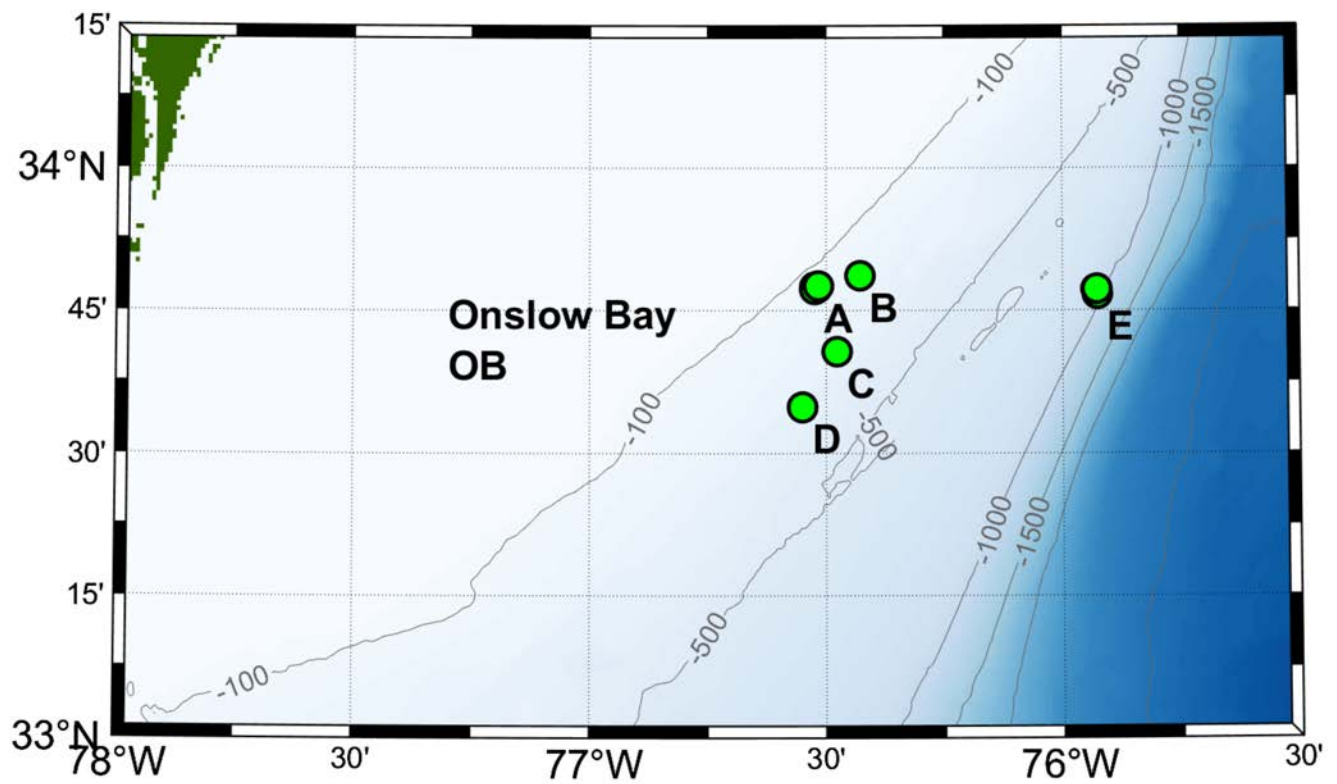


Figure 4: Zoomed-in view of the positions of the individual High-frequency Acoustic Recording Packages (HARPs) deployments at the Onslow Bay (OB) A-E sites.

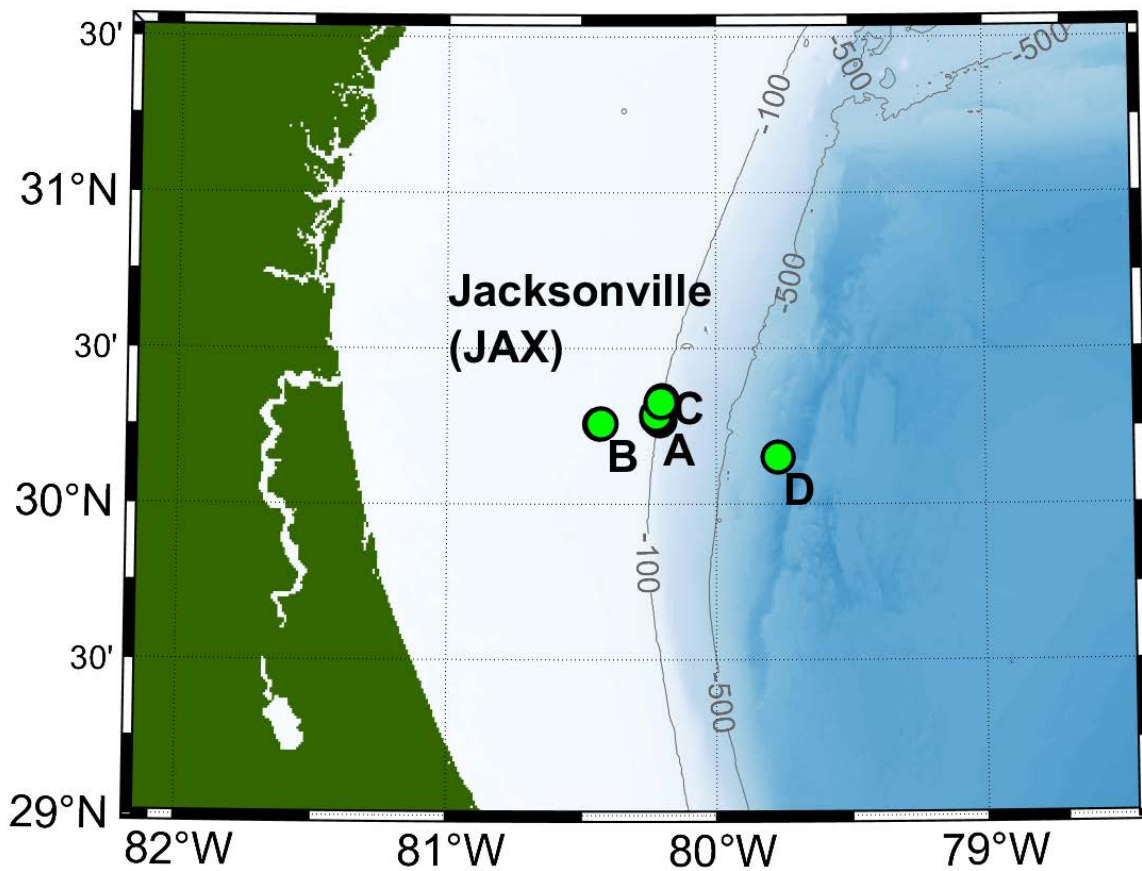


Figure 5: Zoomed-in view of the positions of the individual High-frequency Acoustic Recording Packages (HARPs) deployments at the Jacksonville (JAX) A-D sites.

3 Data Collection and Quality

High-frequency Acoustic Recording Packages (HARPs) are autonomous underwater acoustic recording devices that, depending on configuration, can record sounds over a bandwidth from 10 Hz to 100 kHz and are capable of approximately one year of continuous recording (Wiggins & Hildebrand 2007). The HARPs were deployed in a large mooring configuration with the hydrophone suspended approximately 10 m above the seafloor. Each HARP was calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations.

Across all four recording areas, the vast majority of the data collected were found to be error free. Some deployments experienced intermittent data gaps due to data logger malfunctions or disk write errors, and in select cases, instrument strumming or flow noise elevated low-frequency noise levels. Problematic segments were identified and either excluded or flagged during analysis. Although coverage gaps and flow-related noise may have reduced detectability in certain frequency bands during limited periods, the overall datasets remain sufficient to assess long-term patterns in anthropogenic acoustic activity. Specific deployment details and data quality notes for each recording area are provided below.

3.1 Norfolk Canyon

From 2014 to 2021, six HARPs were deployed near Norfolk Canyon within the Virginia Capes Range Complex.

The vast majority of the data collected were found to be error free. Deployment 02 experienced limited data loss toward the end of the recording period due to a hard drive malfunction. Intermittent data gaps appeared at the end of deployment 03 due to a data logger malfunction, with recording coverage declining from 100% to 84% by the end of the deployment. Deployment 06 had no usable acoustic data after September 14, 2022, likely due to a failure of the hydrophone, hydrophone cable, or ATD board.

3.2 Cape Hatteras

From 2012 to 2020, twelve HARPs were deployed offshore of Cape Hatteras within the Virginia Capes Range Complex. In May 2017, the deployment location 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 deployments HAT02A and HAT03A. These dropouts were very short in duration (between 100 microseconds and 10 milliseconds) and

affected less than one percent of the impacted xwav-format data. The affected segments were corrected using a detector calibrated to the observed amplitude and duration of the dropouts. The end of the HAT04A recording was cut short, likely due to disk write errors.

Intermittent data gaps appeared at the end of deployments HAT06A and HAT01B due to data logger malfunctions, with recording coverage declining from 100% to 82% and 91%, respectively, by the end of the recording periods.

3.3 Onslow Bay

A total of 10 deployments were conducted in the Onslow Bay study area between 2007 and 2013 across five sites spanning a depth gradient: one shallow shelf site (A, ~170 m), three mid-depth shelf sites (B–D, 230–340 m), and one slope site (E, 850–950 m). All recordings were duty cycled to extend deployment duration. As a result, acoustic coverage represents a subsample of real-time conditions, and short-duration or infrequent acoustic events may be underrepresented relative to continuous recordings.

The vast majority of the data collected were found to be error free. Some deployments experienced issues with instrument strumming and flow noise, particularly at the mid-depth shelf and slope sites, which intermittently elevated low-frequency noise levels (<30 Hz). These effects were most pronounced at the slope site during deployments 6E–8E, where strong Gulf Stream currents interacted with the mooring lines. Intermittent strumming was also noted at the mid-depth shelf sites during deployments 4C and 5D.

Intermittent data gaps appeared in deployments 1A and 5A due to data logger malfunctions and disk write errors, with recording coverage declining from 100% to 82% and 91%, respectively, by the end of the recording periods. All other deployments maintained greater than 95% coverage, including deployment 08E, which produced the longest deep-water dataset with 250 days of high-quality recordings despite intermittent flow noise.

Problematic segments were identified and either excluded or flagged during analysis. Although strumming noise and coverage gaps likely reduced detectability in certain frequency bands during limited periods, the overall dataset remains sufficient to assess long-term patterns in anthropogenic acoustic activity.

3.4 Jacksonville

A total of 17 deployments were conducted in the Jacksonville study area between 2009 and 2020 across four subsites spanning a depth gradient: three shallow shelf sites (A–C, 40–90 m) and one slope site (D, 730–800 m).

The vast majority of the data collected were found to be error free. Some deployments experienced issues with instrument strumming and flow noise, which intermittently elevated

low-frequency noise levels (<30 Hz).

Intermittent data gaps occurred in three shelf deployments (1A, 5A, and 9C) due to data logger and disk write issues. One slope deployment (D12) experienced a loss of low-frequency sensitivity shortly after deployment, limiting detectability in the lowest frequency bands for part of the record. All remaining deployments maintained high data recovery, with most achieving greater than 95% usable coverage across the recording period.

Problematic segments were identified and either excluded or flagged during analysis. Although strumming noise and coverage gaps likely reduced detectability in certain frequency bands during limited periods, the overall dataset remains sufficient to assess long-term patterns in anthropogenic acoustic activity.

4 Data Analysis

Anthropogenic signals were identified using a combination of automated detection algorithms and manual logging within Triton (Wiggins et al. 2010). Automated detectors were applied to mid-frequency active sonar (MFAS) using a modified Silbido-based tonal detection framework (Roch et al. 2013; Wiggins 2015), to impulsive signals using a matched-filter detector developed for impulsive sources (Krumpel et al. 2021; Wiggins et al. 2021), and to ship passages using the Ship Detector Remora (Solsona-Berga et al. 2020). In contrast, low-frequency active sonar (LFAS) and high-frequency active sonar/echosounders (HFAS) were manually logged using the Logger Remora in Triton (Wiggins et al. 2010).

Across all signal types, detections were standardized to encounter-based start and end times and used to generate temporal summaries of anthropogenic activity.

Anthropogenic signals analyzed:

- Low-Frequency Active Sonar (LFAS)
- Mid-Frequency Active Sonar (MFAS)
- High-Frequency Active Sonar/Echosounders (HFAS)
- Impulsive Sounds
- Broadband Ships

4.1 Low-Frequency Active Sonar (LFAS)

Low-frequency active sonar (LFAS) includes military sonar transmissions between approximately 100 and 500 Hz as well as other active sonar systems extending to 1 kHz. These signals typically appear as narrowband tonal components or slowly varying frequency-modulated features within the 100–1,000 Hz band. LFAS transmissions may persist for minutes to hours depending on operational patterns and propagation conditions. In LTSAs, LFAS often appears as sustained horizontal bands or repeated tonal elements, while spectrogram expansion reveals structured tonal sequences or modulated sweeps (Figure 6).

LFAS signals were identified through manual review of LTSAs using the Logger Remora in Triton (Wiggins et al. 2010). Analysts scanned 1-hour LTSA windows to identify candidate activity in two frequency ranges: below 500 Hz and between 500–1,000 Hz. When potential LFAS activity was observed, the display was expanded to spectrogram view for confirmation and precise boundary selection.

Logging was conducted using df100 data with display frequencies set to 10–1,000 Hz. For sub-500 Hz detections, spectrogram upper frequency limits were typically reduced to 200 Hz to enhance visibility. FFT lengths generally ranged from 1,000 to 1,500 points with approximately 90% overlap to improve temporal resolution. Brightness and contrast were adjusted as needed to optimize signal clarity. Encounter start and end times were selected directly in spectrogram view. Effort periods were explicitly defined within the logging interface to distinguish active scanning intervals. Confirmed encounters were exported as start and end times and used to generate the LFAS detection time series.

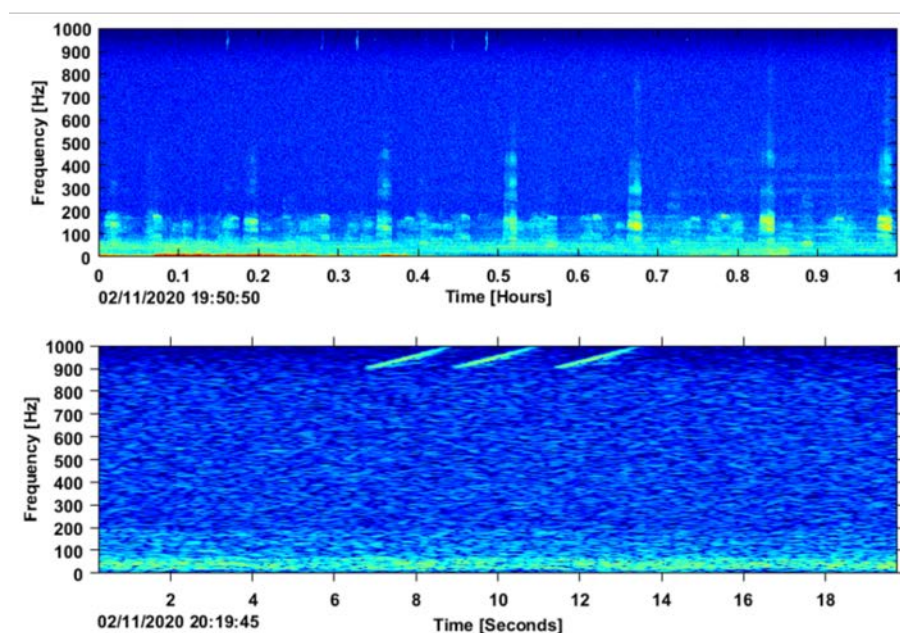


Figure 6: Low-frequency active sonar (LFAS) in LTSA (top) and spectrogram (bottom).

4.2 Mid-Frequency Active Sonar (MFAS)

Mid-frequency active sonar (MFAS) signals occur between 1–5 kHz and are composed of pulses containing both frequency-modulated (FM) sweeps and continuous wave (CW) tones. Individual pulses, or pings, range from less than 1 s to greater than 5 s in duration. Groups of pings constitute packets, and packets are transmitted repetitively with inter-packet intervals typically greater than 20 s (Figure 7). Groups of packets form wave trains (events), and packets separated by more than one hour were treated as independent wave trains. Across all four recording areas, the most commonly observed MFAS signals occurred between 2 and 5 kHz and are commonly referred to as “3.5-kHz” sonar.

MFAS detection was conducted using a modified version of the Silbido detection system (Roch et al. 2013). The algorithm identifies peaks in time-frequency representations and links them into graph structures based on heuristic rules evaluating trajectory continuity, contour intersections, and allowable brief dropouts. Detection graphs are then examined to identify individual tonal contours. For MFAS detection, parameters were adjusted to detect tonal contours at or above 2 kHz in data decimated to a 10 kHz sampling rate. Time-frequency peaks were required to have signal-to-noise ratios of at least 5 dB and contour durations of at least 200 ms with 100 Hz frequency resolution.

Broadband noise associated with instrument disk writes occurring at 75-s intervals produced periodic false detections. To mitigate this, histograms of detection start times relative to the disk-write period were constructed and statistical outliers were removed. Although some valid detections may have coincided with disk-write intervals, the lack of correlation between disk-write timing and sonar transmissions suggests minimal impact on the resulting detection time series.

Because tonal biological signals (e.g., humpback whale song) can overlap the MFAS band, automated detections were manually reviewed. Contiguous clusters of detections were evaluated and either accepted or rejected by trained analysts. In a second processing stage, confirmed event times were used to extract waveform segments. A 2.4–4.5 kHz bandpass filter and a time-domain energy detector were applied after correcting for the instrument transfer function (Wiggins 2015). Refined start and end times of MFAS events were retained for time series construction.

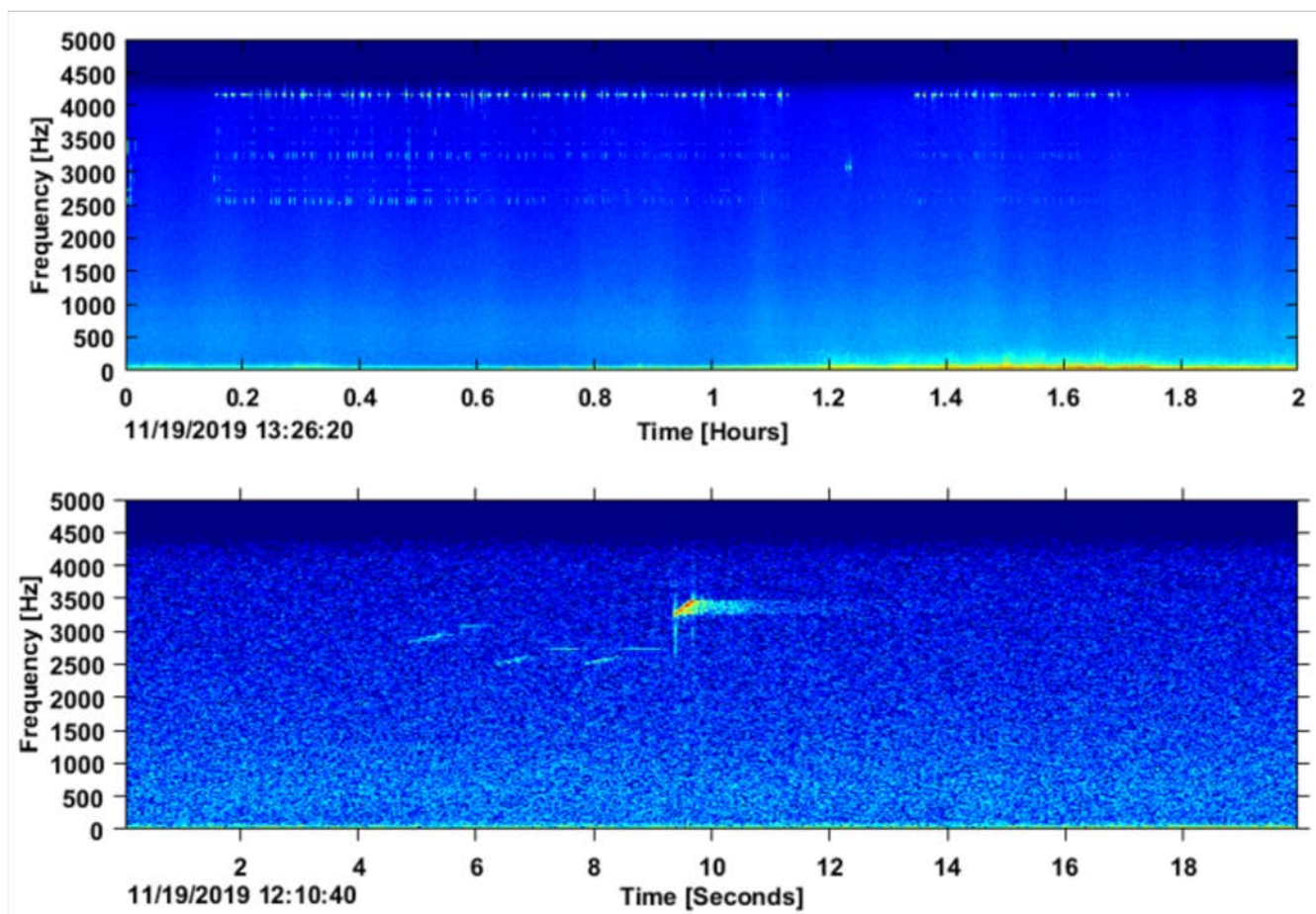


Figure 7: Mid-frequency active sonar (MFAS) in LTSA (top) and spectrogram (bottom).

4.3 High-Frequency Active Sonar/Echosounders (HFAS)

High-frequency active sonar/echosounder (HFAS) signals occur above 5 kHz and may extend through the upper recording bandwidth of the HARP system (up to 100 kHz). These signals are typically characterized by repeated narrowband or broadband pings that may occur at regular intervals. In LTSAs, HFAS signals may appear as intermittent high-frequency bands, while spectrogram expansion reveals discrete impulsive or tonal pulses depending on system type and vessel motion (Figure 8).

HFAS and echosounders were manually logged using the Logger Remora in Triton (Wiggins et al. 2010). Analysts scanned 1-hour LTSA windows generated from full-bandwidth (10–100 kHz) data to identify candidate high-frequency transmissions. When activity was observed, the display was expanded to 60-second spectrogram view for confirmation and boundary definition.

Spectrogram parameters were adjusted as needed to optimize visualization across the high-frequency band, with FFT lengths selected to balance temporal and frequency resolution depending on signal structure.

Encounter start and end times were recorded directly within the logging interface. Effort periods were defined to document active review intervals. Confirmed detections were exported and used to generate the HFAS/echosounder detection time series.

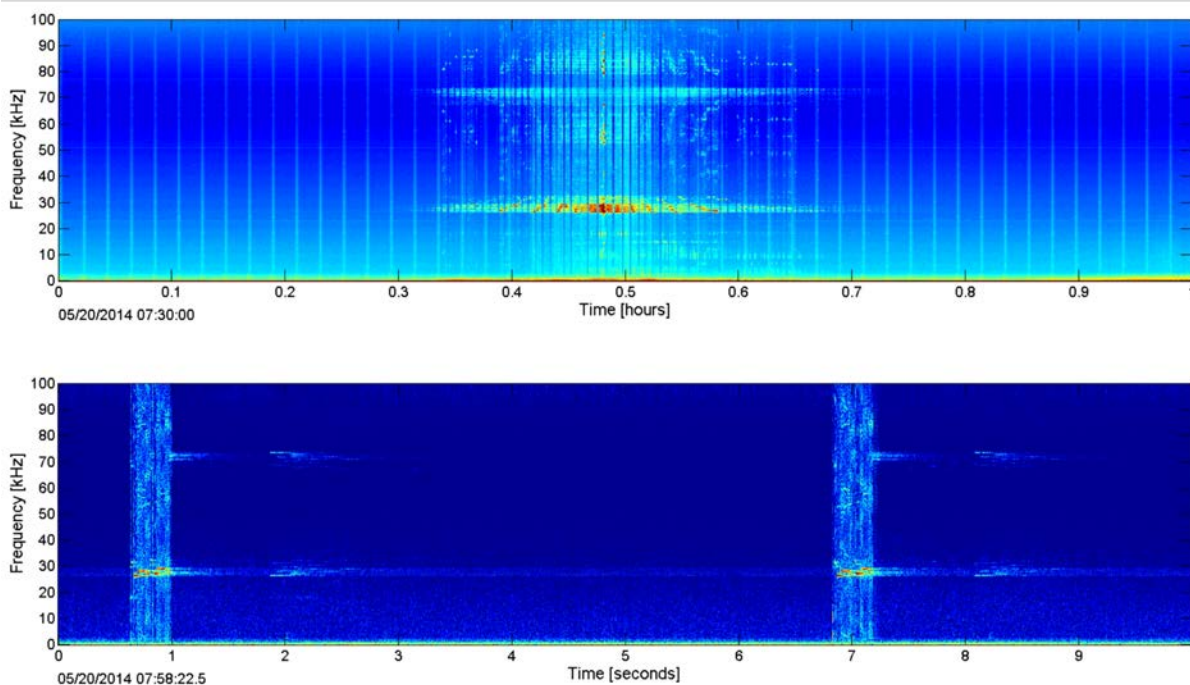


Figure 8: High-frequency active sonar (HFAS) in LTSA (top) and spectrogram (bottom).

4.4 Impulsive Sounds

Impulsive sounds monitored in this analysis included military detonations, geophysical airgun shots (Wiggins et al. 2016), and seal bombs used by the fishing industry (Krumpel et al. 2021). These source types were analyzed collectively because they share similar broadband impulsive acoustic characteristics and were identified using a common impulsive-sound detection framework. Impulsive acoustic signals contain broadband energy that may begin as low as 10 Hz and often extend to 2,000 Hz or higher. Signals typically last a few seconds including reverberation. In LTSAs, impulsive signals appear as vertical broadband spikes; when expanded in spectrogram view, they exhibit a sharp onset followed by reverberant decay (Figure 9).

Impulsive sounds were automatically detected using a matched-filter detector applied to data decimated to 10 kHz. The time series was filtered using a 10th-order Butterworth bandpass filter between 200 and 2,000 Hz. Cross-correlation was computed between 43.25 s of the temporal envelope of the filtered signal and a Hann-windowed explosion template (0.7 s duration). The squared cross-correlation enhanced detection peaks.

An adaptive threshold was calculated using the median cross-correlation value within each 43.25 s window to account for variable background noise conditions. Detections exceeding this threshold were further evaluated. Consecutive impulsive sounds were required to have a minimum separation of 0.5 s.

Additional amplitude and duration criteria were applied to reduce false detections. Detection duration was constrained between 0.03 and 0.55 s, and minimum peak-to-peak and RMS level differences relative to surrounding noise were required. Threshold values were evaluated based on distributions of manually verified detections.

Because the detector was designed to minimize false negatives, all automated detections were manually reviewed. Confirmed start and end times were retained for time series generation.

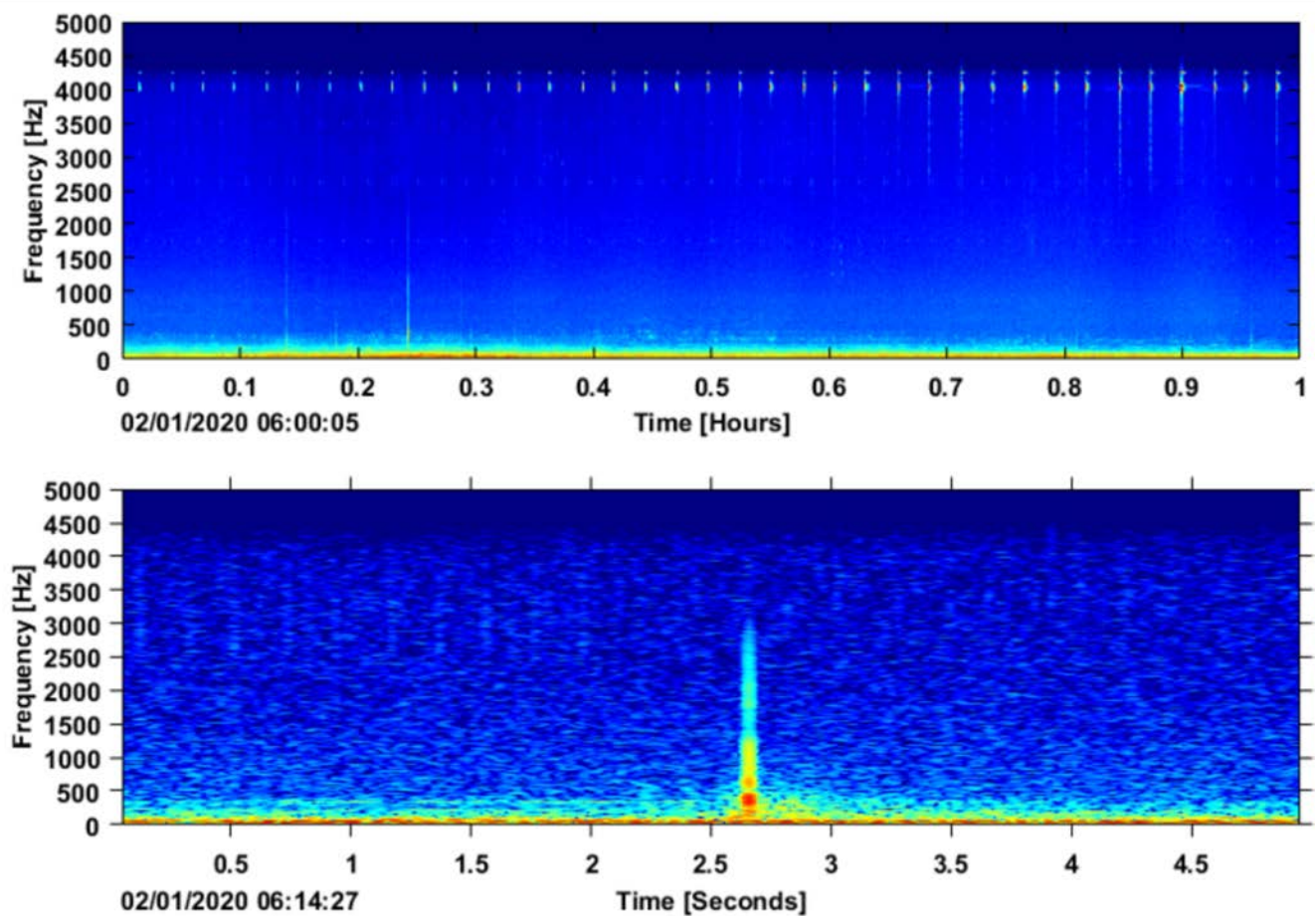


Figure 9: Representative impulsive sound in LTSA (top) and spectrogram (bottom).

4.5 Broadband Ships

Ship passages were detected using the Ship Detector Remora in Triton (Solsona-Berga et al. 2020). Ship noise is typically characterized by sustained low-frequency tonal and broadband energy generated by propeller cavitation and engine machinery. In LTSAs, ship passages appear as elevated energy bands that may persist from minutes to several hours depending on vessel speed and proximity. Spectrogram expansion reveals harmonic structure and broadband components that vary gradually in frequency over time (Figure 10).

The detector operates on LTSAs using sliding analysis windows in which power spectral density (PSD) is averaged across three predefined frequency bands (low, medium, and high). Start and end times are identified when multiple criteria are satisfied.

First, averaged amplitude in each band must exceed a time-dependent threshold derived using a histogram-based method that estimates background and elevated noise levels within the window. Second, duration criteria must be satisfied for either close or distant passage classifications based on band-specific persistence patterns designed to reduce confusion with biological sources. Third, ship passages are distinguished from weather-related noise when low-frequency energy exceeds a specified proportion of background levels.

Overlapping sliding windows were applied to ensure detection continuity across window boundaries. The detector was run in batch mode across each LTSA file. Detection outputs were reviewed and modified when necessary using the evaluation interface. Confirmed detections were retained for time series construction.

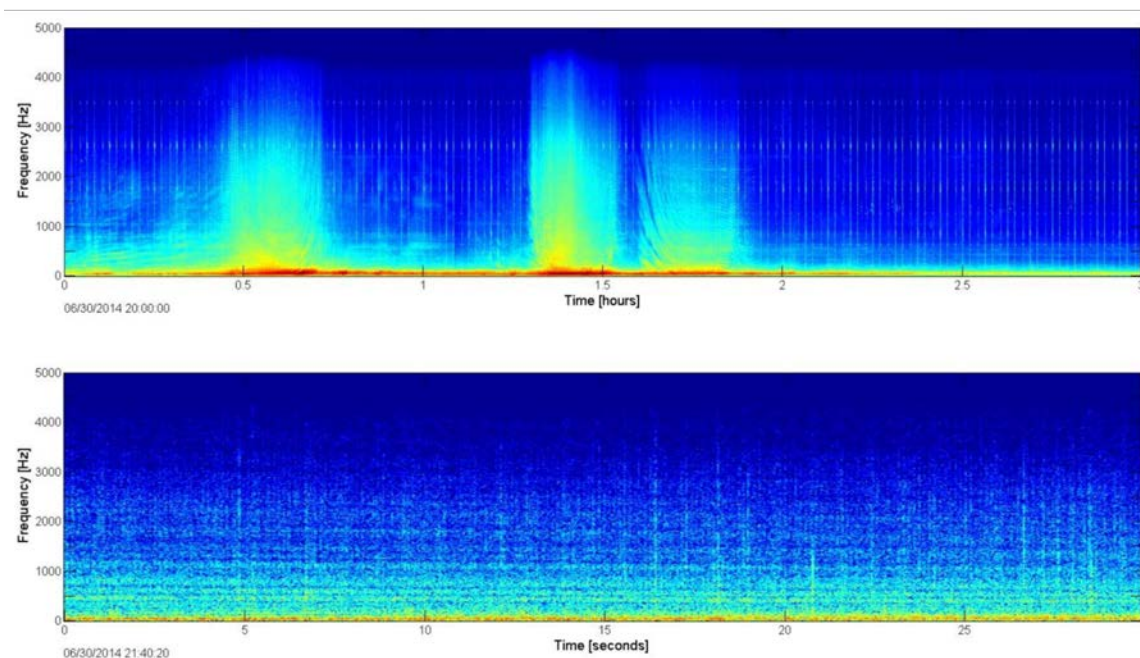


Figure 10: A broadband ship in LTSA (top) and spectrogram (bottom).

5 Results

Anthropogenic acoustic activity varied substantially among regions, signal types, and monitoring sites throughout the western North Atlantic study area. Broadband ship noise represented the most persistent and spatially widespread anthropogenic signal across all regions, with elevated detections occurring at nearly all sites during periods with recording effort. Ship activity generally exhibited pronounced seasonal and interannual variability, although the timing and magnitude of peak activity differed among regions and sites.

Low-frequency active sonar (LFAS), Mid-frequency active sonar (MFAS), and High-frequency active sonar (HFAS)/echosounder activity also varied geographically and by signal type. LFAS detections were generally intermittent and occurred at relatively low levels across monitored regions. MFAS detections exhibited greater variability in both magnitude and temporal structure, with the highest overall activity occurring off Jacksonville and more episodic activity observed at northern sites. HFAS/echosounder activity was most pronounced offshore Cape Hatteras, where prolonged periods of elevated detections were observed, while other regions generally exhibited intermittent or comparatively limited activity.

Impulsive sound detections were sporadic across most monitored regions and generally occurred at substantially lower levels than ship noise or active sonar detections. Elevated occurrence was observed intermittently at select sites, particularly near Norfolk Canyon, Onslow Bay, and Jacksonville, although most weeks were characterized by relatively low detection levels.

Across all signal types, detections generally occurred throughout the 24-hour cycle, and strong or consistent diel patterns were uncommon. Seasonal and interannual variability represented the dominant temporal structure in anthropogenic acoustic activity across the study area. The following sections describe regional and site-specific patterns for each anthropogenic signal type in greater detail.

5.1 Low-Frequency Active Sonar (LFAS)

LFAS detections were generally intermittent across monitored regions and varied substantially in magnitude, seasonal occurrence, and persistence among sites. Norfolk Canyon exhibited episodic LFAS activity concentrated during specific periods of the monitoring record, while offshore Cape Hatteras exhibited relatively low but persistent detections at both sites. LFAS analyses off Jacksonville were limited to sites C and D, where detections were infrequent and occurred at relatively low levels. LFAS analyses were not conducted for the Onslow Bay sites because activity was expected to be limited within the existing dataset based on prior observations and operational context.

LFAS detections generally occurred throughout the 24-hour cycle, although most sites did not exhibit strong or consistent diel patterns. Seasonal variability was evident at several locations, with elevated activity often occurring during summer and fall months.

Summary of Results – LFAS Across Regions

- LFAS detections were generally intermittent across monitored regions.
- Norfolk Canyon exhibited episodic LFAS activity with seasonal variability.
- Offshore Cape Hatteras exhibited relatively low but persistent LFAS activity.
- Jacksonville exhibited limited LFAS detections at sites C and D.
- Most regions did not exhibit strong or consistent diel patterns.

5.1.1 Norfolk Canyon

LFAS detections near Norfolk Canyon were intermittent throughout the monitoring period, with sporadic periods of activity occurring between 2014 and 2021 (Figure 11). Weekly detections were generally low, although several weeks exceeded 3 hours and peak activity approached 4 hours per week.

Monthly mean LFAS presence was highest in March, July, August, and September, and was not logged in May and October (Figure 12). Variability was greatest during summer and early fall months, reflecting interannual differences in detections.

LFAS detections occurred throughout the 24-hour cycle (Figure 13). Activity was observed during both daytime and nighttime hours, with no consistent diel pattern across years.

Summary of Results – LFAS near Norfolk Canyon

- LFAS activity was intermittent throughout the monitoring period.
- Peak weekly detections approached approximately 4 hours.
- Monthly means were highest in March and during summer through early fall months.
- May and October exhibited no LFAS activity.
- Detections occurred across all hours with no consistent diel pattern.

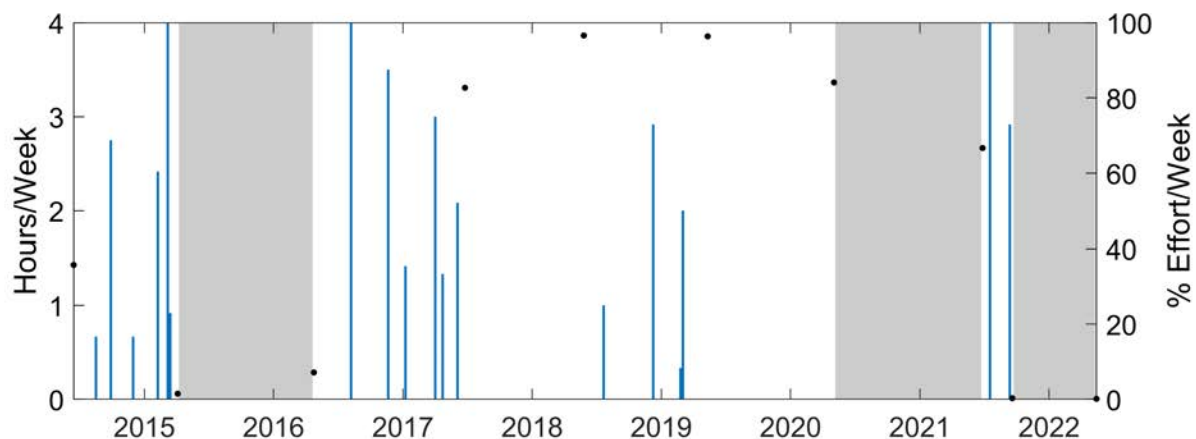


Figure 11: Cumulative hours/week of low-frequency active sonar near Norfolk Canyon. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

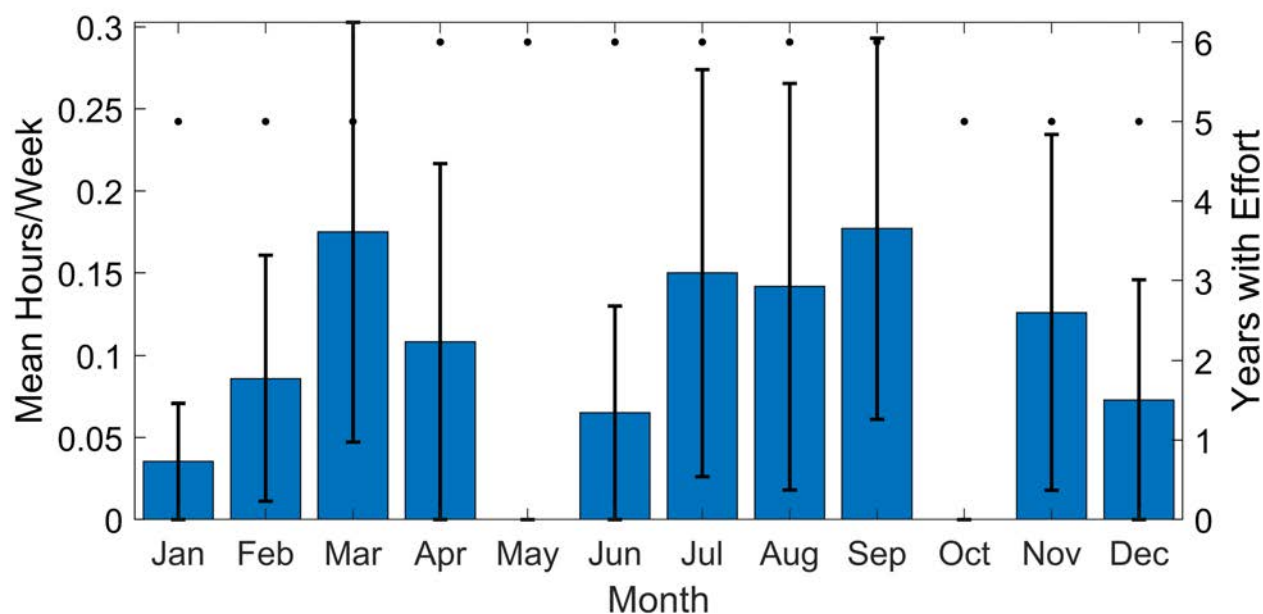


Figure 12: Monthly mean hours per week of low-frequency active sonar near Norfolk Canyon. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

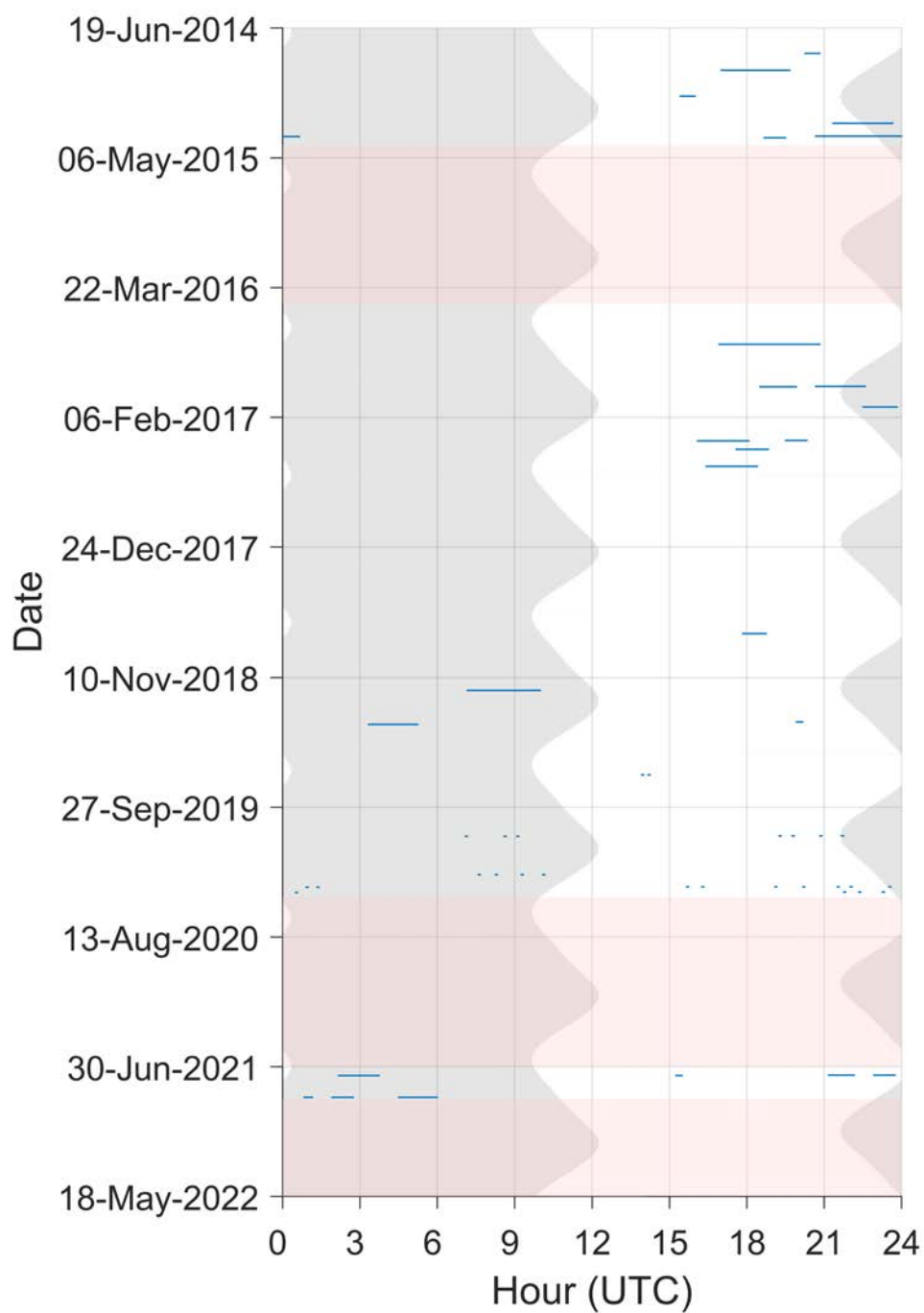


Figure 13: Low-frequency active sonar presence in 5-min bins near Norfolk Canyon. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.1.2 Cape Hatteras

LFAS detections offshore Cape Hatteras were intermittent at both site A and B (Figure 14). Site A exhibited sporadic activity concentrated primarily during 2011, with weekly detections generally remaining below 4 hours per week. Site B exhibited more frequent detections during 2018–2019, with peak weekly LFAS-positive hours approaching 7 hours per week.

Monthly mean LFAS presence differed between sites (Figure 15). At site A, activity was only logged in March, April, and August. Site B exhibited elevated activity in November, with additional detections during February, March, and September.

LFAS detections occurred throughout the 24-hour cycle at both sites (Figure 16). Activity was observed during both daytime and nighttime hours, with no consistent diel concentration evident across years.

Summary of Results – LFAS offshore Cape Hatteras

- LFAS activity was intermittent at both sites A and B.
- Site B exhibited higher overall activity, with peak weekly detections approaching 7 hours.
- Site A showed lower weekly totals, generally below 4 hours.
- Monthly activity at site A was highest in March and for site B was highest in November.
- Detections occurred across all hours at both sites with no consistent diel pattern.

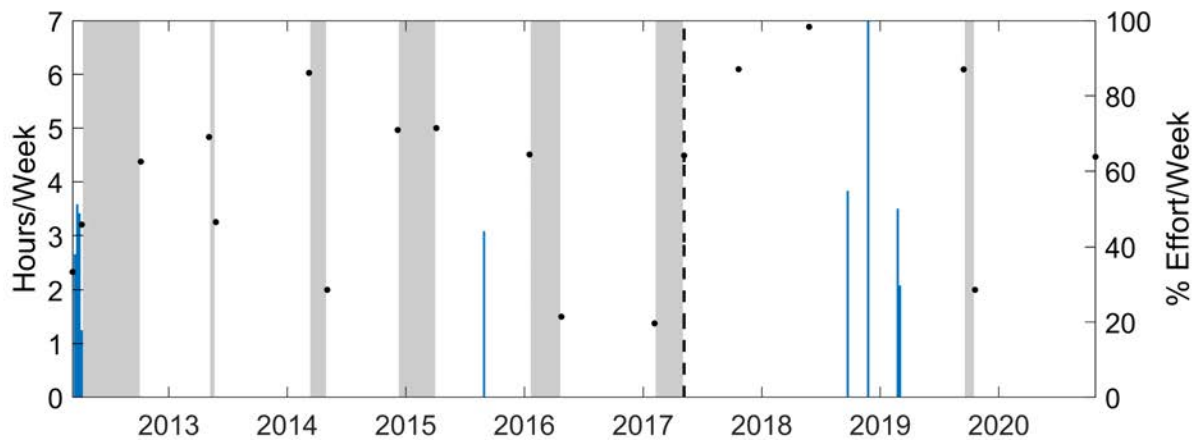


Figure 14: Cumulative hours/week of low-frequency active sonar offshore Cape Hatteras. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The dashed line represents when the instrument moved from site A to site B.

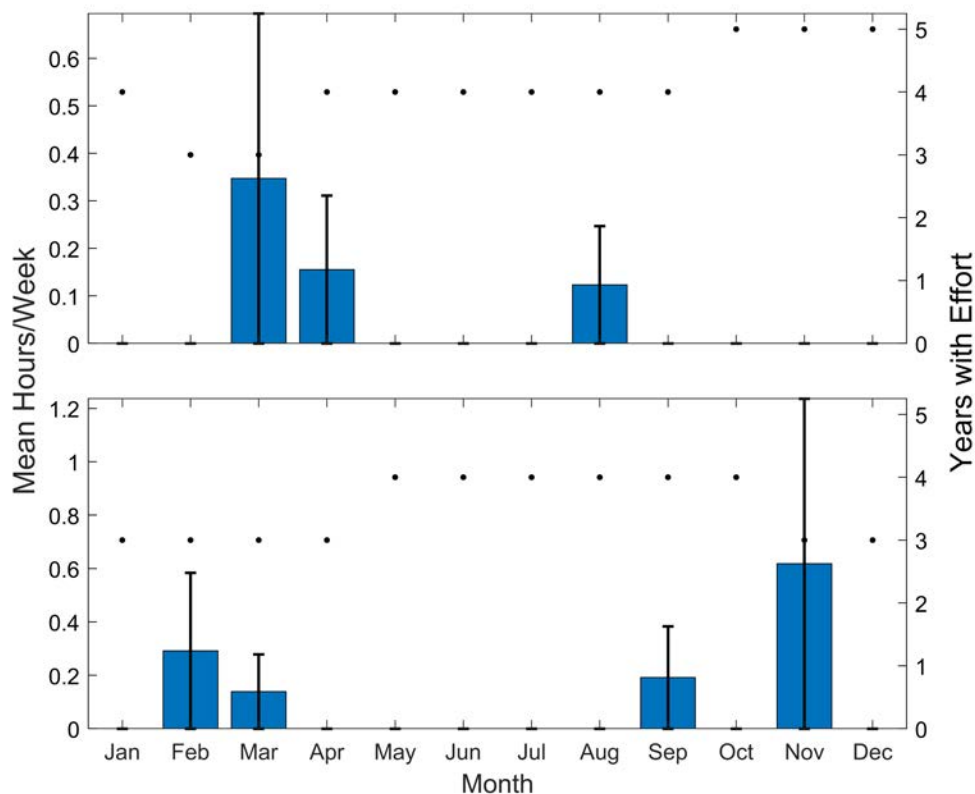


Figure 15: Monthly mean hours per week of low-frequency active sonar offshore Cape Hatteras at site A (top) and site B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

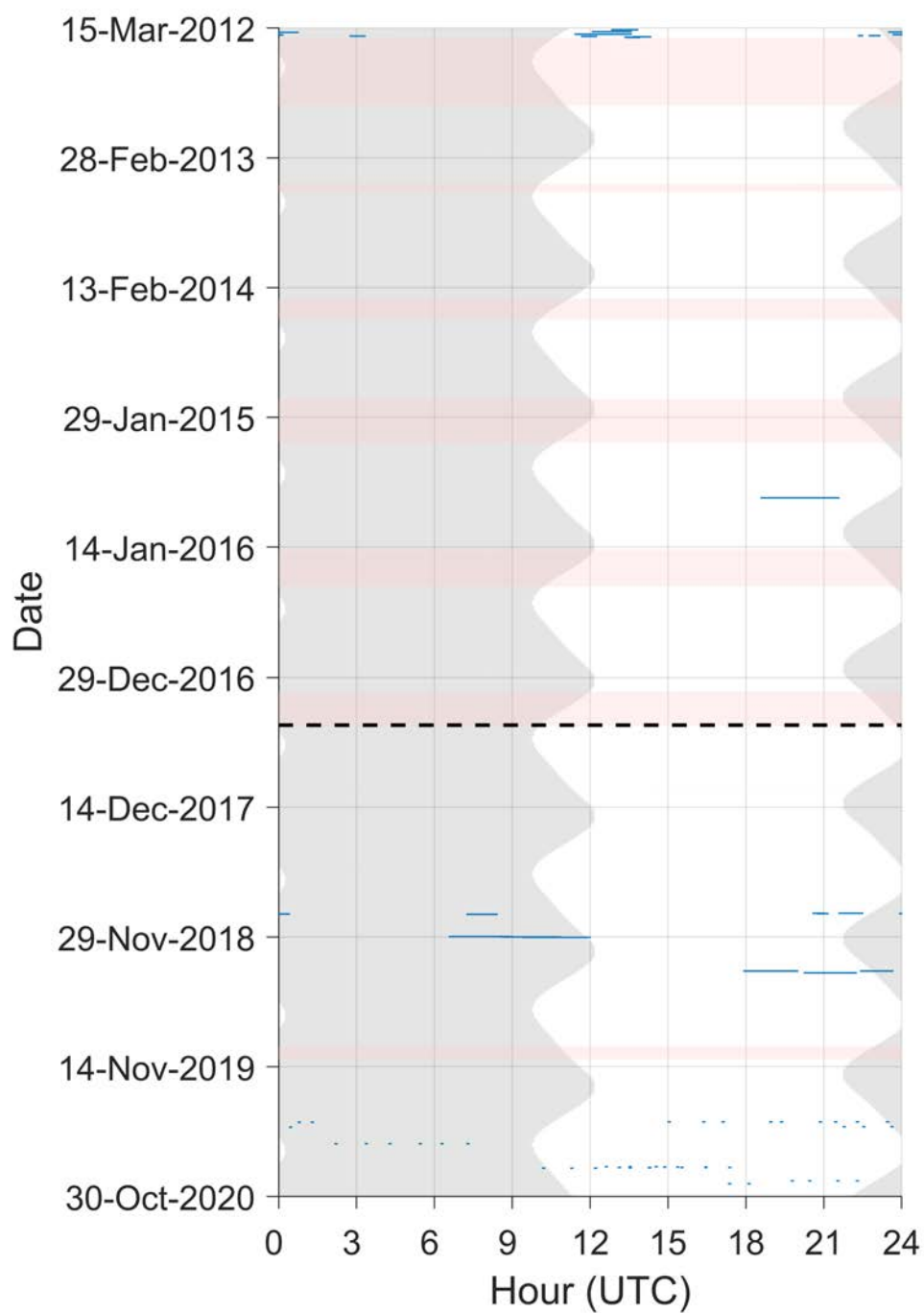


Figure 16: Low-frequency active sonar presence in 5-min bins offshore Cape Hatteras. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The dashed line represents when the instrument moved from site A to site B.

5.1.3 Jacksonville

LFAS analyses off Jacksonville were conducted only for sites C and D because low-frequency active sonar activity was expected to be limited at sites A and B based on prior observations and operational context. Within the analyzed sites, LFAS detections were infrequent overall (Figure 17). Site C exhibited a brief period of elevated activity during 2013, with weekly detections approaching 40 total 5-minute bins per week. Site D showed a smaller episode of activity during 2014–2015, with weekly detections remaining below 20 total 5-minute bins per week.

Monthly mean LFAS presence differed slightly between sites (Figure 18). Site C only exhibited activity in May, while site D showed limited activity in September.

LFAS detections occurred throughout the 24-hour cycle at both sites (Figure 19). No consistent diel pattern was evident.

Summary of Results – LFAS off Jacksonville

- LFAS analyses were conducted only for sites C and D, where detections were infrequent overall.
- Site C exhibited a brief but pronounced period of activity during 2013.
- Site D exhibited lower-magnitude but more persistent activity overall.
- Site C exhibited highest monthly activity in May.
- Site D exhibited limited detections concentrated in February with additional peaks in July and September.
- No consistent diel pattern was evident.

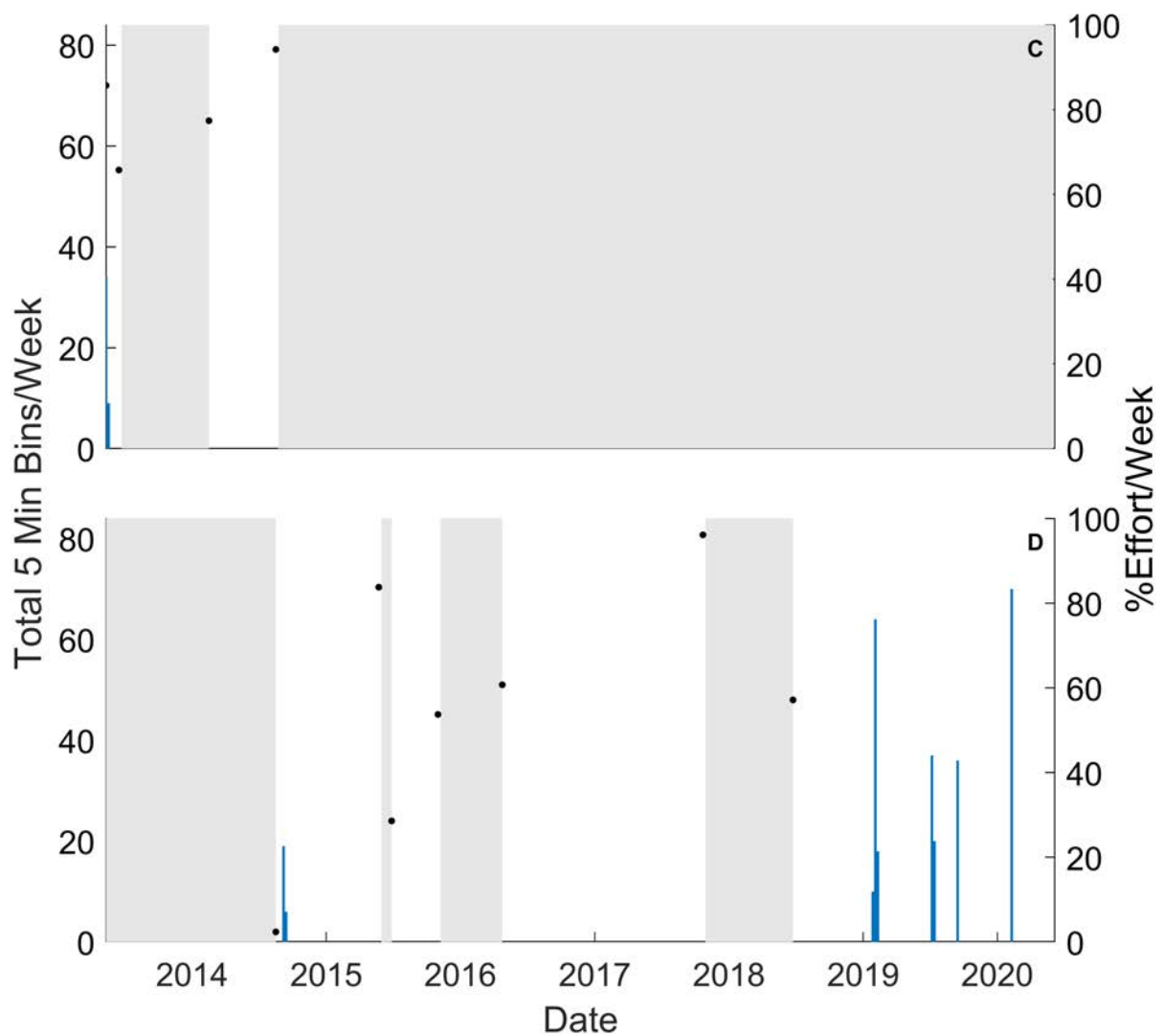


Figure 17: Cumulative hours/week of low-frequency active sonar at Jacksonville sites C and D. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

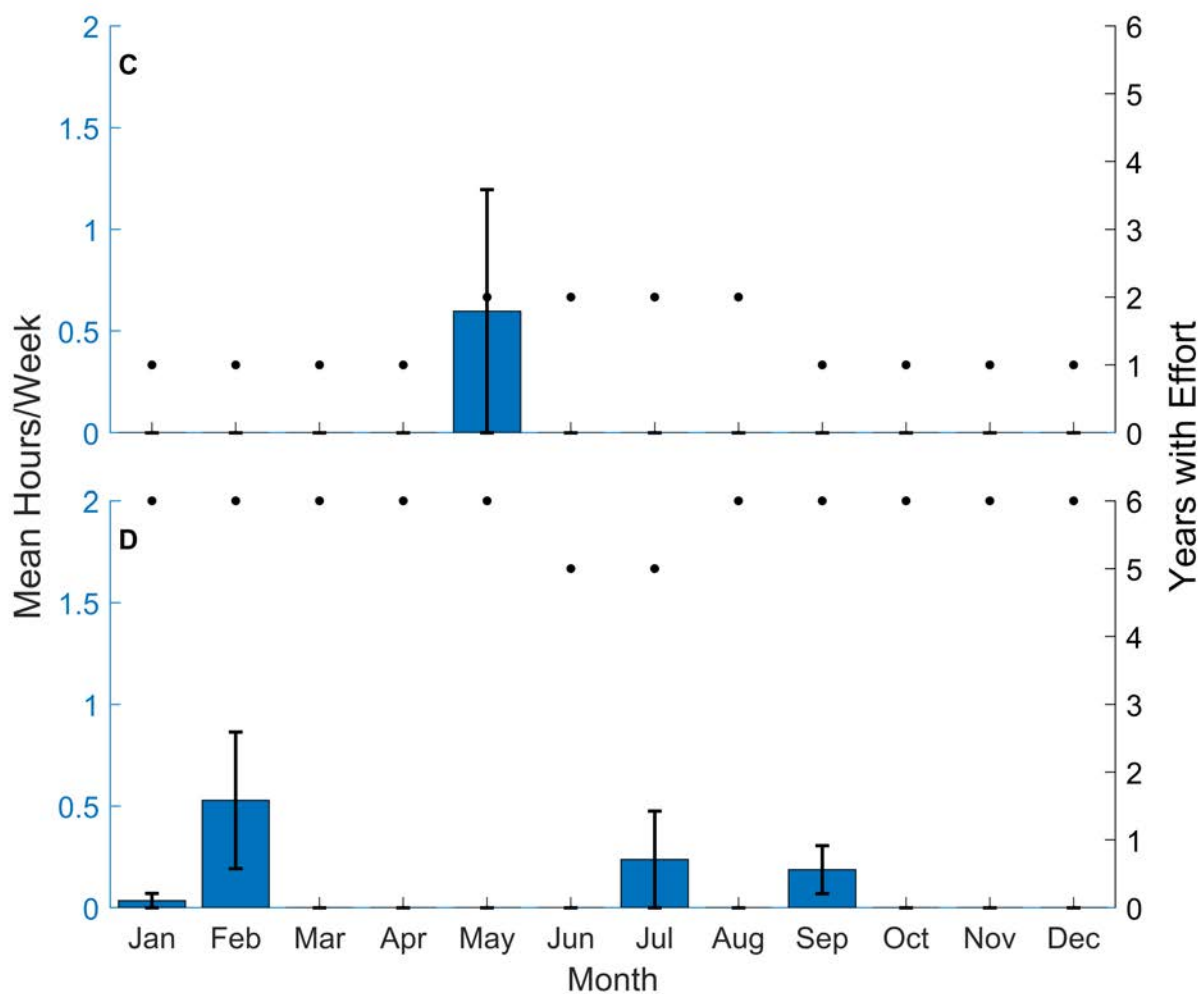


Figure 18: Monthly mean hours per week of low-frequency active sonar at Jacksonville sites C and D. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

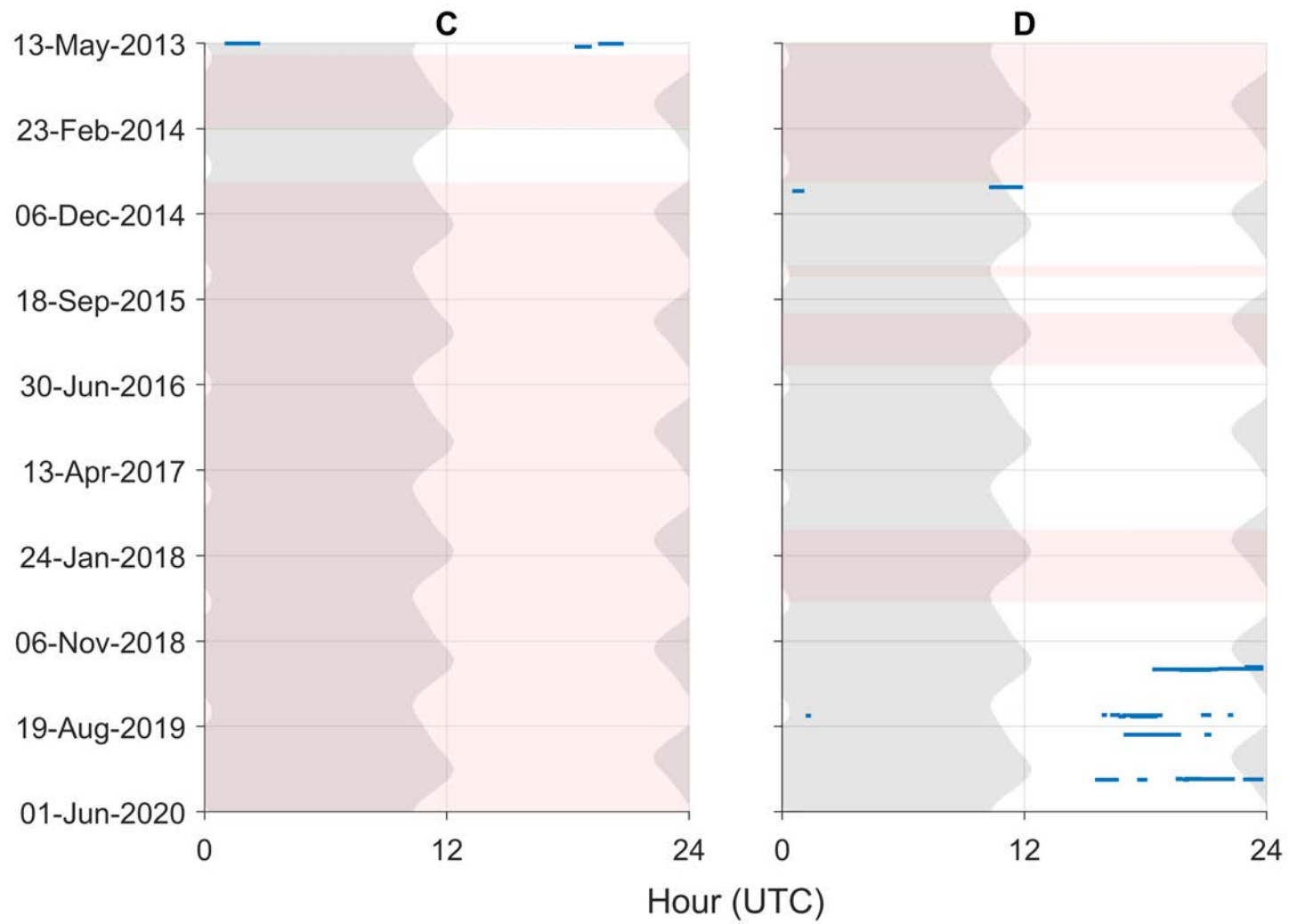


Figure 19: Low-frequency active sonar in 5-min bins at Jacksonville sites C and D. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.2 Mid-frequency Active Sonar (MFAS)

MFAS activity varied among regions in both magnitude and temporal structure, progressing from north to south along the study area. Near Norfolk Canyon, MFAS detections were episodic and concentrated primarily during 2018–2019, with peak weekly detections approaching 18 hours. Monthly means were highest in late summer, and activity occurred across all hours of the day without a consistent diel pattern.

Offshore Cape Hatteras exhibited moderate MFAS activity relative to other regions. Activity differed between sites, with site B showing higher weekly totals and peak detections exceeding 30 hours per week, while site A generally remained below 10 hours per week. Elevated monthly activity occurred in late summer and early fall, particularly at site B. Detections occurred throughout the 24-hour cycle with no consistent diel concentration.

In Onslow Bay, MFAS detections were sporadic across sites. Most weeks exhibited limited activity, with two pronounced episodes at site B and E exceeding 200 total 5-minute bins per week. Seasonal interpretation was limited at several sites due to single-year effort, although site E exhibited relatively consistent detections with slightly higher activity during fall months. No consistent diel pattern was evident.

Off Jacksonville, MFAS activity was the highest among all monitored regions. Sites A and D exhibited slightly higher overall activity relative to the other Jacksonville sites, with multiple weeks exceeding 1,000 total 5-minute bins per week. Clearer seasonal structure was observed relative to northern sites: site A exhibited elevated activity during late fall into winter, while site D showed higher activity from July through February. Sites C and B exhibited more localized periods of increased activity with no clear seasonal pattern. As with other regions, detections occurred across all hours with no consistent diel pattern.

Summary of Results – MFAS Across Regions

- MFAS activity increased in overall magnitude from north to south, with Jacksonville exhibiting the highest levels.
- Norfolk Canyon showed episodic activity concentrated primarily during 2018–2019.
- Offshore Cape Hatteras exhibited moderate activity, with higher levels at site B than A.
- Onslow Bay exhibited generally low activity with two pronounced weekly episodes.
- Jacksonville exhibited the highest overall MFAS activity and the clearest seasonal structure, with slightly higher activity at sites A and D.
- Across all regions, MFAS detections occurred throughout the 24-hour cycle, although slight nighttime increases were observed at some locations.

5.2.1 Norfolk Canyon

MFAS detections near Norfolk Canyon were intermittent throughout the monitoring period and concentrated during 2018–2019, when weekly activity frequently exceeded 10 hours and peaked near 18 hours per week (Figure 20).

Monthly mean MFAS presence was highest in August (approximately 2 hours/week), and lowest in June and December (Figure 21). Variability was greatest in late summer months, reflecting interannual differences.

MFAS detections occurred throughout the 24-hour cycle (Figure 22). Activity was observed during both daytime and nighttime hours, with only a slight increase in detections during nighttime hours.

Summary of Results – MFAS near Norfolk Canyon

- MFAS activity was episodic, with highest levels during 2018–2019.
- Peak weekly detections approached approximately 18 hours.
- Monthly means were highest in August; June and December were lowest.
- Detections occurred across all hours, though there was a slight diel pattern with increased detections during nighttime hours.

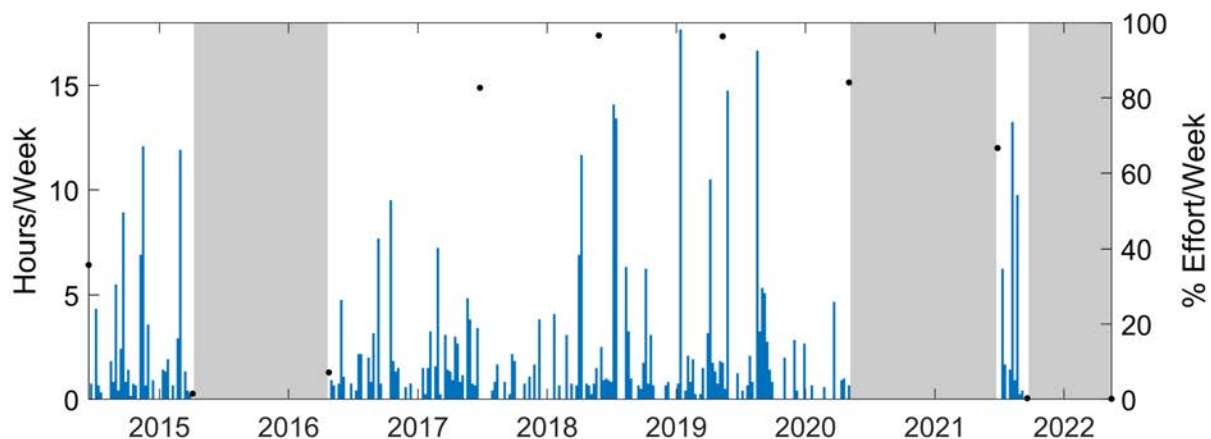


Figure 20: Cumulative hours/week of mid-frequency active sonar near Norfolk Canyon. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

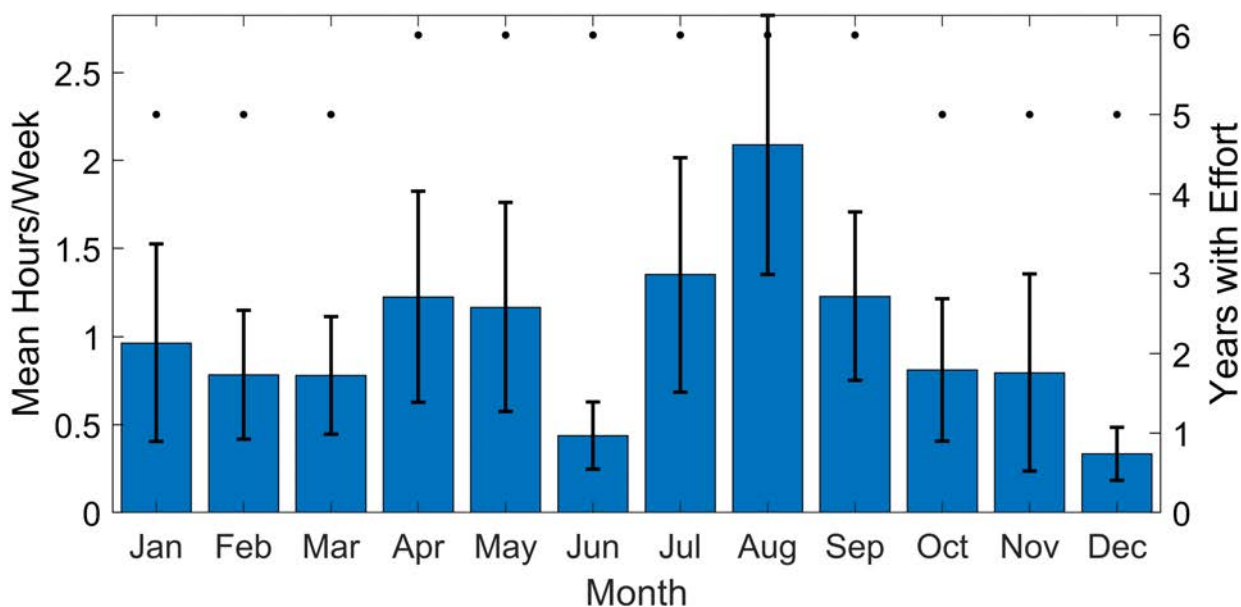


Figure 21: Monthly mean hours per week of mid-frequency active sonar near Norfolk Canyon. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

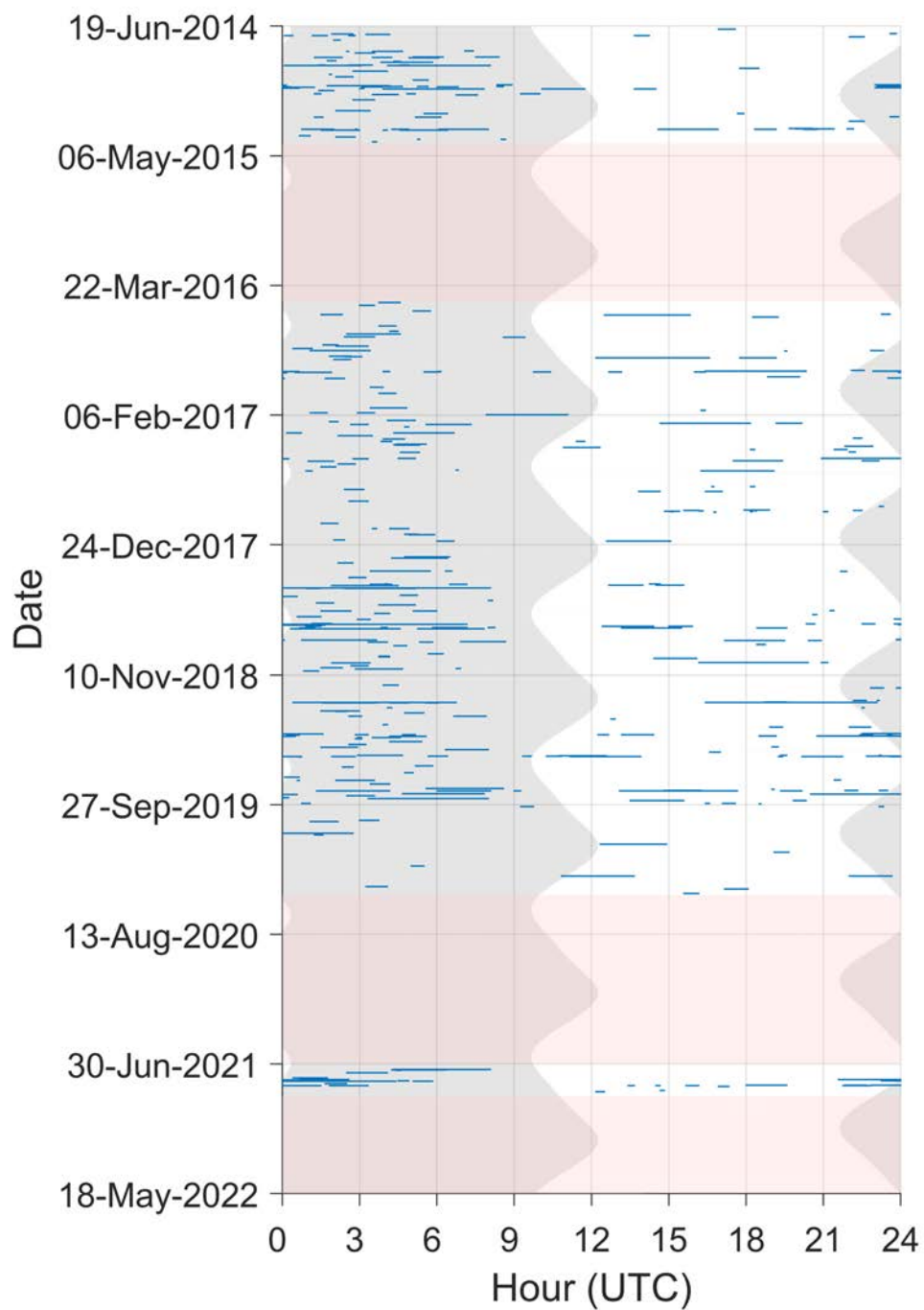


Figure 22: Mid-frequency active sonar presence in 5-min bins near Norfolk Canyon. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.2.2 Cape Hatteras

MFAS detections offshore Cape Hatteras were intermittent at both sites A and B (Figure 23). Site A exhibited sporadic activity, with detections generally remaining below 10 hours per week. Site B had higher-magnitude detections and more frequent activity, with peak weekly MFAS-positive hours exceeding 30 hours per week during two weeks in 2018 and 2019.

Monthly mean MFAS presence differed between sites (Figure 24). At site A, activity was highest in October, September, and March and lowest in December, January, and April. Site B exhibited elevated activity in late summer and early fall, particularly August through October, with minimal activity during winter and early spring months.

MFAS detections occurred throughout the 24-hour cycle at both sites (Figure 25). Activity was observed during both daytime and nighttime hours, with no consistent diel concentration evident across years.

Summary of Results – MFAS offshore Cape Hatteras

- MFAS activity was intermittent at both sites A and B.
- Site B exhibited higher overall activity, with peak weekly detections exceeding 30 hours.
- Site A showed lower weekly totals, generally below 10 hours.
- Monthly activity at site B was elevated in late summer and early fall.
- Detections occurred across all hours at both sites with no consistent diel pattern.

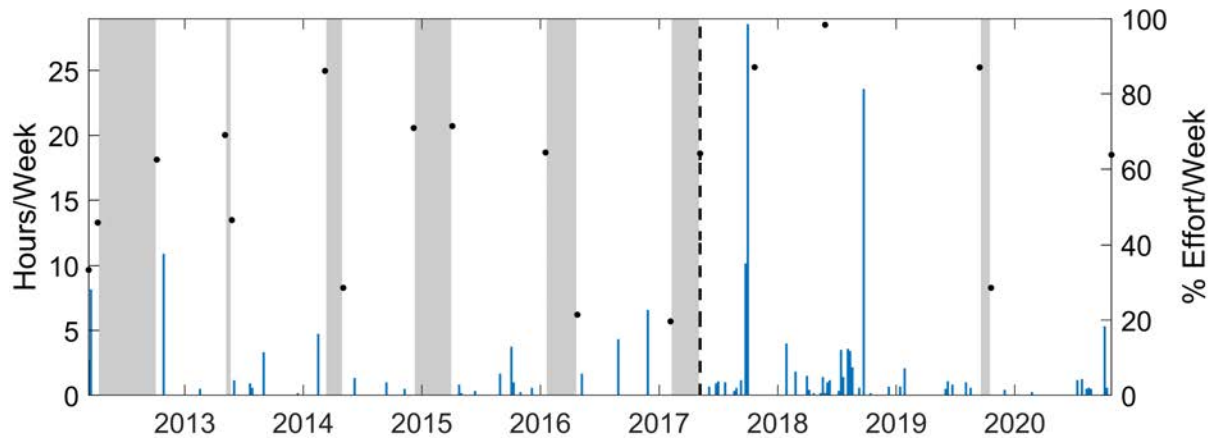


Figure 23: Cumulative hours/week of mid-frequency active sonar off Cape Hatteras. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The dashed line represents when the instrument moved from site A to site B.

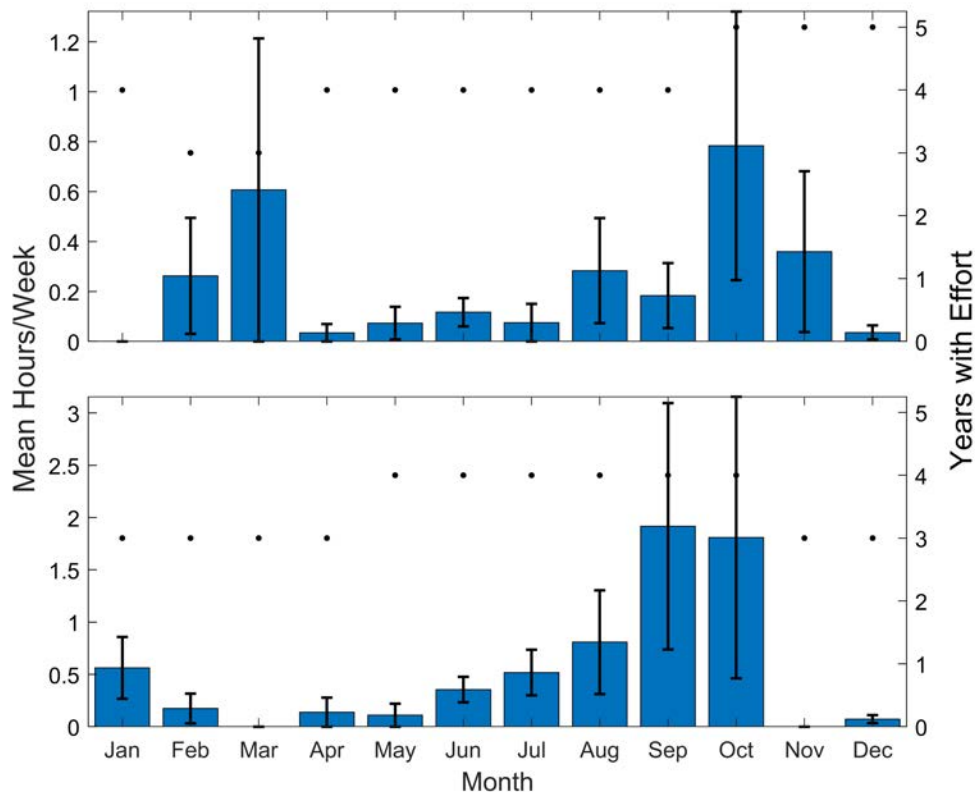


Figure 24: Monthly mean hours per week of mid-frequency active sonar off Cape Hatteras at site A (top) and site B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

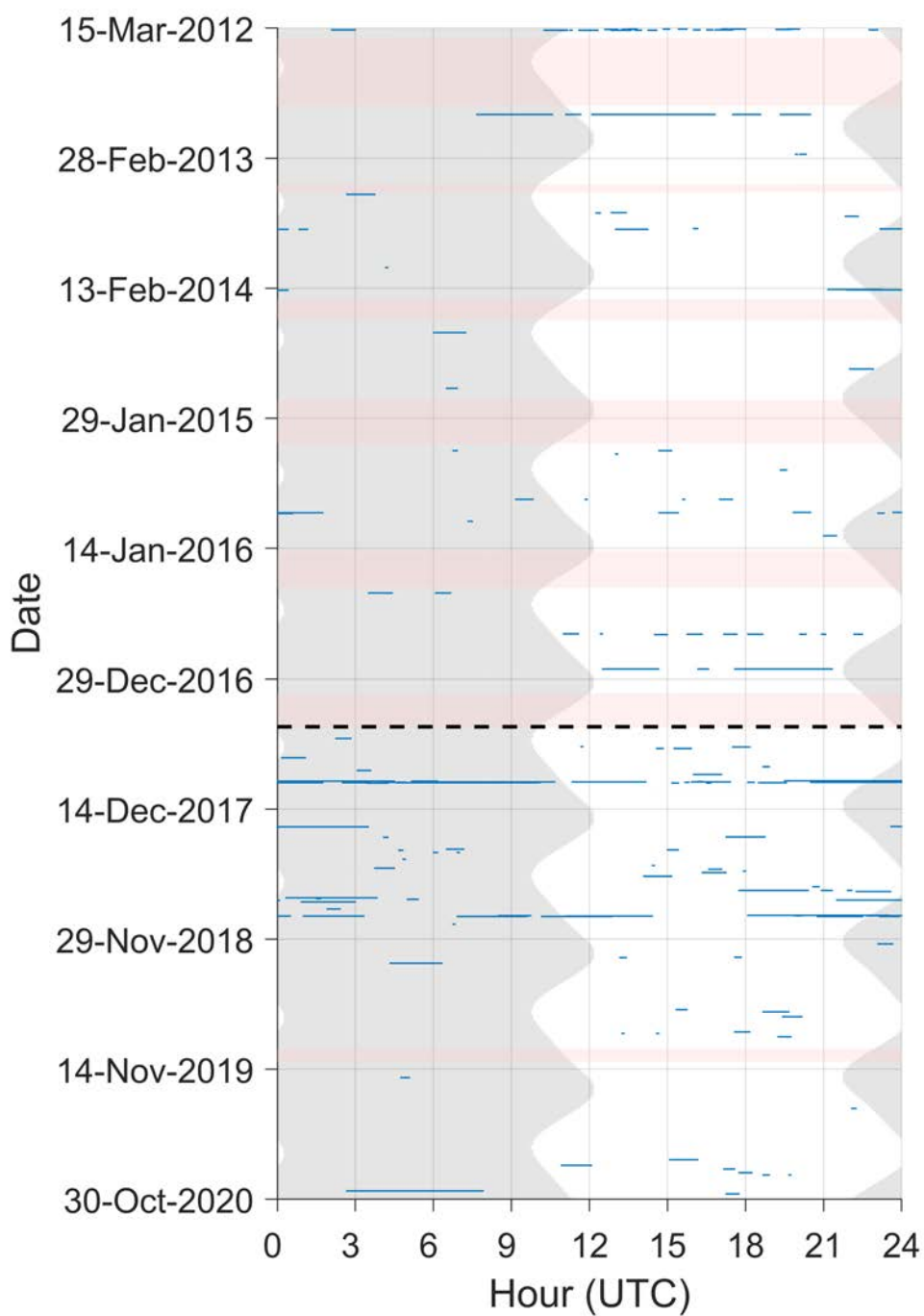


Figure 25: Mid-frequency active sonar presence in 5-min bins off Cape Hatteras. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The dashed line represents when the instrument moved from site A to site B.

5.2.3 Onslow Bay

MFAS detections in Onslow Bay were sporadic across sites (Figure 26). Most weeks exhibited limited activity. Two pronounced episodes were observed: one at site B and another at site E, where weekly detections exceeded 200 total 5-minute bins per week.

Monthly mean MFAS presence varied among sites (Figure 27). At site A, detections were lowest from March through September. Sites B, C, and D each had only one year of recording effort, limiting interpretation of seasonal patterns. At site E, detections were relatively consistent across months, with slightly higher activity during fall months. However, overall detection levels were low, making clear seasonal trends difficult to discern.

MFAS detections occurred throughout the 24-hour cycle at all sites (Figure 28). No consistent diel pattern was evident.

Summary of Results – MFAS in Onslow Bay

- MFAS detections were sporadic across sites.
- Two pronounced episodes occurred, one at site B and one at site E, exceeding 200 total 5-minute bins per week.
- Site A showed lowest monthly activity from March through September.
- Sites B–D each had only one year of effort, limiting seasonal interpretation.
- Site E exhibited relatively consistent monthly detections with slightly higher activity in fall.
- No consistent diel pattern was evident.

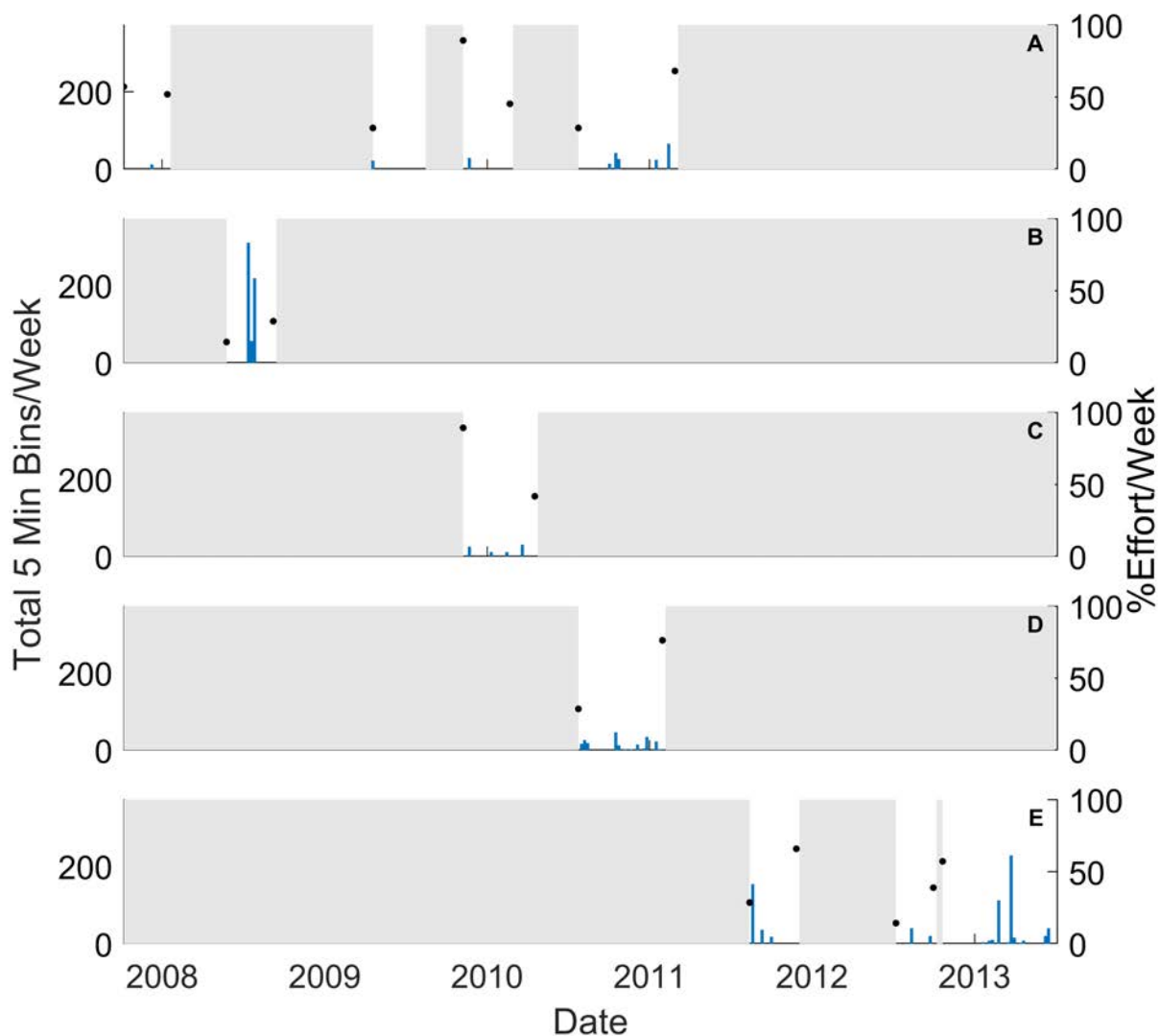


Figure 26: Cumulative hours/week of mid-frequency active sonar at all Onslow Bay sites. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

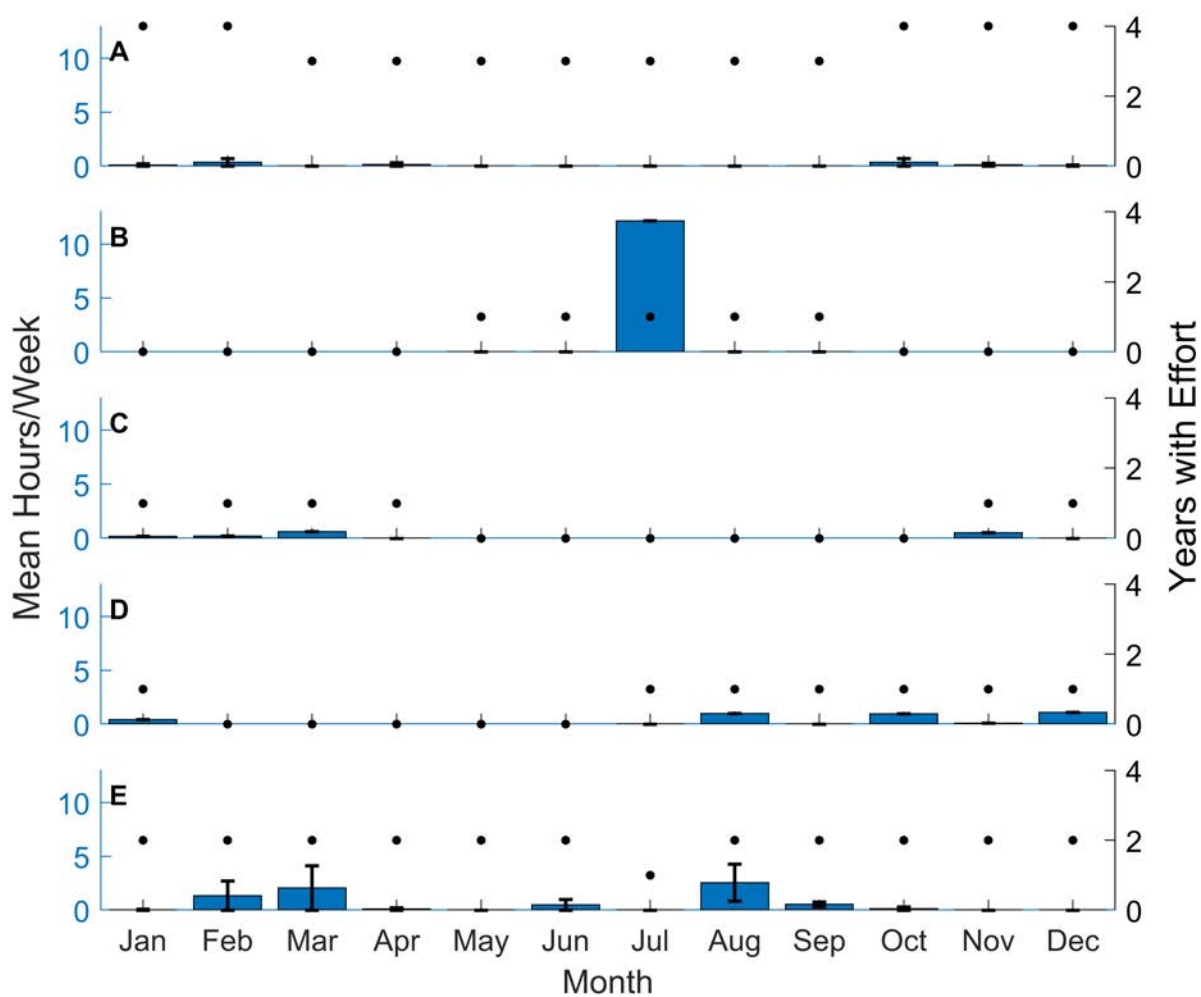


Figure 27: Monthly mean hours per week of mid-frequency active sonar at all Onslow Bay sites. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

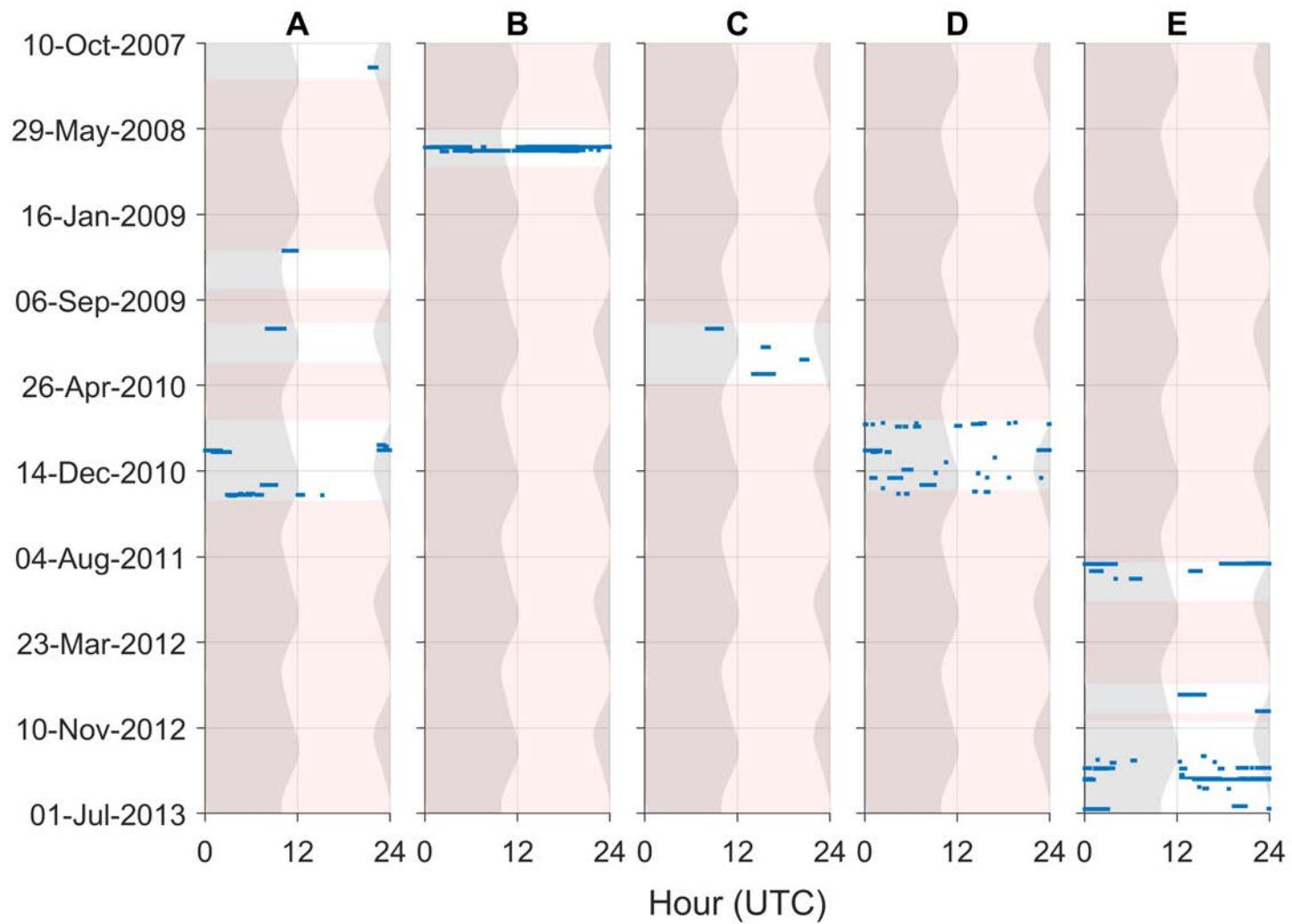


Figure 28: Mid-frequency active sonar in 5-min bins at all Onslow Bay sites. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.2.4 Jacksonville

MFAS detections off Jacksonville exhibited the highest overall activity among all monitored regions and varied among sites (Figure 29). Sites A and D exhibited slightly higher overall activity relative to the other Jacksonville sites, with multiple weeks exceeding 1,000 total 5-minute bins per week. Site B also exhibited several periods of elevated activity, while site C showed only a brief interval of increased detections. Outside of these periods, weekly detections were generally low across sites.

Monthly mean MFAS presence differed among sites (Figure 30). Site A exhibited elevated activity during late fall into winter, while site D showed higher activity from July through February. Site B exhibited increased activity from March through August. Site C exhibited localized increases during spring months, particularly March through May, with lower activity during the remainder of the year.

MFAS detections occurred throughout the 24-hour cycle at all sites (Figure 31). No consistent diel pattern was evident.

Summary of Results – MFAS off Jacksonville

- Jacksonville exhibited the highest overall MFAS activity among all monitored regions.
- Sites A and D exhibited slightly higher overall activity relative to the other Jacksonville sites, with multiple weeks exceeding 1,000 total 5-minute bins per week.
- Site A exhibited elevated monthly activity during late fall into winter.
- Site D showed increased activity from July through February.
- No consistent diel pattern was evident.

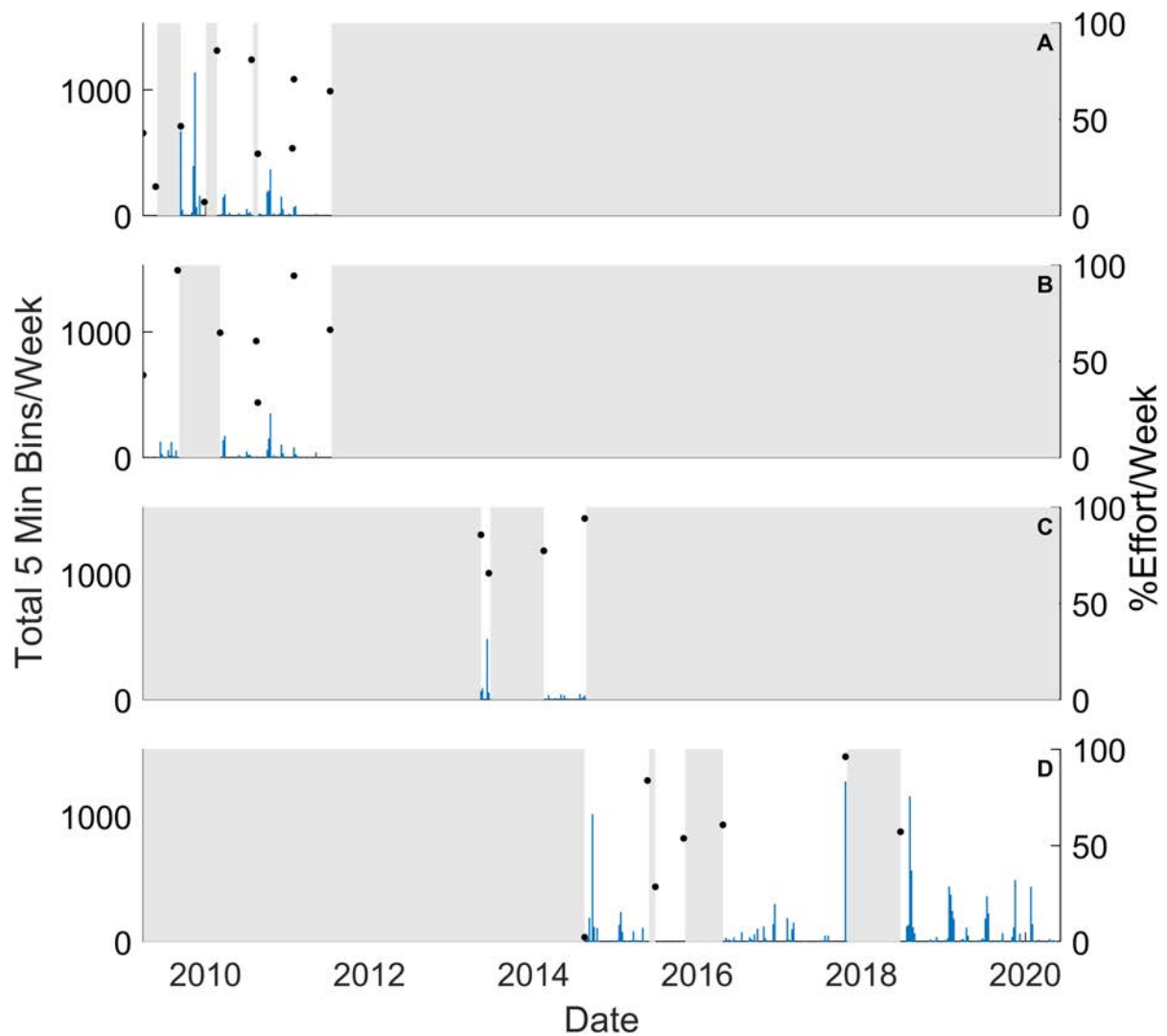


Figure 29: Cumulative hours/week of mid-frequency active sonar at all Jacksonville sites. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

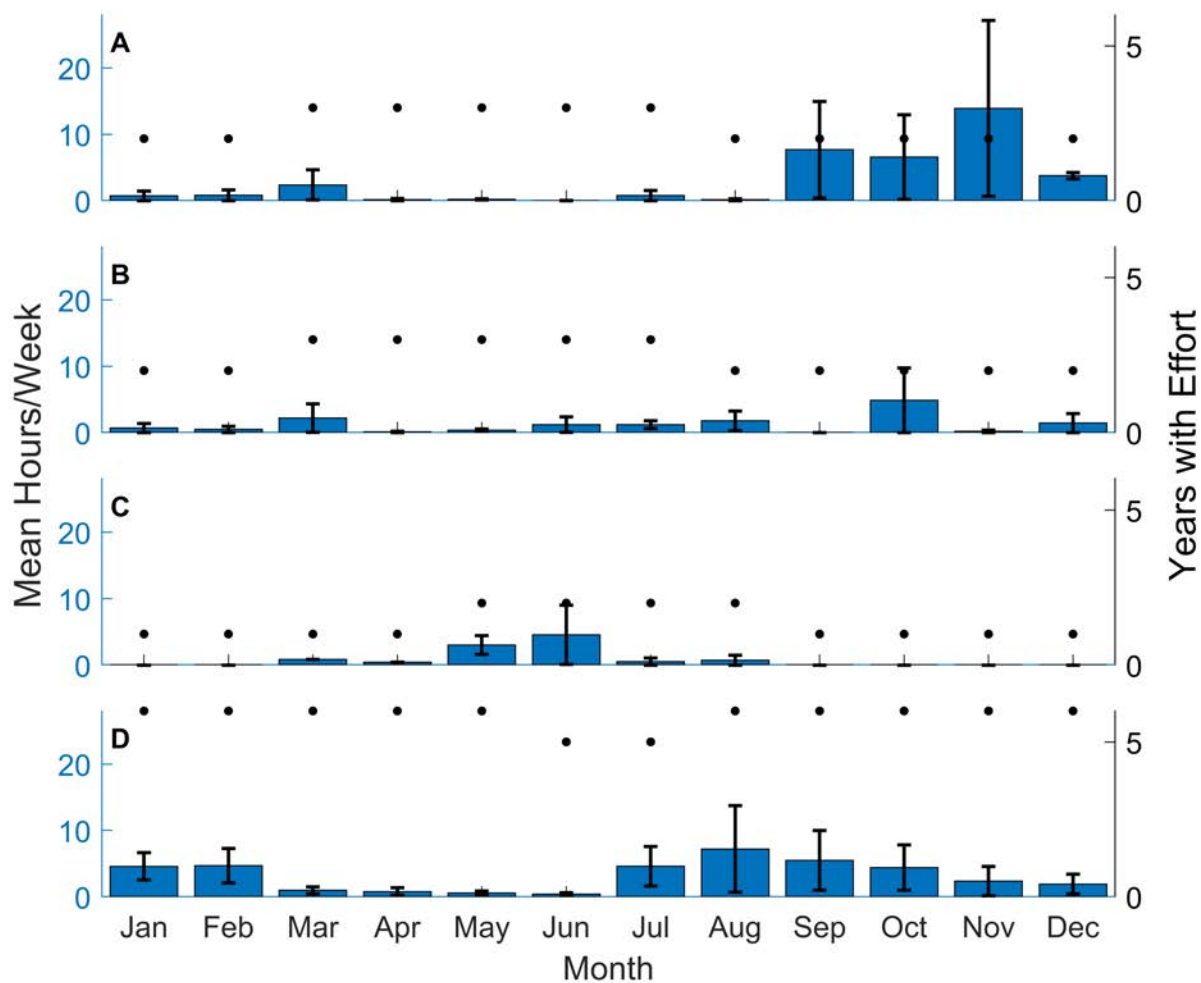


Figure 30: Monthly mean hours per week of mid-frequency active sonar at all Jacksonville sites. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

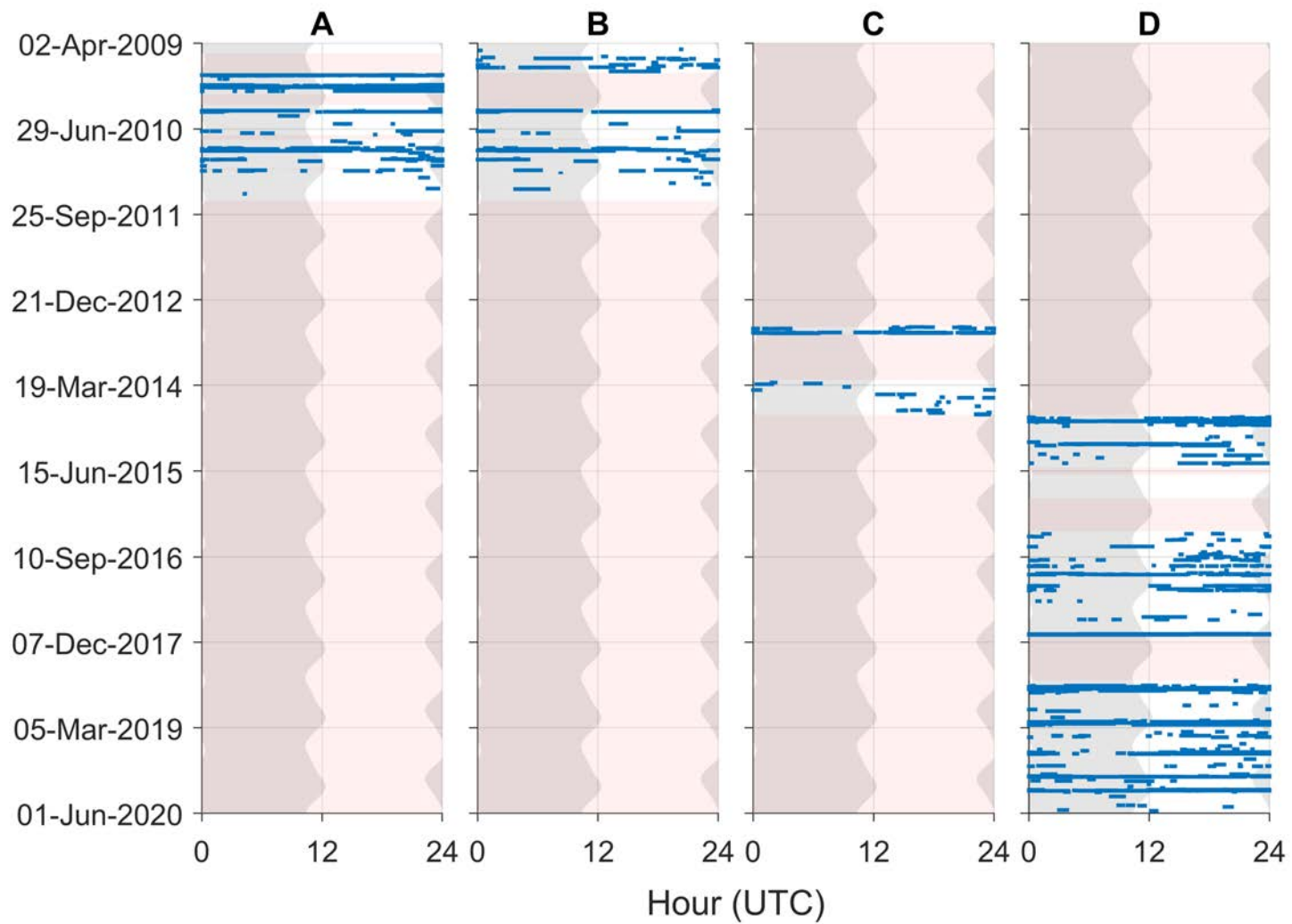


Figure 31: Mid-frequency active sonar in 5-min bins at all Jacksonville sites. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.3 High-Frequency Active Sonar/Echosounders

HFAS/echosounder detections varied substantially among monitored regions and sites. Norfolk Canyon exhibited intermittent but recurring HFAS activity, with elevated detections occurring primarily during 2016–2018. Offshore Cape Hatteras exhibited the highest overall HFAS activity, particularly at site A, where detections remained persistently elevated throughout much of the monitoring period. HFAS analyses off Jacksonville were limited to sites C and D, where detections were minimal overall. HFAS analyses were not conducted for the Onslow Bay sites because high-frequency active acoustic activity was expected to be limited within the existing dataset based on prior observations and operational context.

HFAS activity generally occurred throughout the 24-hour cycle and most regions did not exhibit strong or consistent diel patterns. Seasonal variability was observed at several sites, particularly offshore Cape Hatteras where activity was elevated during winter months.

Summary of Results – High-Frequency Active Sonar/Echosounders Across Regions

- HFAS activity varied substantially among monitored regions.
- Norfolk Canyon exhibited intermittent HFAS activity with elevated detections during 2016–2018.
- Offshore Cape Hatteras exhibited the highest overall HFAS activity, particularly at site A.
- HFAS analyses off Jacksonville were limited to Sites C and D, where detections were minimal overall.
- HFAS detections generally occurred throughout the 24-hour cycle with no strong consistent diel patterns.

5.3.1 Norfolk Canyon

High-frequency active sonar/echosounder (HFAS) detections near Norfolk Canyon were intermittent throughout the monitoring period, with most weekly detections remaining below 10 hours per week (Figure 32). Periods of elevated activity occurred during 2016–2018, when weekly detections occasionally exceeded 20 hours and peaked near 35 hours per week.

Monthly mean HFAS activity was highest in June, with elevated activity also occurring during July, August, October, and November (Figure 33). Lowest activity occurred during April and December. Variability was greatest during summer and fall months, reflecting interannual differences.

HFAS activity occurred throughout the 24-hour cycle, with no consistent diel pattern evident across years (Figure 34).

Summary of Results – High-Frequency Active Sonar/Echosounder near Norfolk Canyon

- HFAS activity was intermittent throughout the monitoring period.
- Peak weekly detections approached 35 hours per week during 2016–2018.
- Monthly means were highest in June, with elevated activity also occurring during summer and fall months.
- Lowest monthly activity occurred during April and December.
- Detections occurred across all hours with no consistent diel pattern.

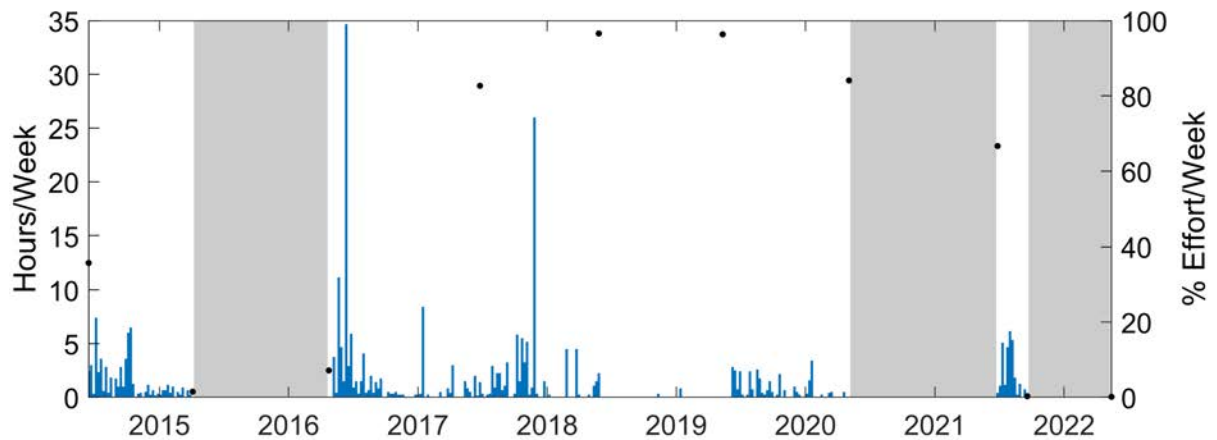


Figure 32: Cumulative hours/week of high-frequency active sonar/echosounders near Norfolk Canyon. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

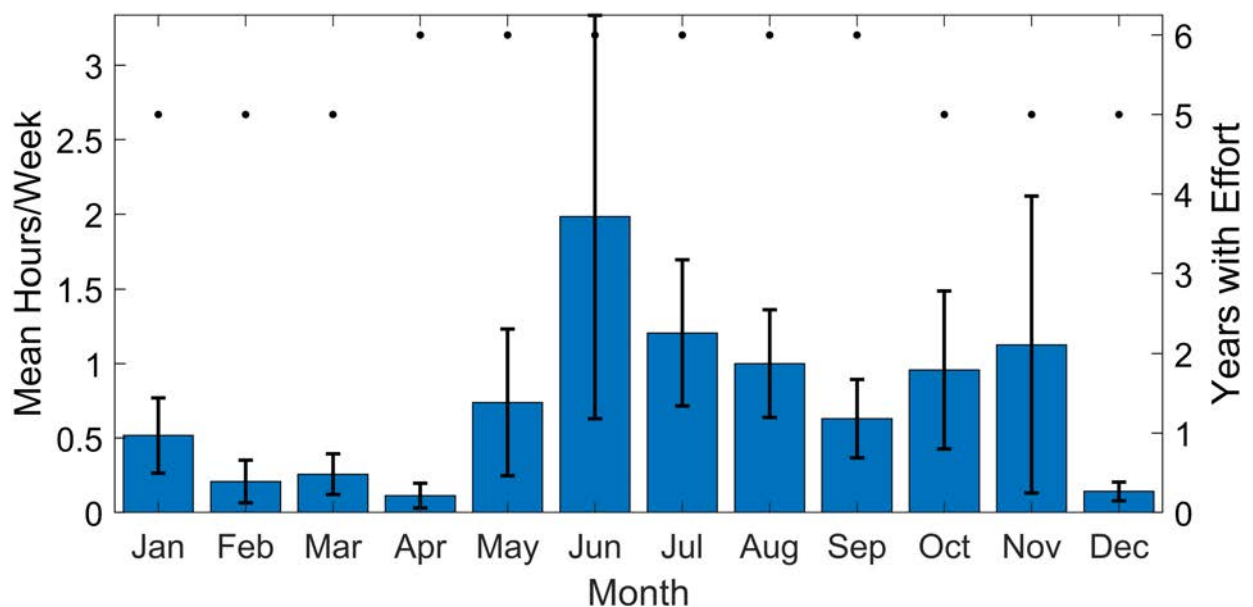


Figure 33: Monthly mean hours per week of high-frequency active sonar/echosounders near Norfolk Canyon. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

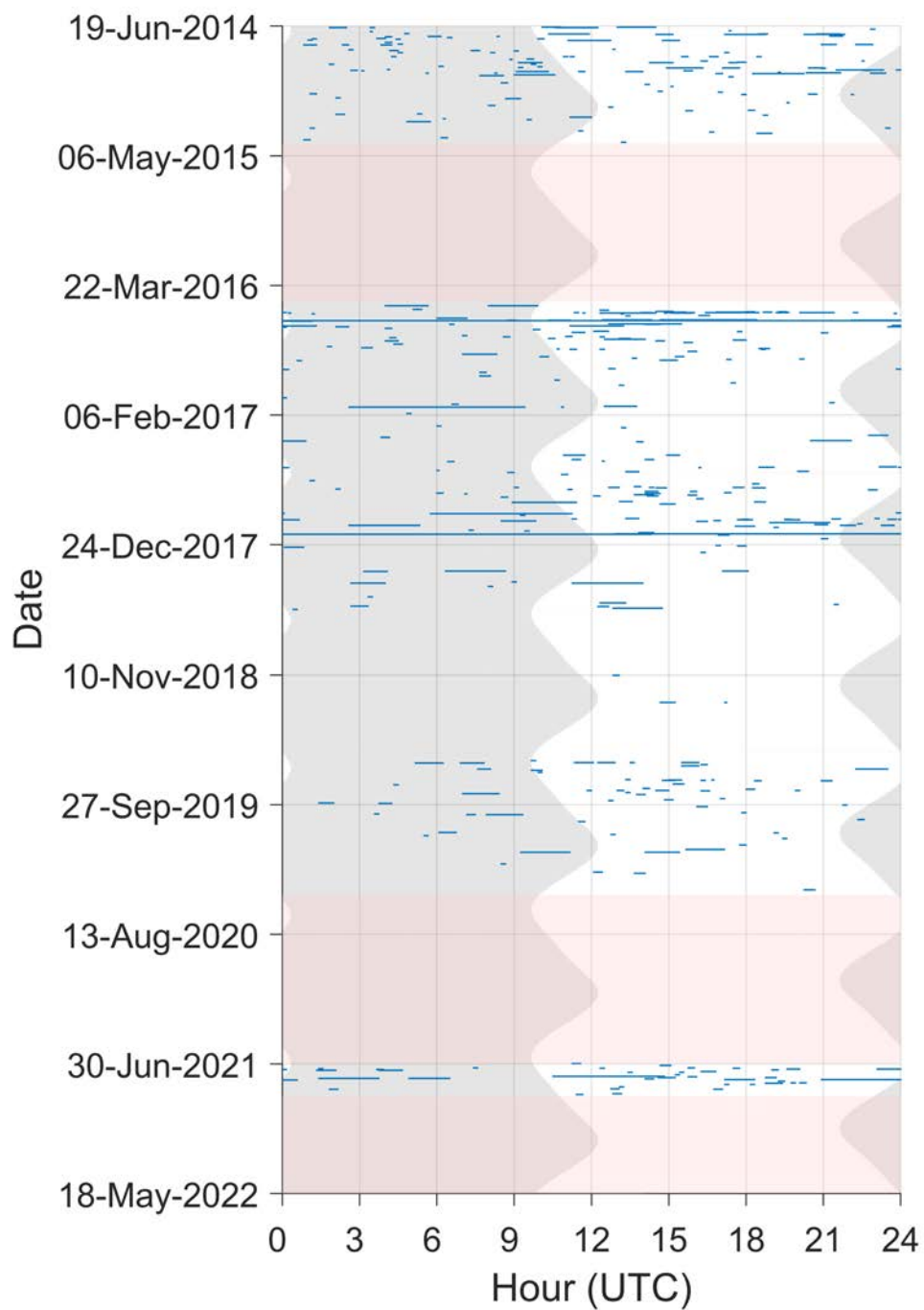


Figure 34: High-frequency active sonar/echosounder presence in 5-min bins near Norfolk Canyon. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.3.2 Cape Hatteras

High-frequency active sonar/echosounder (HFAS) detections offshore Cape Hatteras were intermittent at both sites A and B (Figure 35). Site A exhibited moderate but persistent activity throughout the monitoring period, with several weeks exceeding 100 hours per week and peak detections approaching 170 hours per week. Site B also exhibited intermittent activity, including a prolonged period of elevated detections exceeding 100 hours per week for several months during 2017–2018, followed by minimal activity from mid-2018 until 2020.

Monthly mean HFAS activity differed between sites (Figure 36). At site A, activity was highest during winter months, particularly January and February, with reduced activity during spring and early fall. Site B also exhibited elevated activity during winter months, particularly November – February, with lower activity during spring and summer months.

HFAS activity occurred throughout the 24-hour cycle at both sites (Figure 37). Activity was observed during both daytime and nighttime hours, with no consistent diel concentration evident across years.

Summary of Results – High-Frequency Active Sonar/Echosounder off Cape Hatteras

- HFAS activity was intermittent at both sites A and B.
- Site A exhibited persistent activity throughout the monitoring period, with peak weekly detections approaching 170 hours per week.
- Site B exhibited a prolonged period of elevated activity during 2017–2018, with detections exceeding 100 hours per week for several months.
- HFAS activity at site B was minimal from mid-2018 until 2020.
- Monthly activity at both sites was highest during winter months.
- Detections occurred across all hours with no consistent diel pattern.

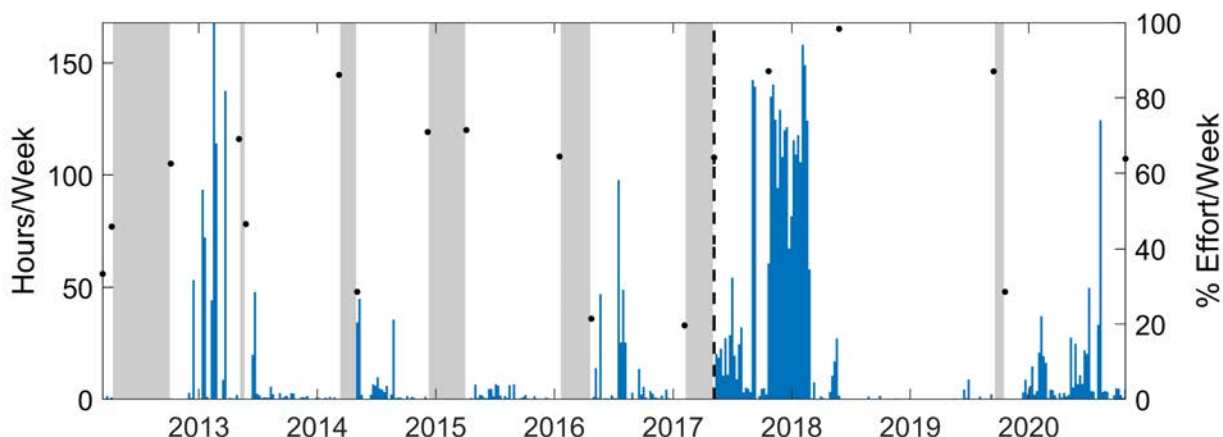


Figure 35: Cumulative hours/week of high-frequency active sonar/echosounders off Cape Hatteras. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The dashed line represents when the instrument moved from site A to site B.

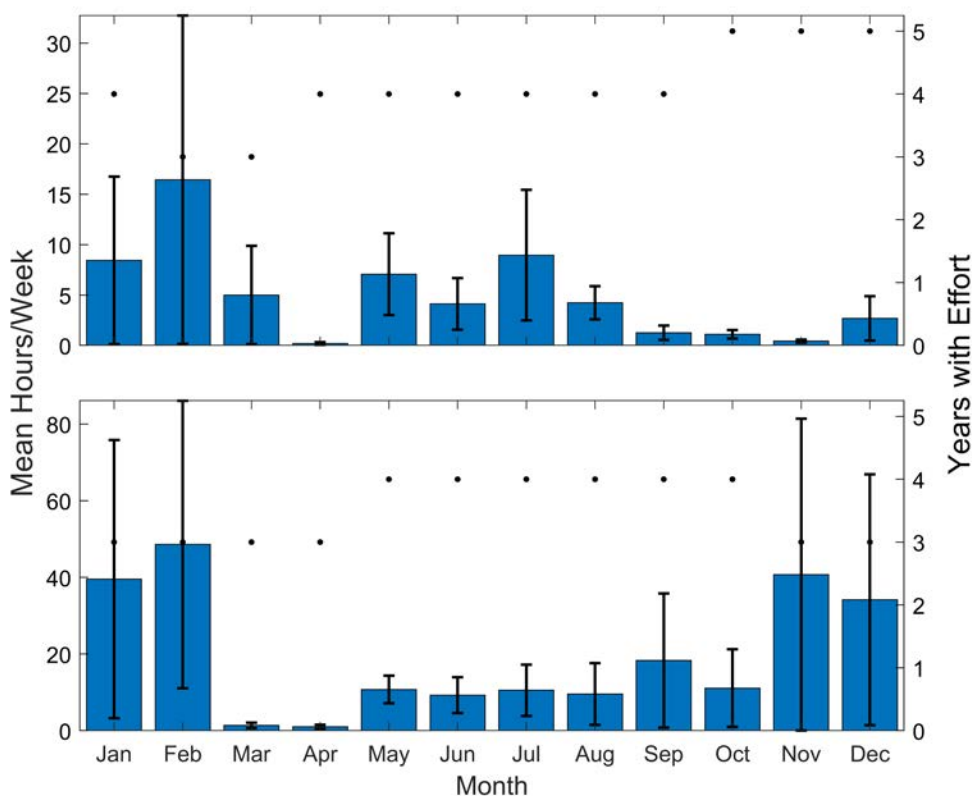


Figure 36: Monthly mean hours per week of high-frequency active sonar/echosounders off Cape Hatteras at site A (top) and site B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

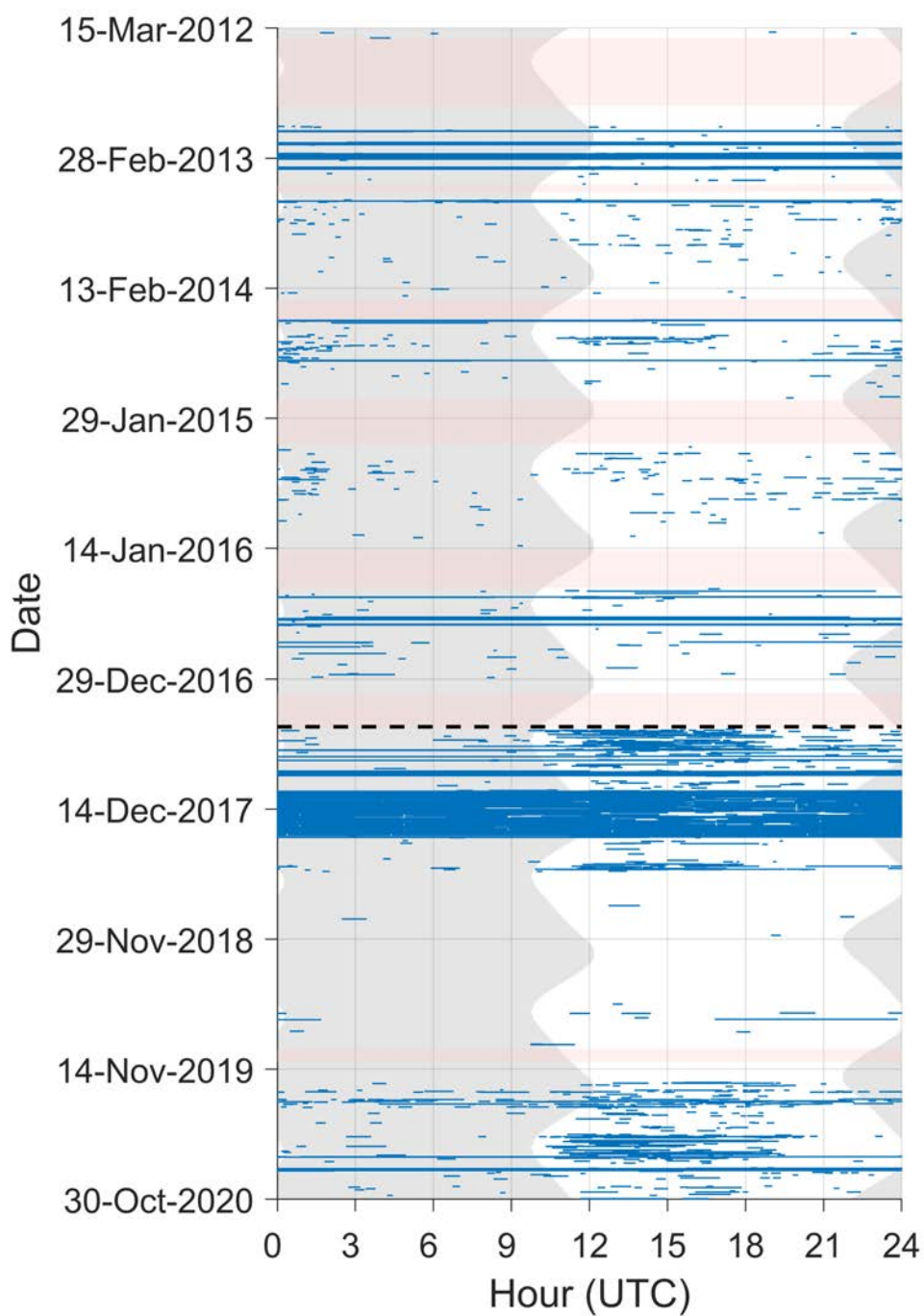


Figure 37: High-frequency active sonar/echosounder presence in 5-min bins off Cape Hatteras. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The dashed line represents when the instrument moved from site A to site B.

5.3.3 Jacksonville

High-frequency active sonar/echosounder (HFAS) analyses off Jacksonville were conducted only for sites C and D because HFAS activity was expected to be limited at sites A and B based on prior observations and operational context. Within the analyzed sites, HFAS detections were minimal overall (Figure 38). Site C exhibited episodic HFAS activity throughout the 2013-2014. Site D also exhibited limited activity, with sporadic detections from 2014-2020.

Monthly mean HFAS activity was extremely low at both sites (Figure 39). Site C only showed activity in May, while site D only exhibited activity in August. Monthly activity during all remaining months was zero.

Site C exhibited slightly higher HFAS during the daytime hours (Figure 40). At site D, HFAS activity was too limited to identify any diel trends.

Summary of Results – High-Frequency Active Sonar/Echosounder off Jacksonville

- HFAS analyses were conducted only for sites C and D, where activity was sporadic.
- Site C exhibited episodic HFAS detections between 2013–2014 and had a seasonal peak in the spring and early summer.
- Site D exhibited minimal, sporadic activity between 2014–2020 and had increased activity during the late summer and winter.
- Monthly activity remained near zero at both sites throughout most of the year.
- Site C exhibited slightly higher HFAS during the daytime hours.

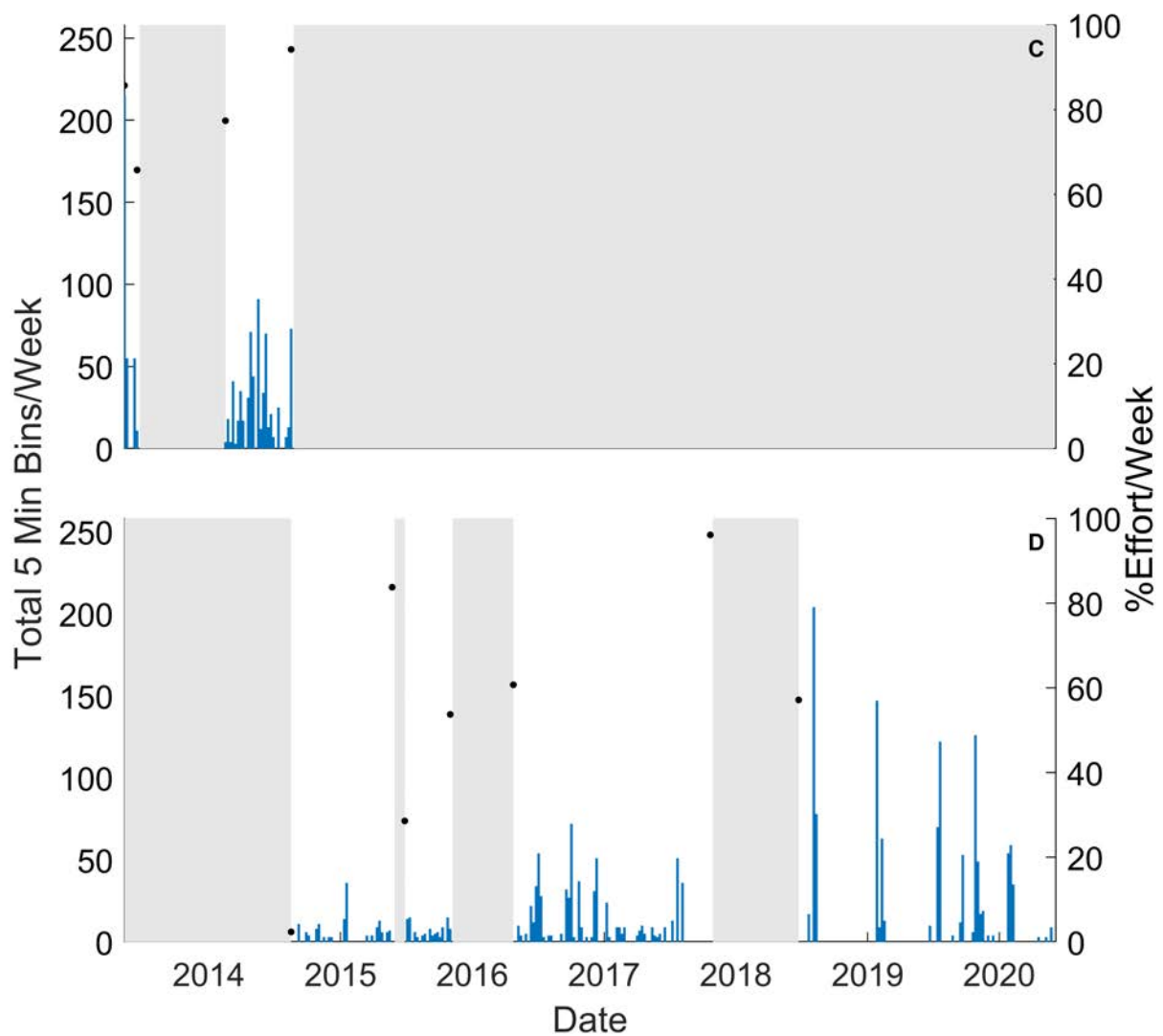


Figure 38: Cumulative hours/week of high-frequency active sonar/echosounders at Jacksonville sites C and D. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

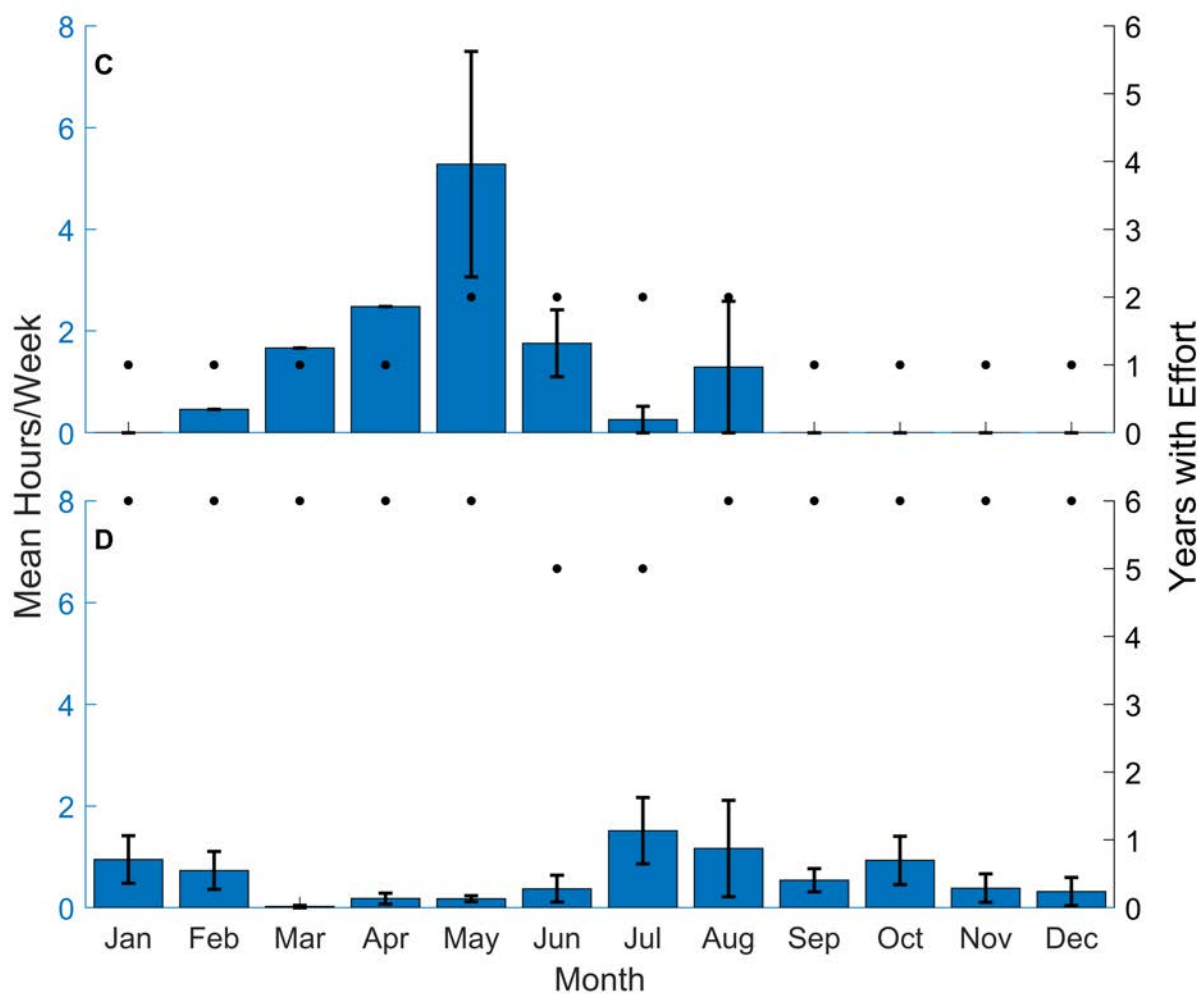


Figure 39: Monthly mean hours per week of high-frequency active sonar/echosounders at Jacksonville sites C and D. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

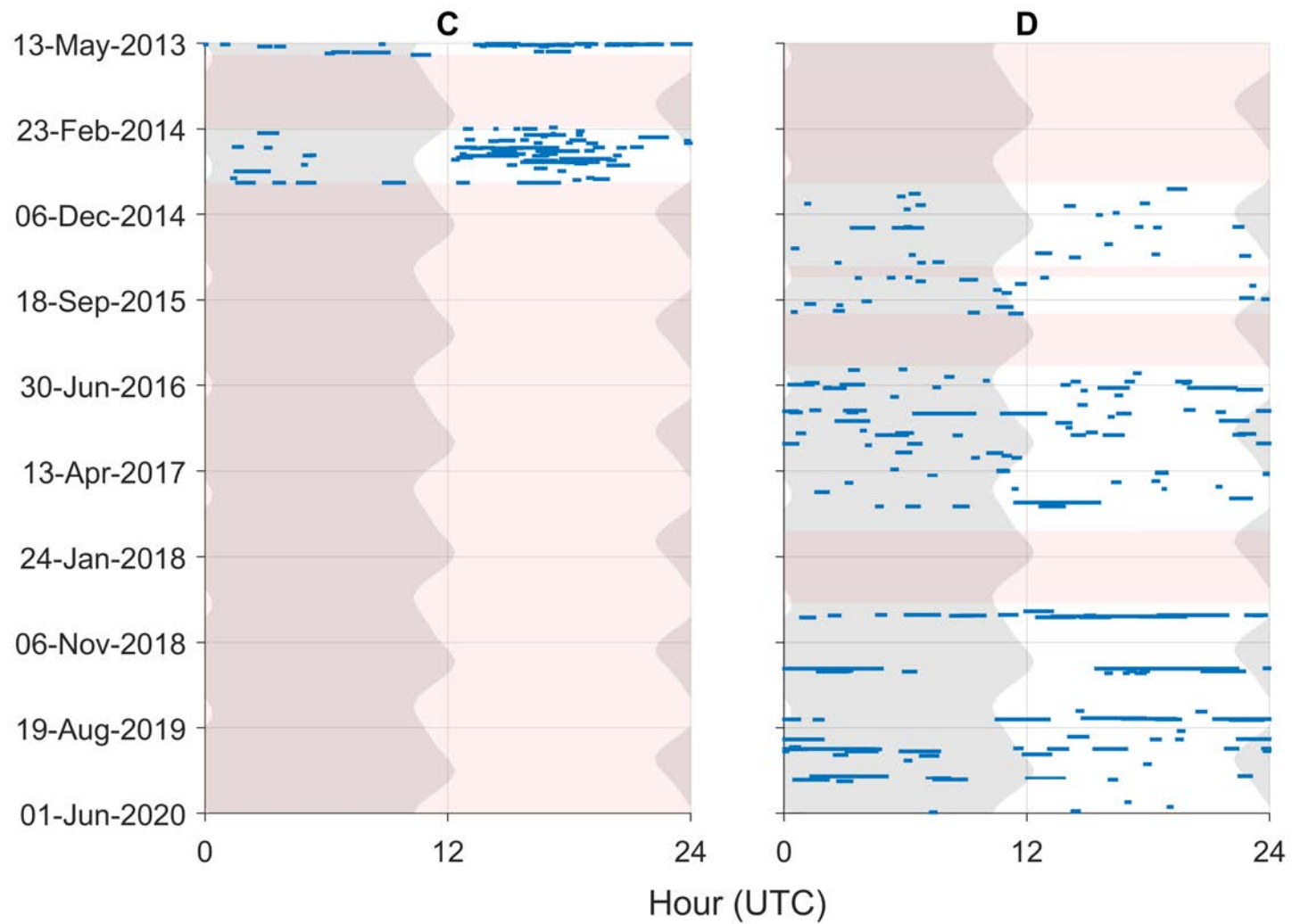


Figure 40: High-frequency active sonar/echosounder in 5-min bins at Jacksonville sites C and D. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.4 Impulsive Sounds

Impulsive sounds (including geophysical airguns, fishing-vessel seal bombs, military detonations, and other explosion-like acoustic events) varied substantially among regions in both magnitude and temporal structure, with generally low and intermittent detections across most sites. This category was analyzed collectively because all sources were identified using the same impulsive-sound detection framework. Near Norfolk Canyon, impulsive sound detections were episodic and occurred primarily during 2018–2020, with peak weekly detections approaching 8 hours per week. Monthly activity was highest during summer and fall months, particularly July and August, and detections occurred throughout the 24-hour cycle, although activity was more frequently observed during daytime hours prior to 2019.

Offshore Cape Hatteras exhibited relatively low levels of impulsive sounds at both sites. Site A showed persistent but minimal activity throughout the monitoring period, while site B exhibited elevated detections primarily during 2018–2019. Monthly activity at both sites peaked during August, with additional seasonal variability between sites. Detections occurred throughout both daytime and nighttime hours with no consistent diel concentration.

In Onslow Bay, impulsive sound detections were sporadic across sites and generally remained at low levels. Site A exhibited several isolated periods of elevated activity between 2009 and 2011, while site E exhibited the highest and most persistent activity in the region during 2011–2012. Sites B, C, and D exhibited only limited detections. Site E also exhibited the clearest seasonal pattern, with elevated activity from August through November and peak monthly activity in September. No consistent diel pattern was evident across sites.

Off Jacksonville, impulsive sound detections were limited and localized. Site A exhibited the highest activity, with intermittent detections during 2009–2011 and peak weekly detections exceeding 100 total 5-minute bins per week. Site B exhibited only a single brief period of activity, while sites C and D each exhibited isolated detections. Monthly activity was generally low across all sites, with site A exhibiting elevated activity during spring and early summer months. Detections were too limited to identify consistent diel patterns.

Summary of Results – Impulsive Sounds Across Regions

- Impulsive sounds were generally intermittent and low across all regions.
- Norfolk Canyon exhibited episodic activity primarily during 2018–2020, with highest monthly activity during summer and fall.
- Offshore Cape Hatteras exhibited persistent but low levels of activity, with elevated detections at site B during 2018–2019.
- Onslow Bay exhibited sporadic activity, with site E showing the highest and most persistent detections during 2011–2012.
- Jacksonville exhibited limited and localized activity, primarily concentrated at site A during 2009–2011.

5.4.1 Norfolk Canyon

Impulsive sound detections near Norfolk Canyon were intermittent throughout the monitoring period, with most weekly detections remaining below 2 hours per week (Figure 41). Elevated activity occurred primarily during 2018–2020, when weekly detections occasionally exceeded 5 hours and peaked near 8 hours per week.

Monthly mean impulsive sound detections were highest in July, with elevated activity also occurring during August and October (Figure 42). Lowest activity occurred during February and March. Variability was greatest during summer and fall months, reflecting interannual differences in occurrence.

Impulsive sound detections occurred throughout the 24-hour cycle, although detections were most frequently observed during daytime hours, particularly before 2019 (Figure 43).

Summary of Results – Impulsive Sounds near Norfolk Canyon

- Impulsive sounds were intermittent throughout the monitoring period.
- Peak weekly detections approached 8 hours per week during 2018–2020.
- Monthly means were highest in July, with elevated activity also occurring during August and October.
- Lowest monthly activity occurred during February and March.
- Detections occurred throughout the 24-hour cycle, with activity most frequently observed during daytime hours before 2019.

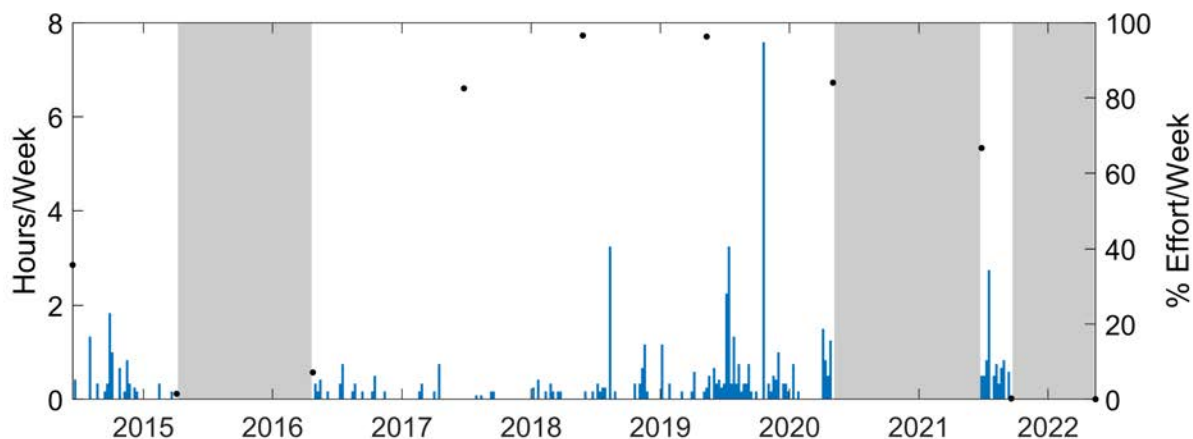


Figure 41: Cumulative hours/week of impulsive sounds near Norfolk Canyon. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

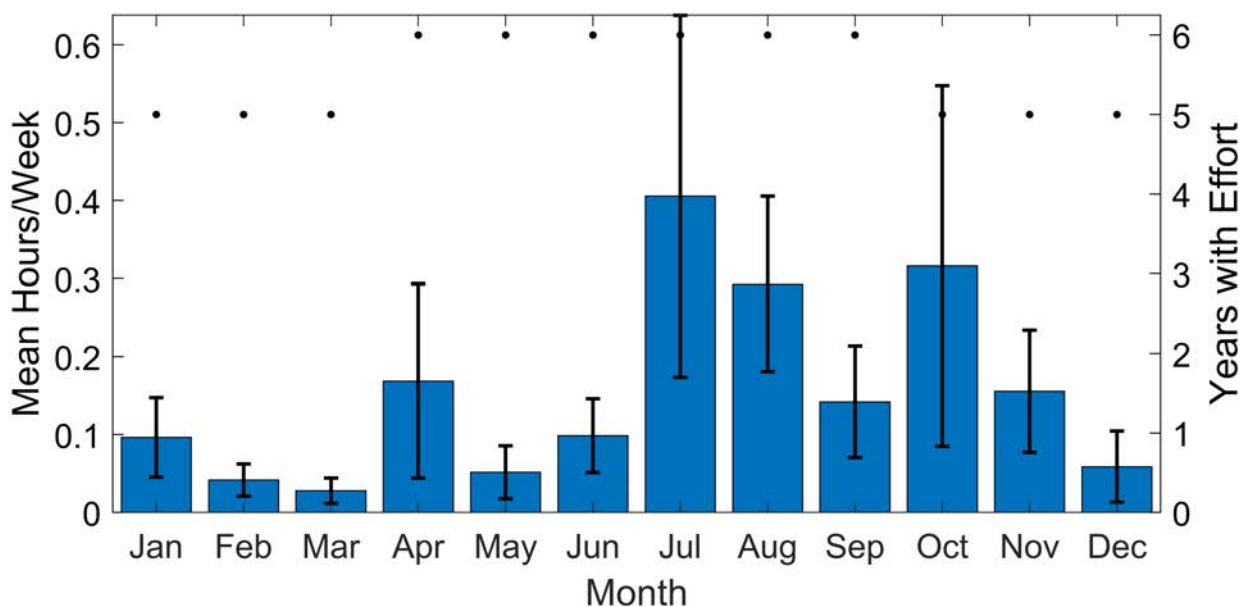


Figure 42: Monthly mean hours per week of impulsive sounds near Norfolk Canyon. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

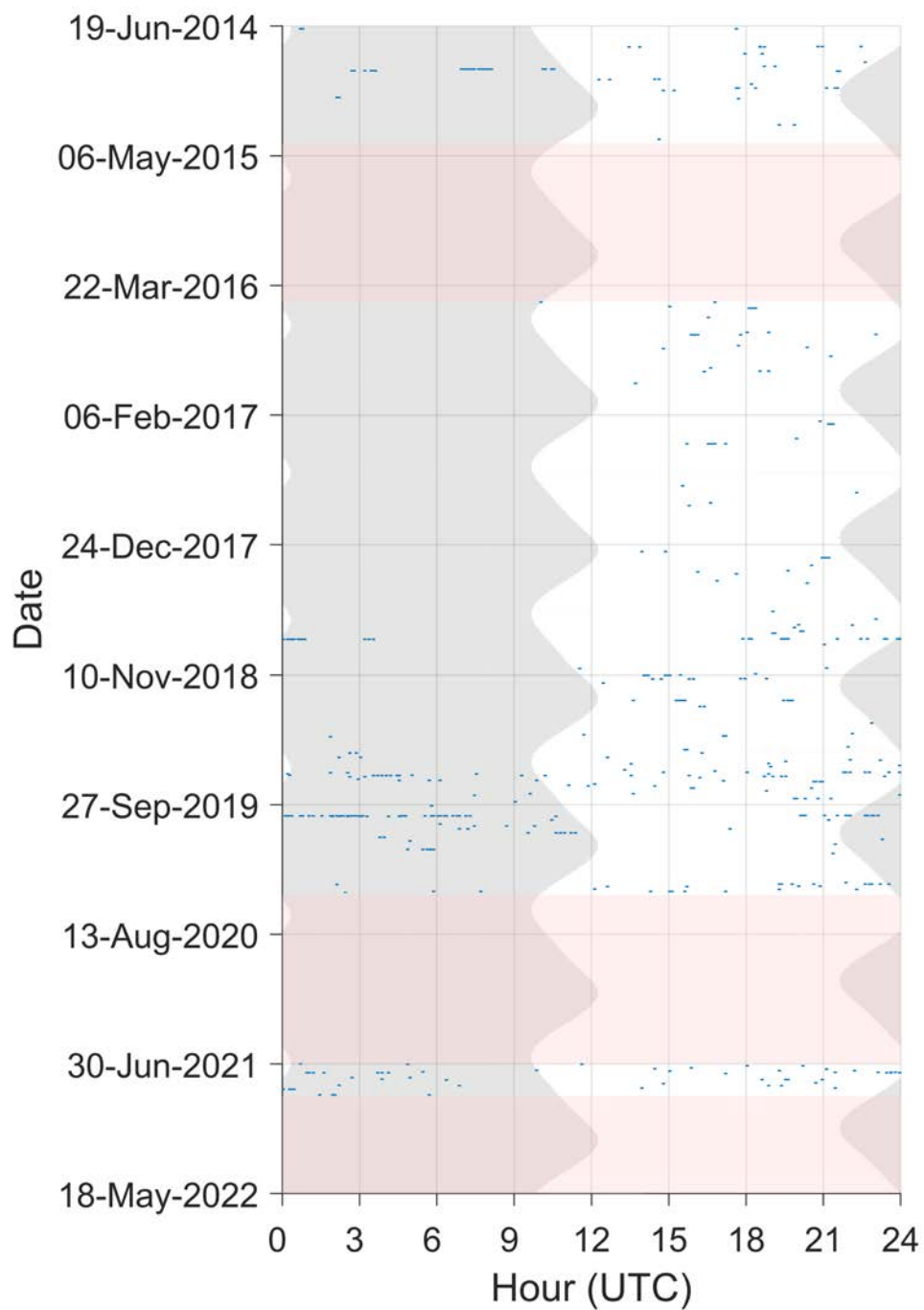


Figure 43: Impulsive sound detections in 5-min bins near Norfolk Canyon. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.4.2 Cape Hatteras

Impulsive sound detections offshore Cape Hatteras were intermittent at both sites A and B (Figure 44). Site A exhibited low levels of activity throughout the monitoring period, with most weekly detections remaining below 1 hour per week and occasional peaks approaching 4 hours per week. Site B also exhibited intermittent activity, with elevated detections occurring primarily during 2018–2019, when weekly detections occasionally exceeded 2 hours per week.

Monthly mean impulsive sound detections differed between sites (Figure 45). At site A, activity was highest in August, with elevated activity also occurring during May. Lowest activity occurred during winter and early spring months. Site B also exhibited highest activity in August, with secondary peaks during February and March, and minimal activity during early summer and fall months.

Impulsive sound detections occurred throughout the 24-hour cycle at both sites (Figure 46). Activity was observed during both daytime and nighttime hours, with no consistent diel concentration evident across years.

Summary of Results – Impulsive Sounds off Cape Hatteras

- Impulsive sounds were intermittent at both sites A and B.
- Site A exhibited consistently low levels of activity, with most weekly detections remaining below 1 hour per week.
- Site B exhibited elevated activity primarily during 2018–2019, when weekly detections occasionally exceeded 2 hours per week.
- Monthly activity at site A was highest in August and May, while site B exhibited highest activity in August with secondary peaks during February and March.
- Detections occurred across all hours with no consistent diel pattern.

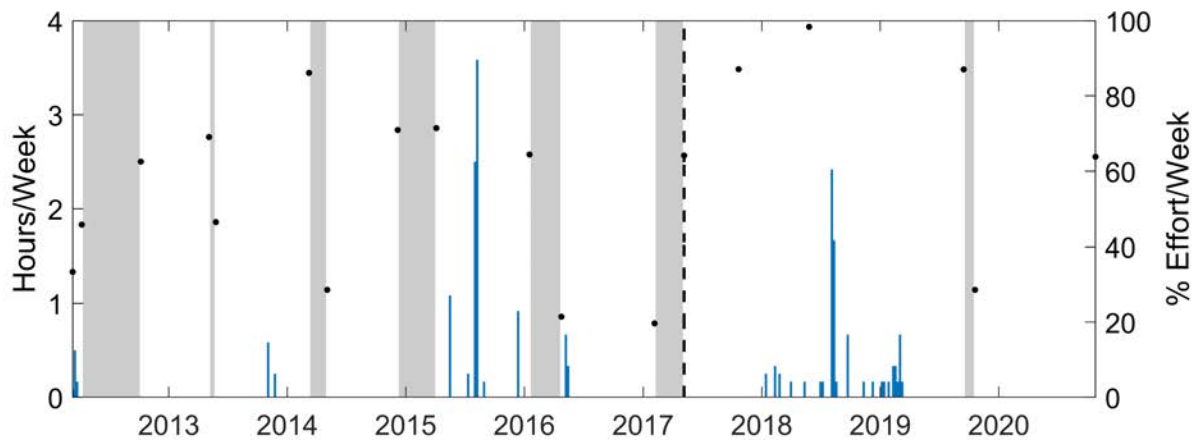


Figure 44: Cumulative hours/week of impulsive sounds off Cape Hatteras. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The dashed line represents when the instrument moved from site A to site B.

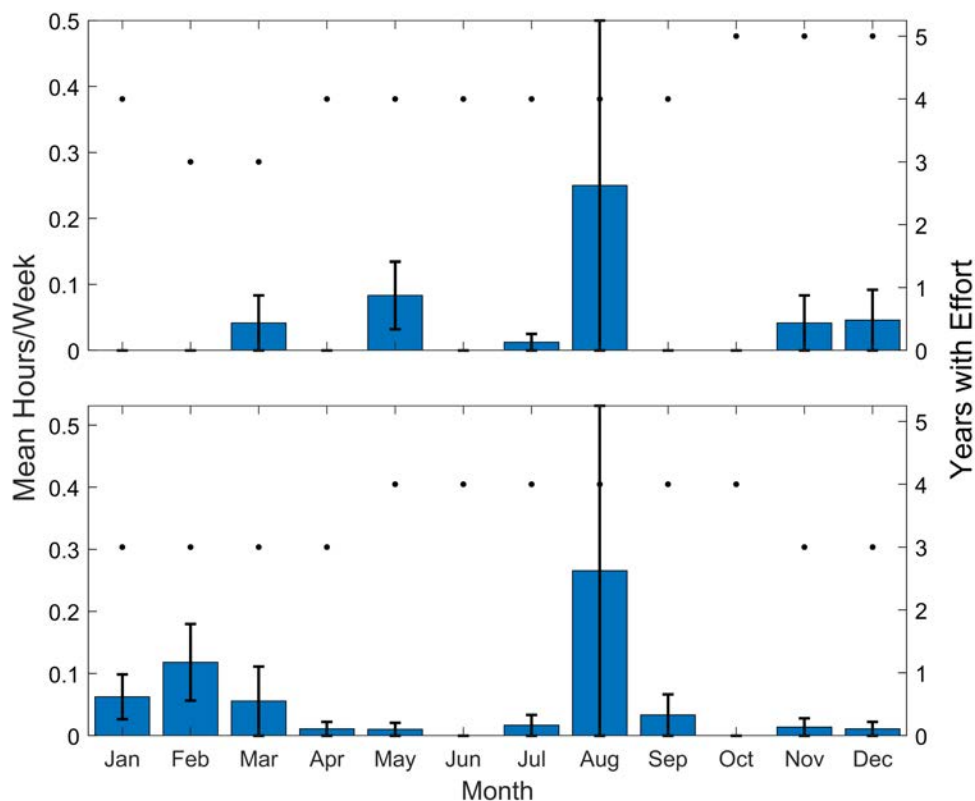


Figure 45: Monthly mean hours per week of impulsive sounds off Cape Hatteras at site A (top) and site B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

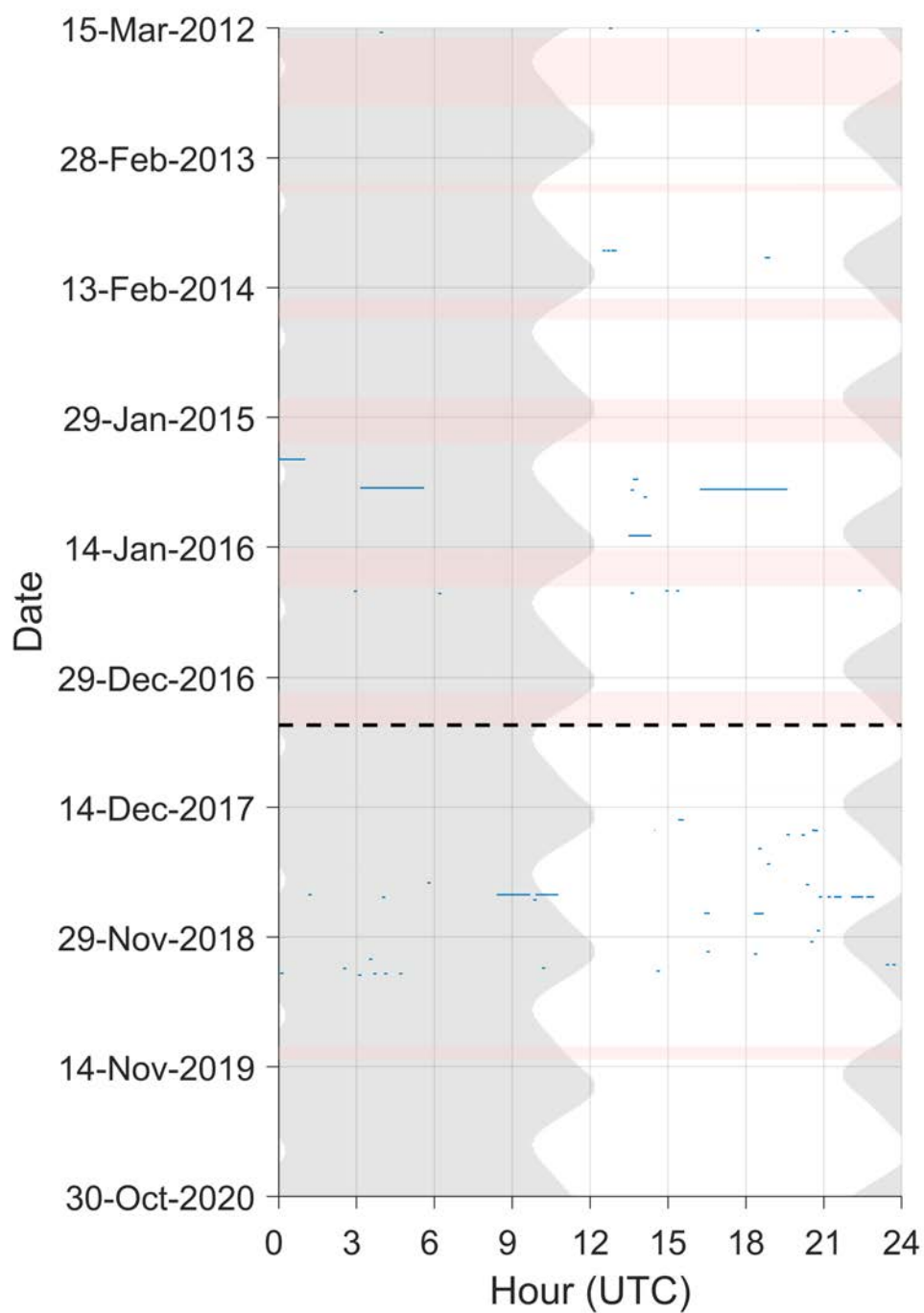


Figure 46: Impulsive sound detections in 5-min bins off Cape Hatteras. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The dashed line represents when the instrument moved from site A to site B.

5.4.3 Onslow Bay

Impulsive sound detections in Onslow Bay were sporadic across sites (Figure 47). Most weeks exhibited low levels of activity, generally remaining below 10 total 5-minute bins per week. Site A exhibited several isolated periods of elevated activity between 2009 and 2011, with peak detections approaching 50 total 5-minute bins per week. Site E exhibited the highest and most persistent activity, with elevated detections occurring during 2011–2012 and weekly totals occasionally approaching 50 total 5-minute bins per week. Site B, C, and D exhibited only limited and intermittent detections.

Monthly mean impulsive sound detections varied among sites (Figure 48). Site A exhibited elevated activity during April and fall months, although overall detection levels remained low. Sites B, C, and D each had limited recording effort and low detection rates, restricting interpretation of seasonal patterns. Site E exhibited the highest monthly activity overall, with elevated detections occurring primarily from August through November and peak activity in September.

Impulsive sound detections occurred throughout the 24-hour cycle at all sites (Figure 49). No consistent diel pattern was evident.

Summary of Results – Impulsive Sounds in Onslow Bay

- Impulsive sound detections were sporadic across all sites.
- Site A exhibited several isolated periods of elevated activity between 2009 and 2011, with peak weekly detections approaching 50 total 5-minute bins per week.
- Site E exhibited the highest and most persistent activity, particularly during 2011–2012.
- Sites B, C, and D exhibited limited and intermittent detections, restricting seasonal interpretation.
- Site E exhibited highest monthly activity from August through November, with peak activity in September.
- No consistent diel pattern was evident.

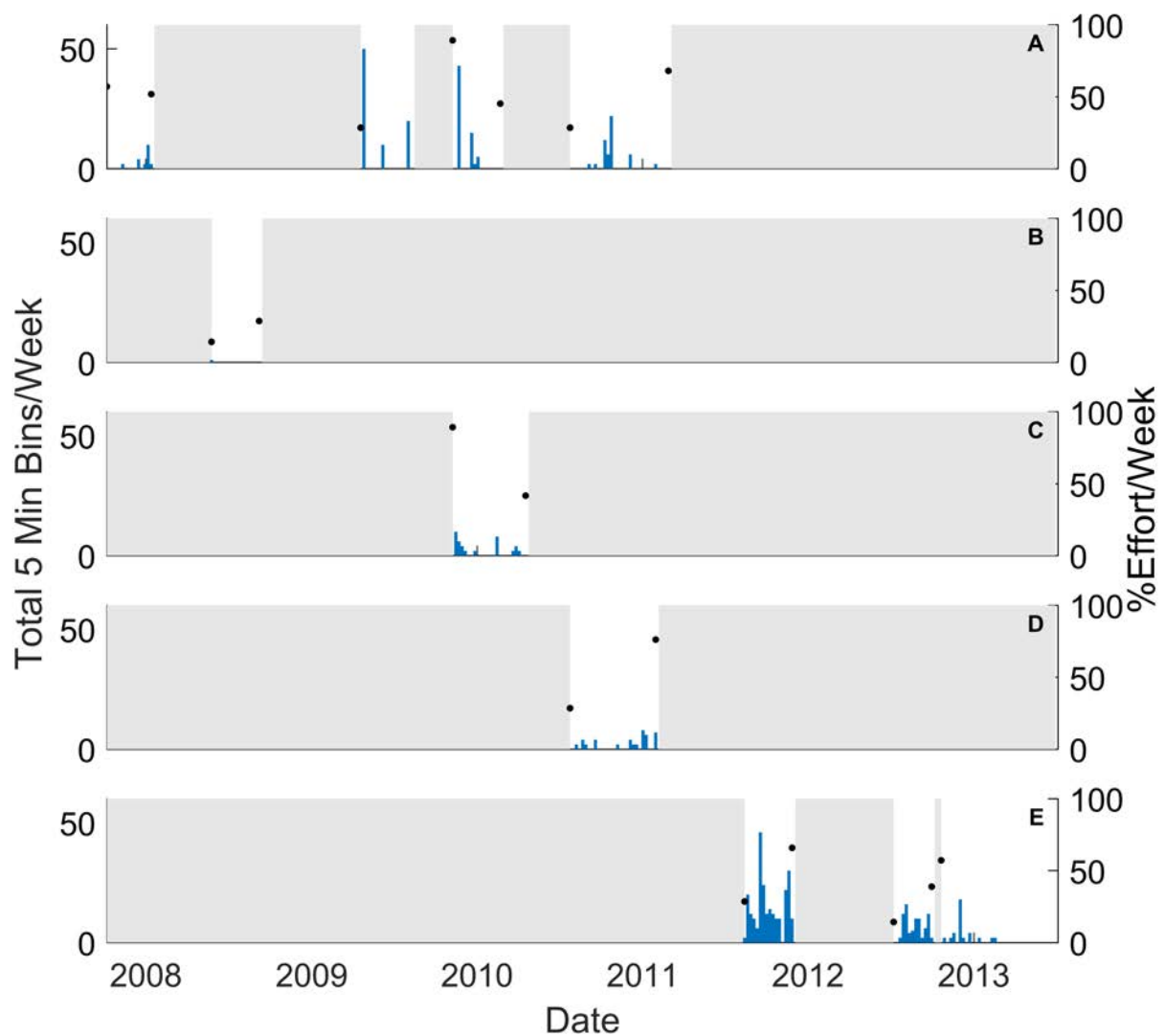


Figure 47: Cumulative hours/week of impulsive sounds at all Onslow Bay sites. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

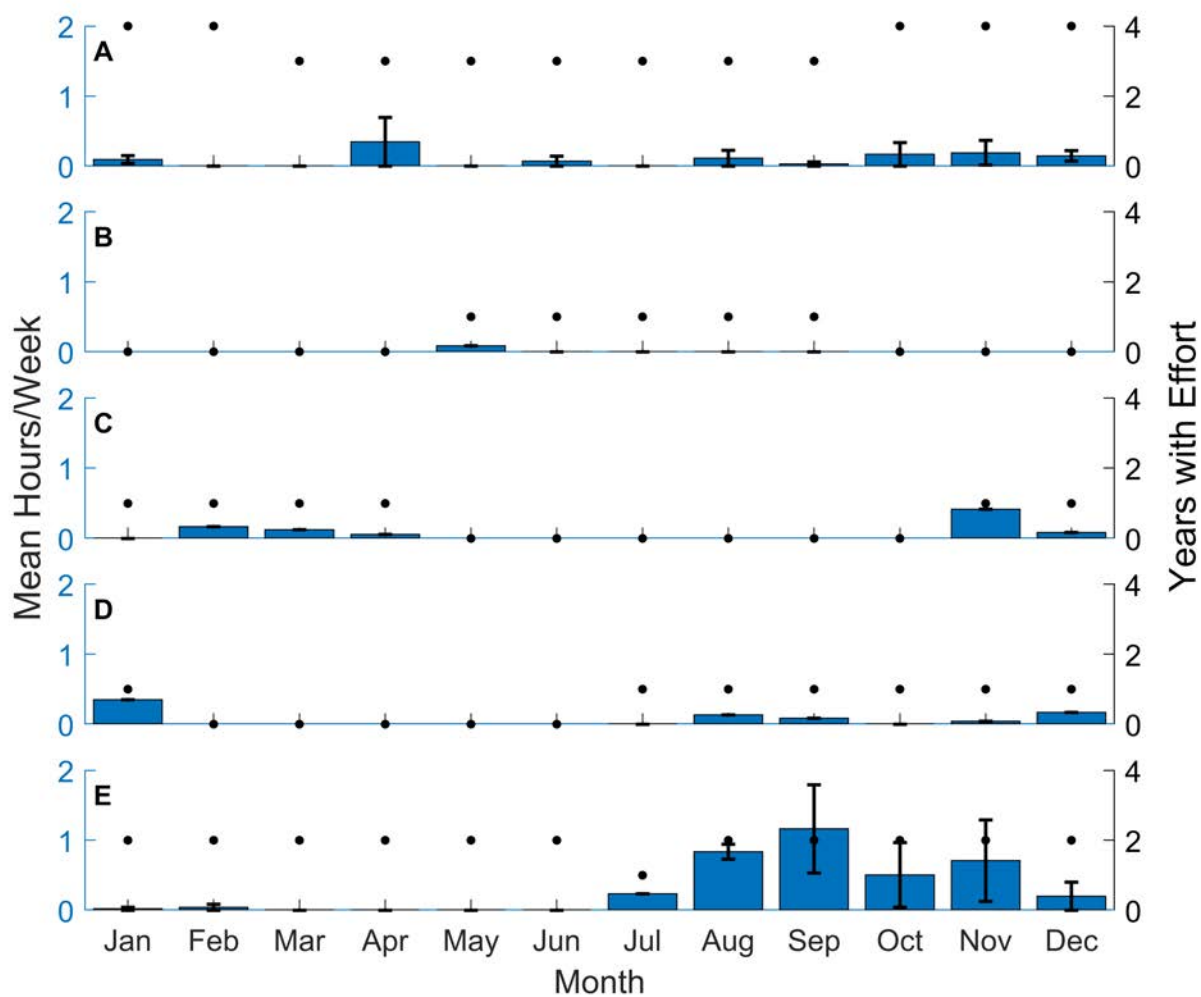


Figure 48: Monthly mean hours per week of impulsive sounds at all Onslow Bay sites. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

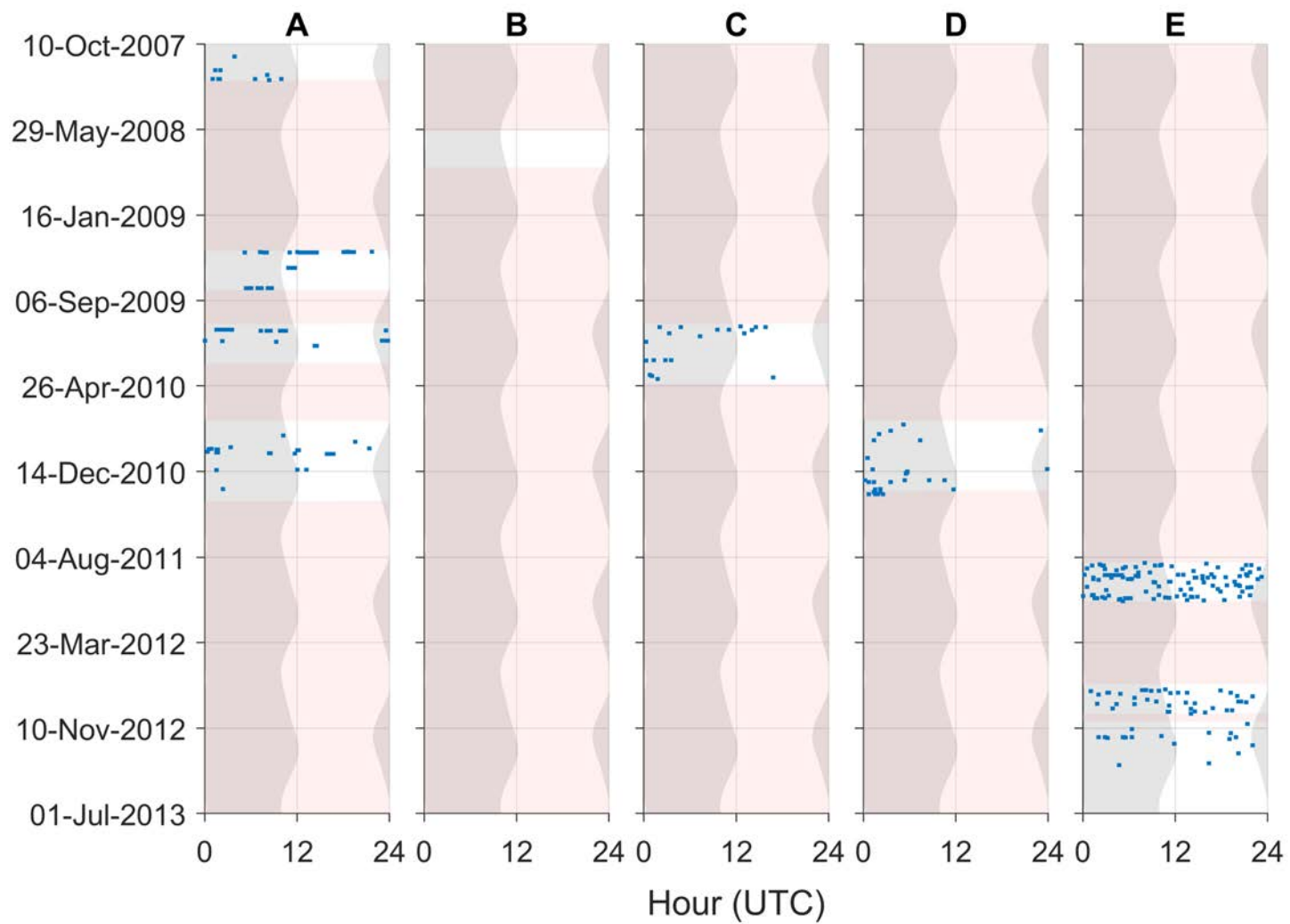


Figure 49: Impulsive sound detections in 5-min bins at all Onslow Bay sites. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.4.4 Jacksonville

Impulsive sound detections off Jacksonville were limited and sporadic across sites (Figure 50). Site A exhibited the highest activity, with intermittent detections occurring primarily during 2009–2011 and peak weekly detections exceeding 100 total 5-minute bins per week. Site B exhibited only a single brief detection period during 2009–2010. Site C and D exhibited an isolated detection at each site.

Monthly mean impulsive sound detections were generally low across sites (Figure 51). Site A exhibited highest activity during spring and early summer months, particularly May, with little to no activity during fall and winter. Sites B, C, and D exhibited minimal monthly activity overall, limiting interpretation of seasonal trends.

Impulsive sound detections were too limited to identify consistent diel patterns across sites (Figure 52).

Summary of Results – Impulsive Sounds off Jacksonville

- Impulsive sound detections were limited and sporadic across all sites.
- Site A exhibited the highest activity, with intermittent detections during 2009–2011 and peak weekly detections exceeding 100 total 5-minute bins per week.
- Site B exhibited only a single brief period of activity during 2009–2010.
- Sites C and D exhibited isolated detections.
- Monthly activity was generally low across all sites, with site A exhibiting highest activity during spring and early summer.
- No consistent diel pattern was evident.

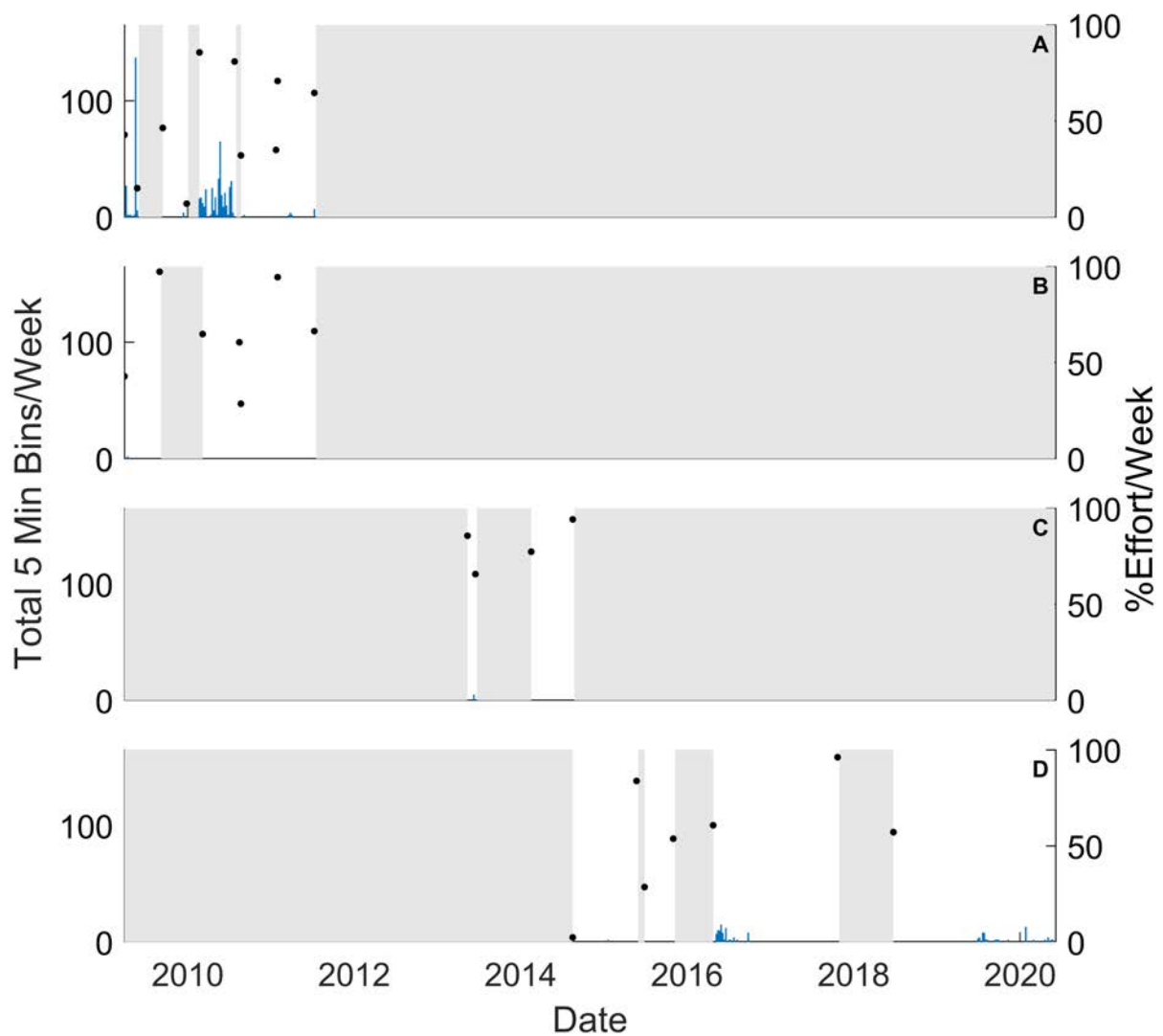


Figure 50: Cumulative hours/week of impulsive sounds at Jacksonville sites A-D. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

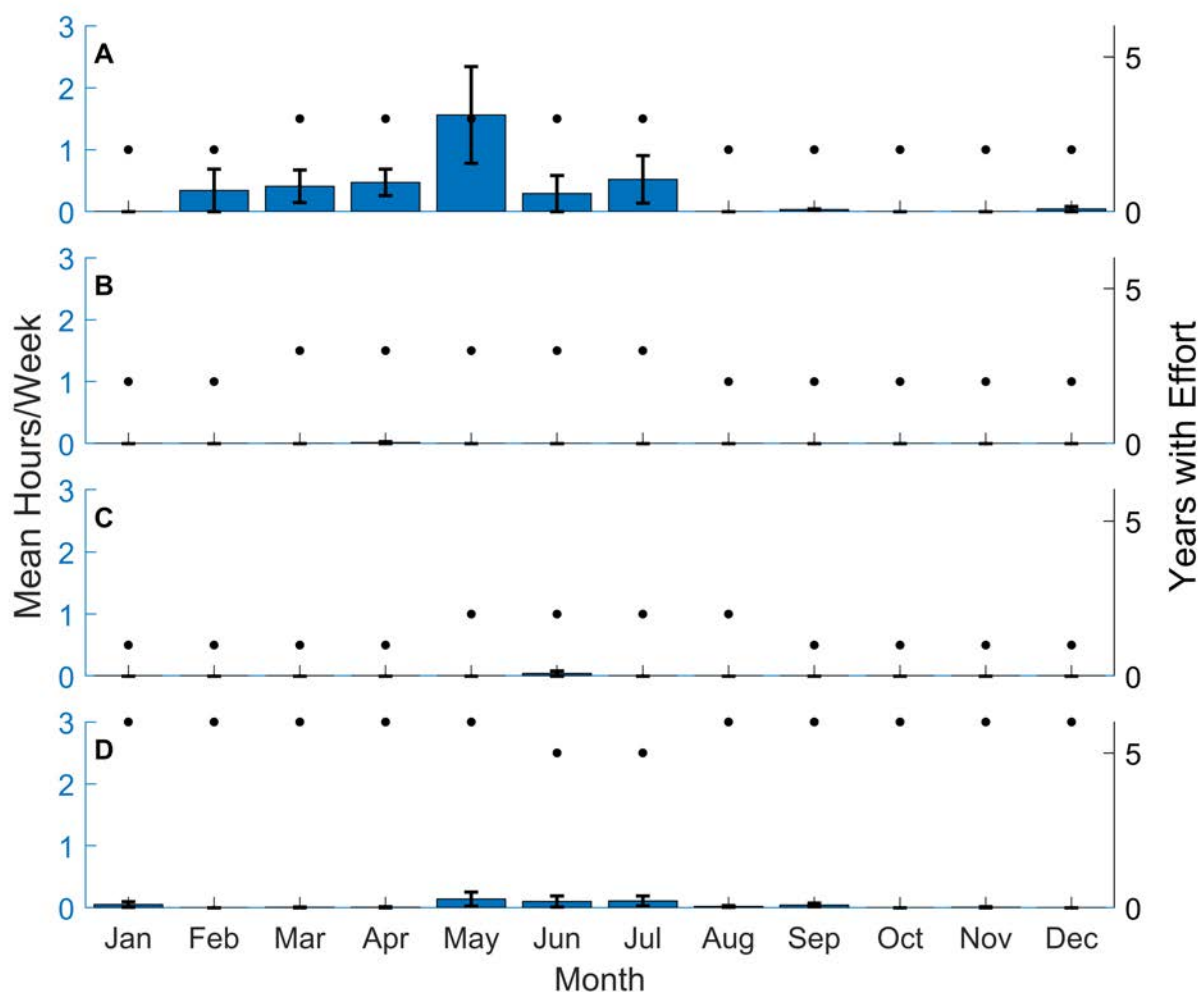


Figure 51: Monthly mean hours per week of impulsive sounds at Jacksonville sites A-D. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

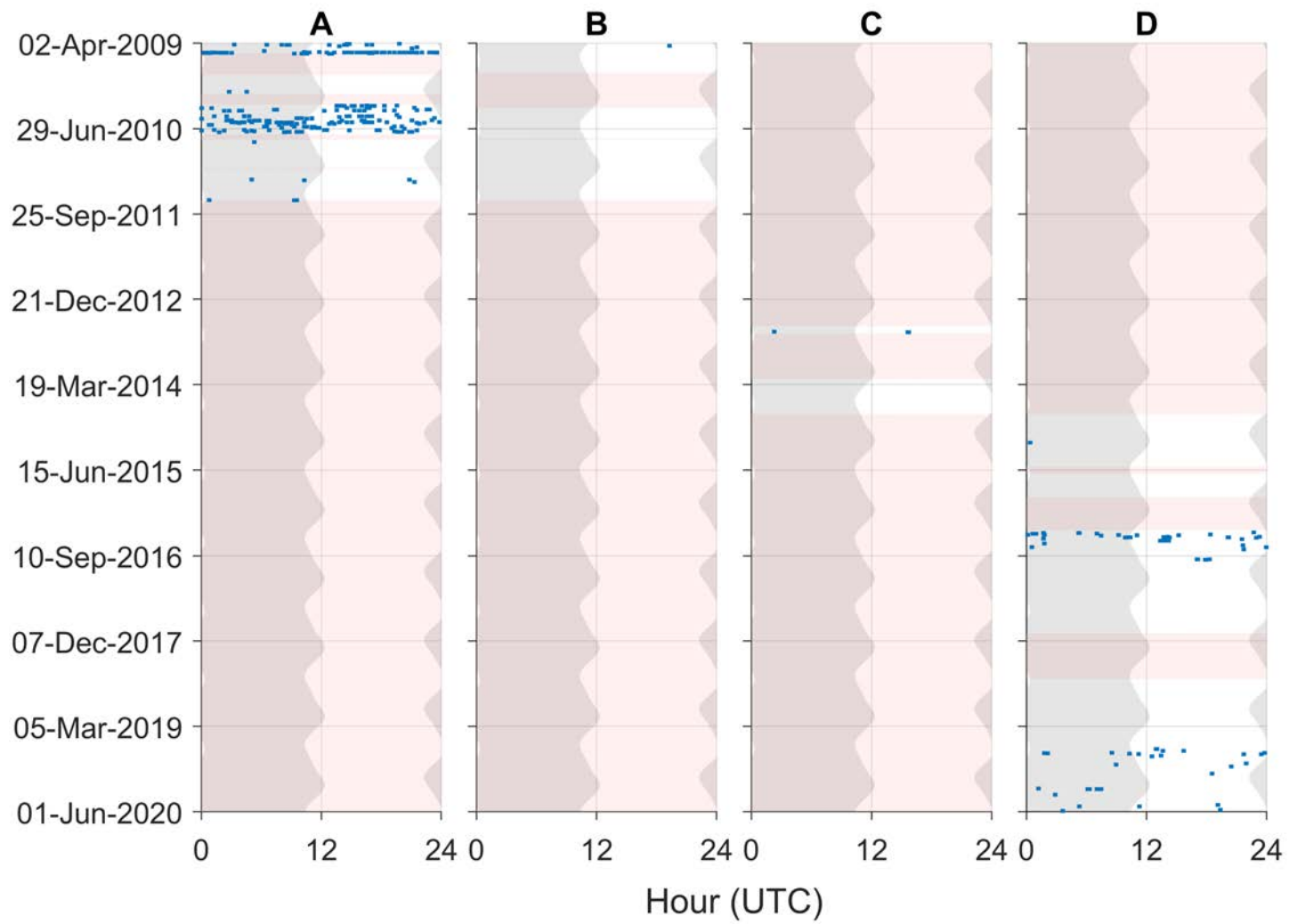


Figure 52: Impulsive sound detections in 5-min bins at Jacksonville sites A-D. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.5 Broadband Ships

Broadband ship detections were prevalent across all regions during periods with recording effort, although activity levels, seasonal patterns, and interannual variability differed among sites. In general, ship presence exhibited strong temporal structure, with recurring periods of elevated and reduced activity that suggested seasonal fluctuations in vessel traffic rather than consistently uniform occurrence.

Near Norfolk Canyon, ship detections were persistent throughout the monitoring period, with weekly detections commonly exceeding 20 hours per week and peak activity approaching 40 hours per week. Activity was highest during summer and early fall months, particularly June through September, with peak monthly means occurring in August. Ship detections occurred throughout the 24-hour cycle, with activity observed during both daytime and nighttime hours.

Offshore Cape Hatteras exhibited consistently elevated ship activity at both sites throughout the monitoring period. Site A exhibited relatively stable activity from 2012–2016, while site B exhibited particularly elevated activity during 2018–2019, with peak weekly detections exceeding 80 hours per week. Seasonal patterns differed somewhat between sites, although activity was generally elevated during late spring, summer, and early fall months. Ship detections occurred continuously throughout the 24-hour cycle with no strong diel concentration.

In Onslow Bay, ship detections were elevated across all sites during periods with recording effort, although the timing and magnitude of activity varied among locations. Sites A and E exhibited the most persistent and sustained activity, with weekly detections frequently exceeding 100 total 5-minute bins per week and occasional peaks approaching 500 total 5-minute bins per week. Sites B, C, and D also exhibited pronounced seasonal periods of elevated activity during shorter recording intervals. Seasonal structure differed among sites, although elevated activity most commonly occurred during summer and fall months. Ship detections occurred throughout both daytime and nighttime hours, with no consistent diel pattern evident across sites.

Off Jacksonville, ship detections were also elevated across all sites during periods with recording effort. Sites A and B exhibited sustained activity during 2009–2011, while site C exhibited elevated activity during 2013–2014 and site D exhibited persistent activity during 2015–2020. Across all sites, weekly detections frequently exceeded 100 total 5-minute bins per week and occasionally exceeded 300 total 5-minute bins per week. Ship activity fluctuated seasonally and interannually, with distinct periods of elevated and reduced detections that varied among sites. Seasonal peaks differed regionally, occurring during fall at site A, spring at sites B and C, and summer at site D. Ship detections occurred throughout the 24-hour cycle with no strong consistent diel pattern.

Summary of Results – Broadband Ships Across Regions

- Broadband ship detections were prevalent across all regions during periods with recording effort.
- Ship activity exhibited strong seasonal and interannual variability, with recurring periods of elevated and reduced detections across sites.
- Norfolk Canyon exhibited persistent moderate to high ship activity, with highest detections during summer and early fall.
- Offshore Cape Hatteras exhibited consistently elevated ship activity throughout the monitoring period, particularly at site B during 2018–2019.
- Onslow Bay and Jacksonville both exhibited elevated ship activity across all sites, although the timing and magnitude of seasonal peaks differed among locations.
- Ship detections occurred throughout the 24-hour cycle across all regions, with no strong or consistent diel patterns evident.

5.5.1 Norfolk Canyon

Ship detections near Norfolk Canyon were persistent throughout the monitoring period, with elevated activity occurring during most years with recording effort (Figure 53). Weekly detections commonly exceeded 20 hours per week, with peak detections approaching 40 hours per week in 2016. Activity remained elevated through much of the monitoring period, particularly during summer months.

Monthly mean ship activity was highest during summer and early fall months, particularly June through September, with peak activity occurring in August (Figure 54). Lowest activity occurred during late winter and early spring months, particularly February and March. Variability was greatest during summer months, reflecting interannual differences in ship occurrence and intensity.

Ship detections occurred throughout the 24-hour cycle, with activity observed across all hours of the day (Figure 55). Detections were most frequent during sunrise and sunset hours, particularly between approximately 10:00 and 22:00 UTC, although overnight activity was also common.

Summary of Results – Ships near Norfolk Canyon

- Ship activity was persistent throughout the monitoring period.
- Weekly detections commonly exceeded 20 hours per week, with peaks approaching 40 hours per week in 2016.
- Monthly means were highest during June–September, with peak activity occurring in August.
- Lowest monthly activity occurred during February and March.
- Detections occurred throughout the 24-hour cycle, with highest activity during daytime and evening hours.

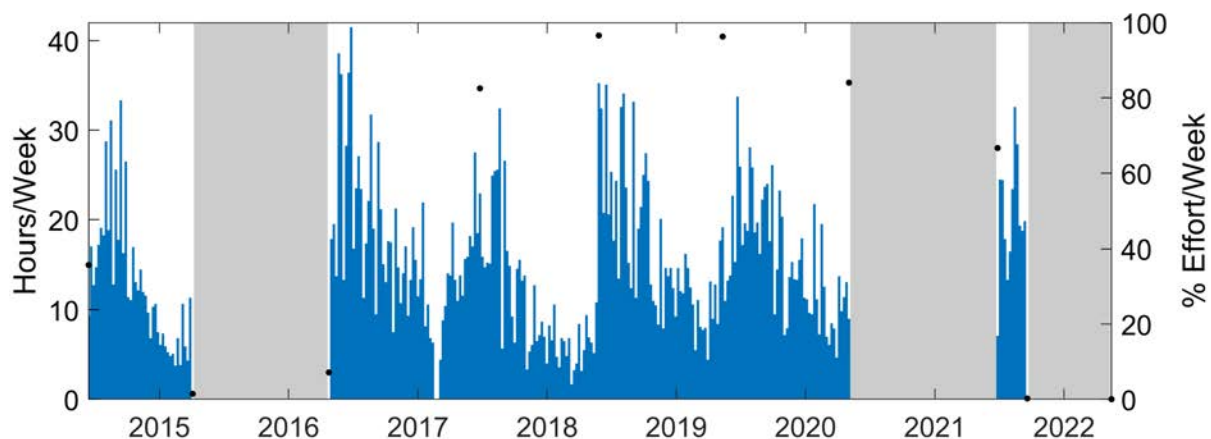


Figure 53: Cumulative hours/week of broadband ships near Norfolk Canyon. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

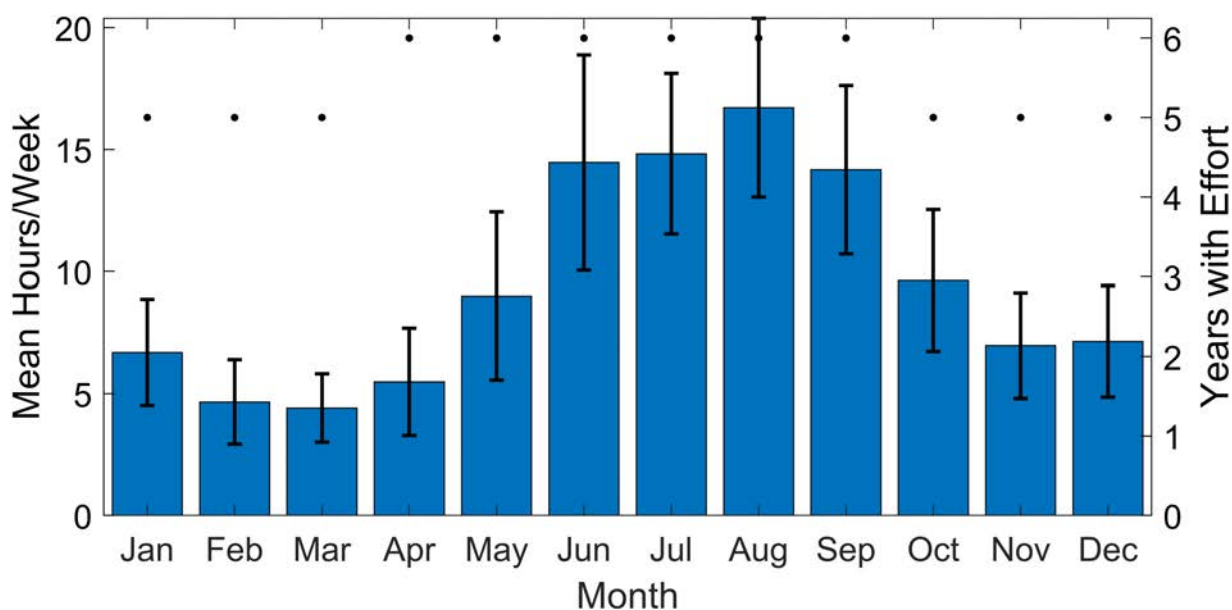


Figure 54: Monthly mean hours per week of broadband ships near Norfolk Canyon. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

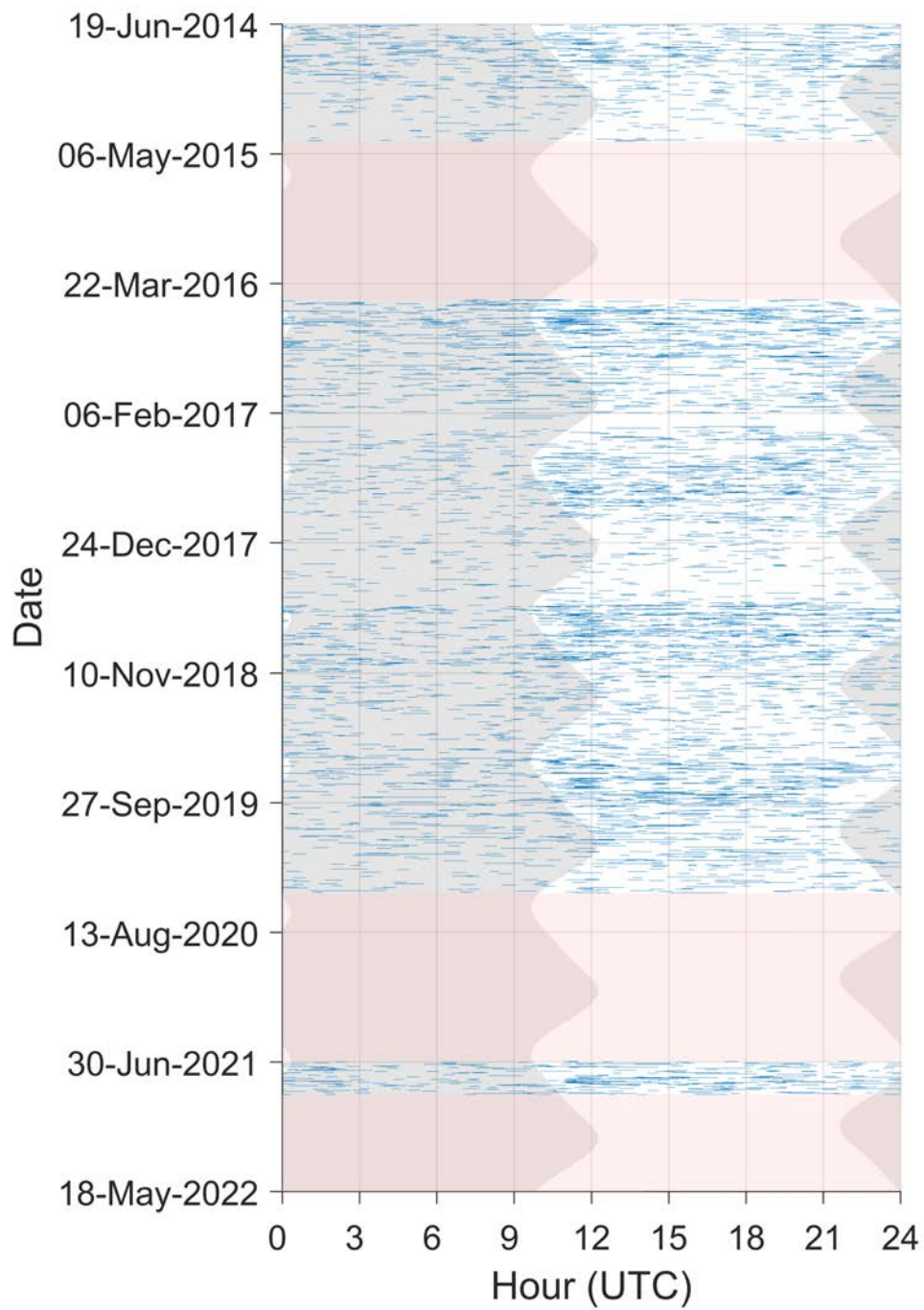


Figure 55: Broadband ship presence in 5-min bins near Norfolk Canyon. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.5.2 Cape Hatteras

Ship detections offshore Cape Hatteras were persistent throughout the monitoring period at both sites A and B (Figure 56). Site A exhibited relatively stable activity from 2012–2016, with weekly detections generally ranging between 5 and 25 hours per week. Site B exhibited higher activity, with sustained elevated detections and peak weekly totals exceeding 80 hours per week during 2019. Ship activity remained consistently present throughout nearly the entire monitoring period at both sites.

Monthly mean ship activity differed between sites (Figure 57). At site A, activity increased during late spring and summer months, with highest mean activity occurring from May through August. Site B exhibited highest monthly activity during February and March, with elevated activity also occurring during late spring and summer months.

Ship detections occurred continuously throughout the 24-hour cycle at both sites (Figure 58). Activity was consistently observed during both daytime and nighttime hours, with no strong diel concentration evident across years.

Summary of Results – Ships off Cape Hatteras

- Ship activity was persistent throughout the monitoring period at both sites A and B.
- Site A exhibited relatively stable activity from 2012–2016, with weekly detections generally ranging between 5 and 25 hours per week.
- Site B exhibited higher activity, with peak weekly detections exceeding 80 hours per week during 2019.
- Monthly activity at site A was highest from May through August, while site B exhibited highest activity during February and March.
- Ship detections occurred continuously throughout the 24-hour cycle with no strong diel pattern.

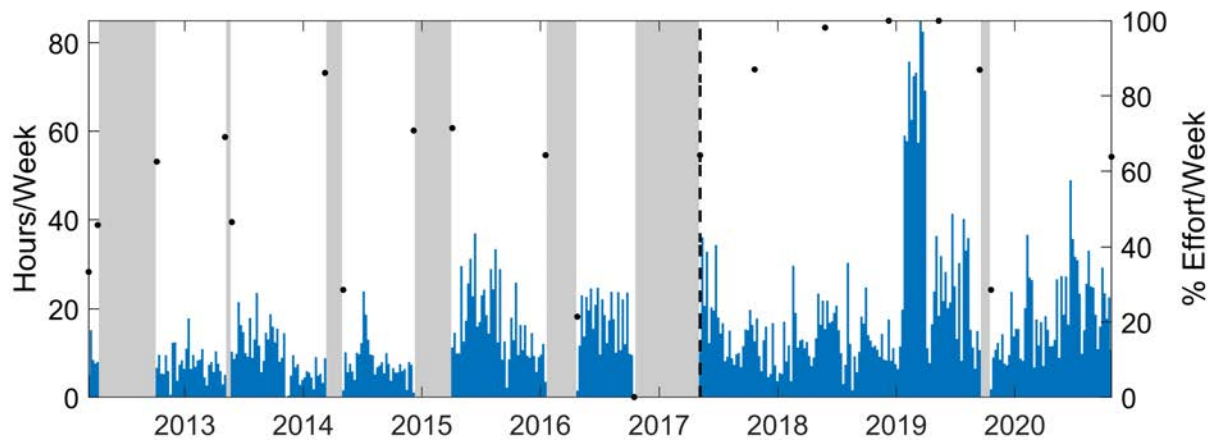


Figure 56: Cumulative hours/week of broadband ships off Cape Hatteras. Gray bars indicate times of no effort and black dots represent weeks with partial effort. The dashed line represents when the instrument moved from site A to site B.

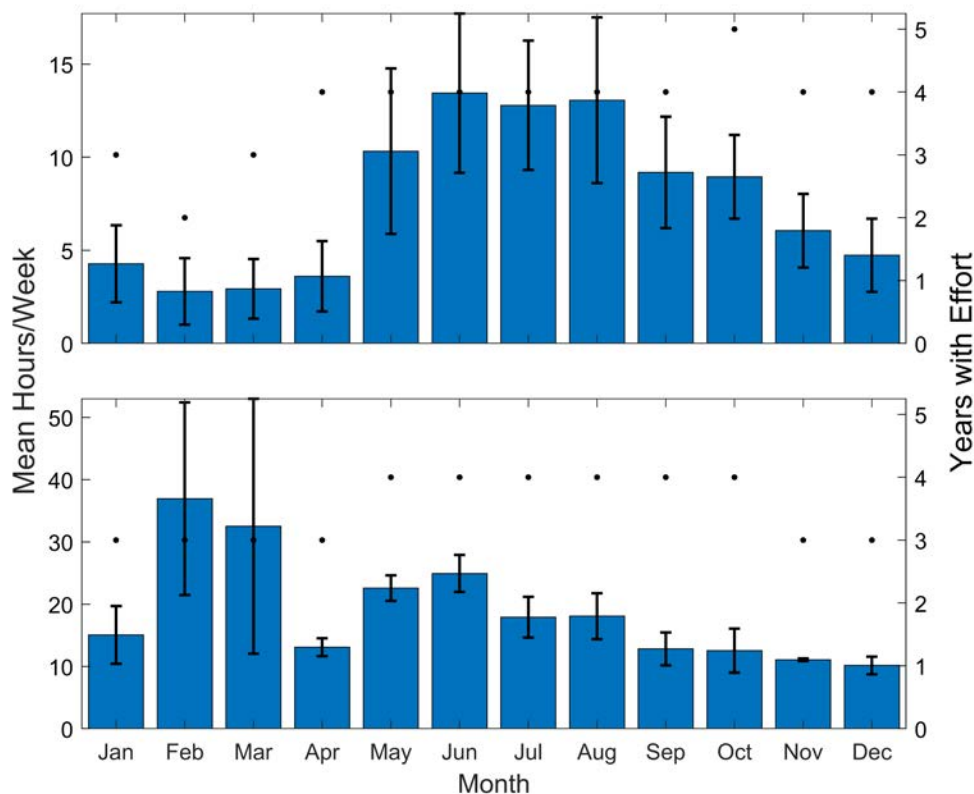


Figure 57: Monthly mean hours per week of broadband ships off Cape Hatteras at site A (top) and site B (bottom). Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

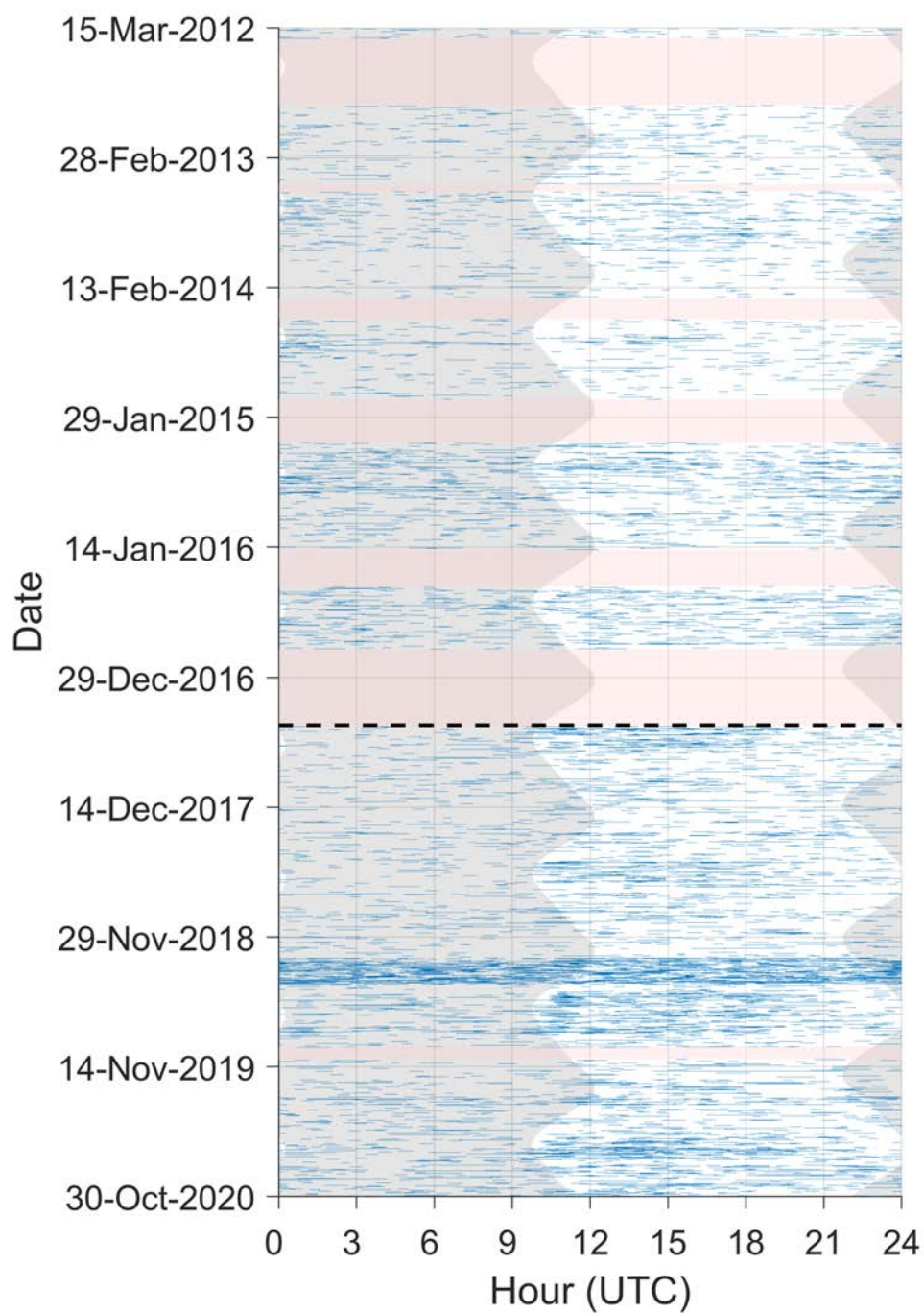


Figure 58: Broadband ship presence in 5-min bins off Cape Hatteras. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort. The dashed line represents when the instrument moved from site A to site B.

5.5.3 Onslow Bay

Ship detections in Onslow Bay were persistent across several sites, although activity levels varied substantially among locations (Figure 59). Site A exhibited the most prolonged activity, with sustained detections during 2007–2008 and again during 2009–2011, when weekly detections frequently exceeded 200 total 5-minute bins per week and occasionally approached 500 total 5-minute bins per week. Site E also exhibited persistent activity during 2011–2013, with weekly detections commonly exceeding 100 total 5-minute bins per week. Site B exhibited a shorter period of elevated activity during 2008, while sites C and D exhibited relatively limited and intermittent detections.

Monthly mean ship activity varied among sites (Figure 60). Site A exhibited elevated activity during winter, late summer, and fall months, with lowest activity during March and April. Site B exhibited highest activity during June–August, although interpretation was limited by sparse recording effort. Sites C and D exhibited generally low activity throughout the year. Site E exhibited relatively consistent activity year-round, with elevated detections occurring during July–November and peak activity during August and November.

Ship detections occurred throughout the 24-hour cycle at all sites (Figure 61). Activity was observed during both daytime and nighttime hours, with no strong or consistent diel concentration evident across sites.

Summary of Results – Ships in Onslow Bay

- Ship detections were persistent at sites A and E, with lower and more intermittent activity at sites B–D.
- Site A exhibited the most prolonged activity, with weekly detections occasionally approaching 500 total 5-minute bins per week during 2007–2011.
- Site E exhibited sustained activity during 2011–2013, with weekly detections commonly exceeding 100 total 5-minute bins per week.
- Sites C and D exhibited relatively limited and intermittent detections.
- Monthly activity at site E was highest during July–November, with peaks during August and November.
- Ship detections occurred throughout the 24-hour cycle with no strong consistent diel pattern.

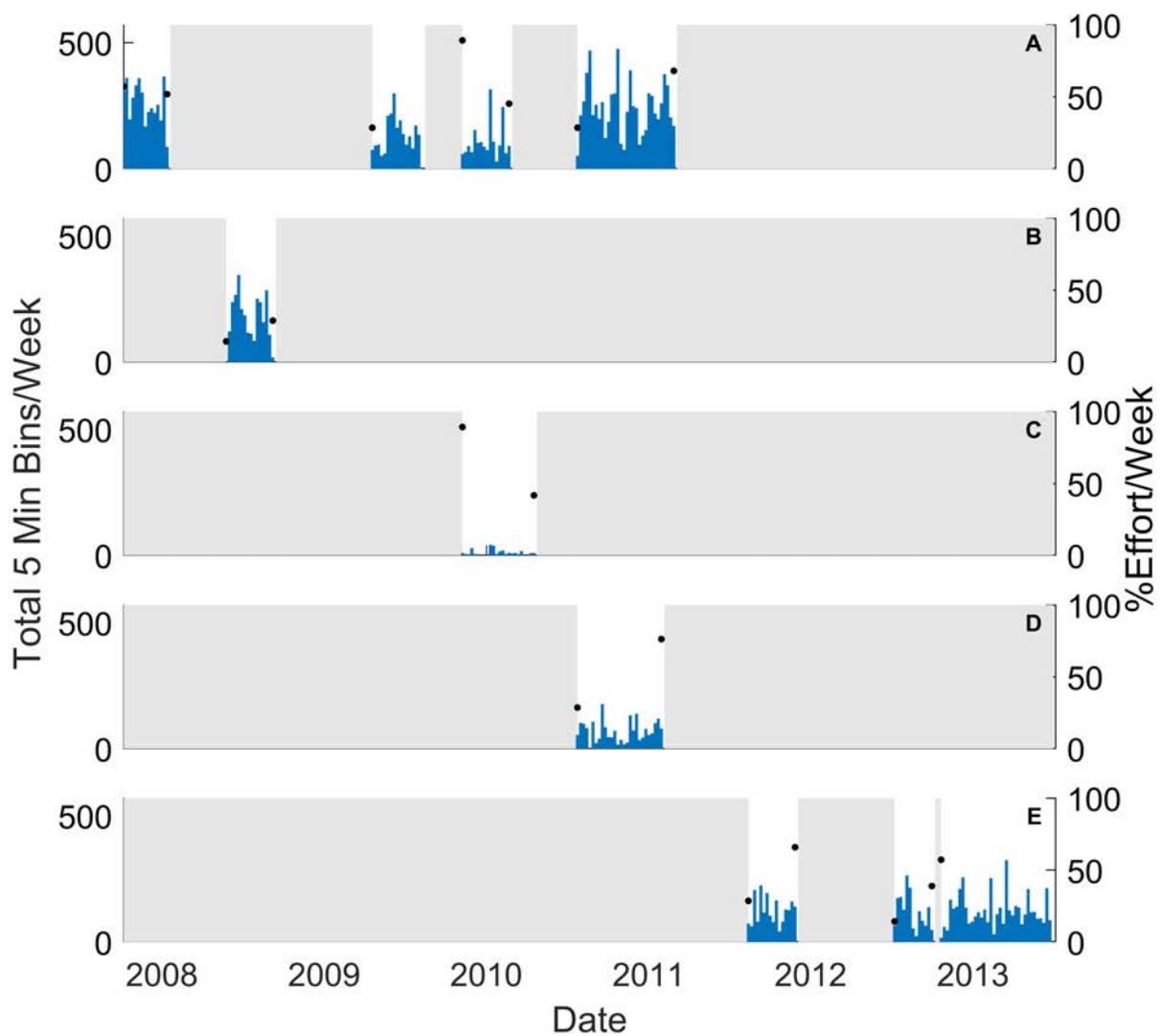


Figure 59: Cumulative hours/week of broadband ships at all Onslow Bay sites. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

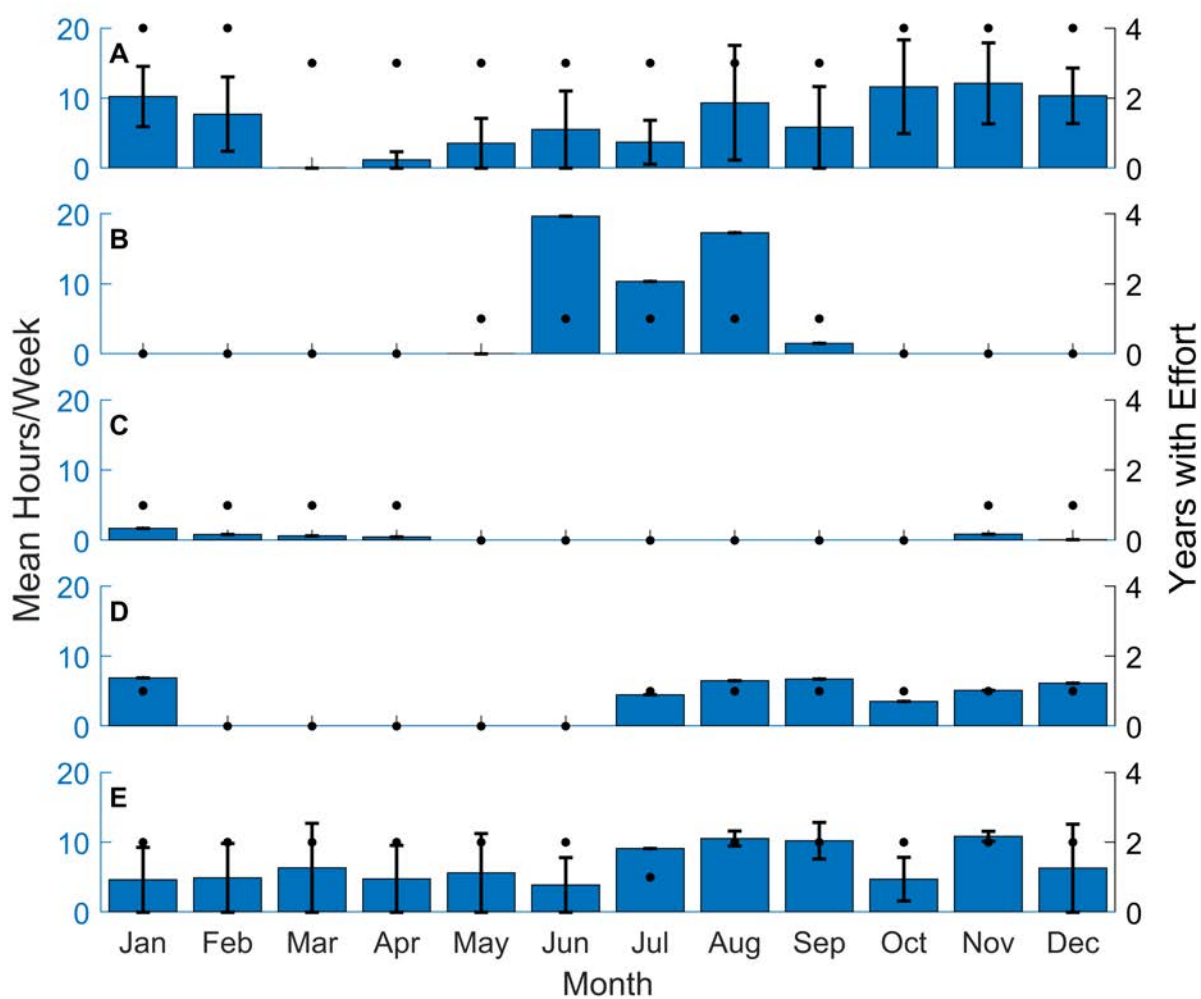


Figure 60: Monthly mean hours per week of broadband ships at all Onslow Bay sites. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

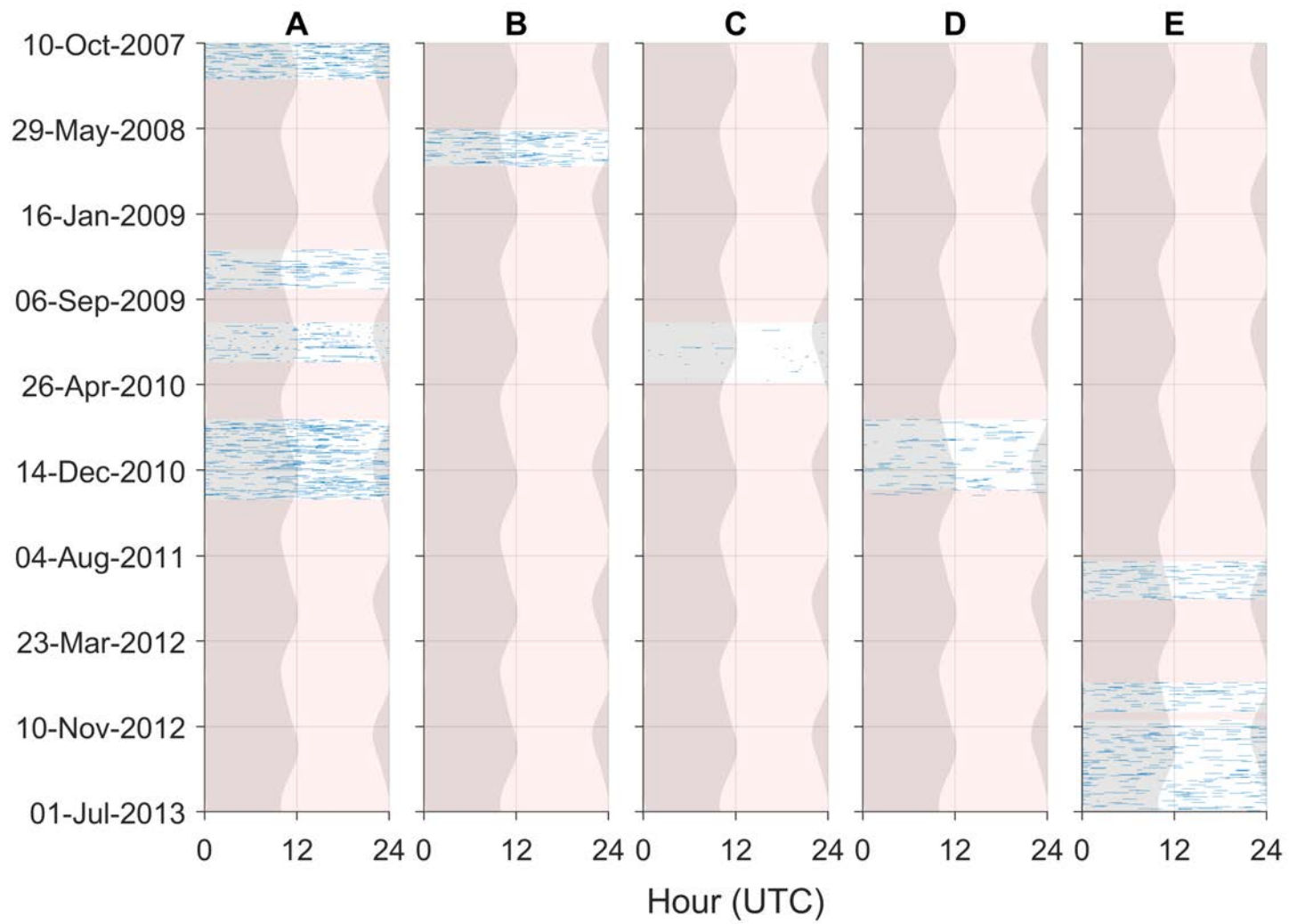


Figure 61: Broadband ships in 5-min bins at all Onslow Bay sites. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

5.5.4 Jacksonville

Ship detections off Jacksonville were elevated across all sites during periods with recording effort, although activity varied seasonally and interannually (Figure 62). Sites A and B exhibited the longest periods of recording effort and correspondingly the longest periods of sustained detections during 2009–2011, with weekly totals frequently exceeding 100 total 5-minute bins per week and occasional peaks exceeding 300 total 5-minute bins per week. Site C also exhibited elevated activity during its shorter recording period in 2013–2014, with weekly detections frequently exceeding 100 total 5-minute bins per week and peaks approaching 300 total 5-minute bins per week. Similarly, site D exhibited persistent moderate to high activity during 2015–2020, with recurring periods of elevated detections and occasional peaks exceeding 300 total 5-minute bins per week. Across all sites, ship activity exhibited pronounced temporal variability, with alternating periods of elevated and reduced detections that suggested seasonal fluctuations in vessel presence.

Monthly mean ship activity differed among sites but generally reflected strong seasonal structure (Figure 63). Site A exhibited elevated activity during fall months, particularly September–November. Sites B and C exhibited highest activity during spring, particularly March–May, while site D exhibited elevated activity during summer months, with peak monthly means occurring during July–September. These patterns indicate that ship activity was seasonally dynamic across the Jacksonville region, although the timing of peak activity differed among sites.

Ship detections occurred throughout the 24-hour cycle at all sites (Figure 64). Activity was observed during both daytime and nighttime hours, with no strong or consistent diel pattern evident across sites.

Summary of Results – Ships off Jacksonville

- Ship detections were elevated across all sites during periods with recording effort.
- Sites A and B exhibited the longest periods of sustained activity during 2009–2011, with peak weekly detections occasionally exceeding 300 total 5-minute bins per week.
- Site C exhibited elevated activity during 2013–2014, while site D exhibited persistent moderate to high activity during 2015–2020.
- Ship activity fluctuated seasonally and interannually across all sites, with alternating periods of elevated and reduced detections.
- Seasonal peaks differed among sites, occurring during fall at site A, spring at sites B and C, and summer at site D.
- Ship detections occurred throughout the 24-hour cycle with no strong consistent diel pattern.

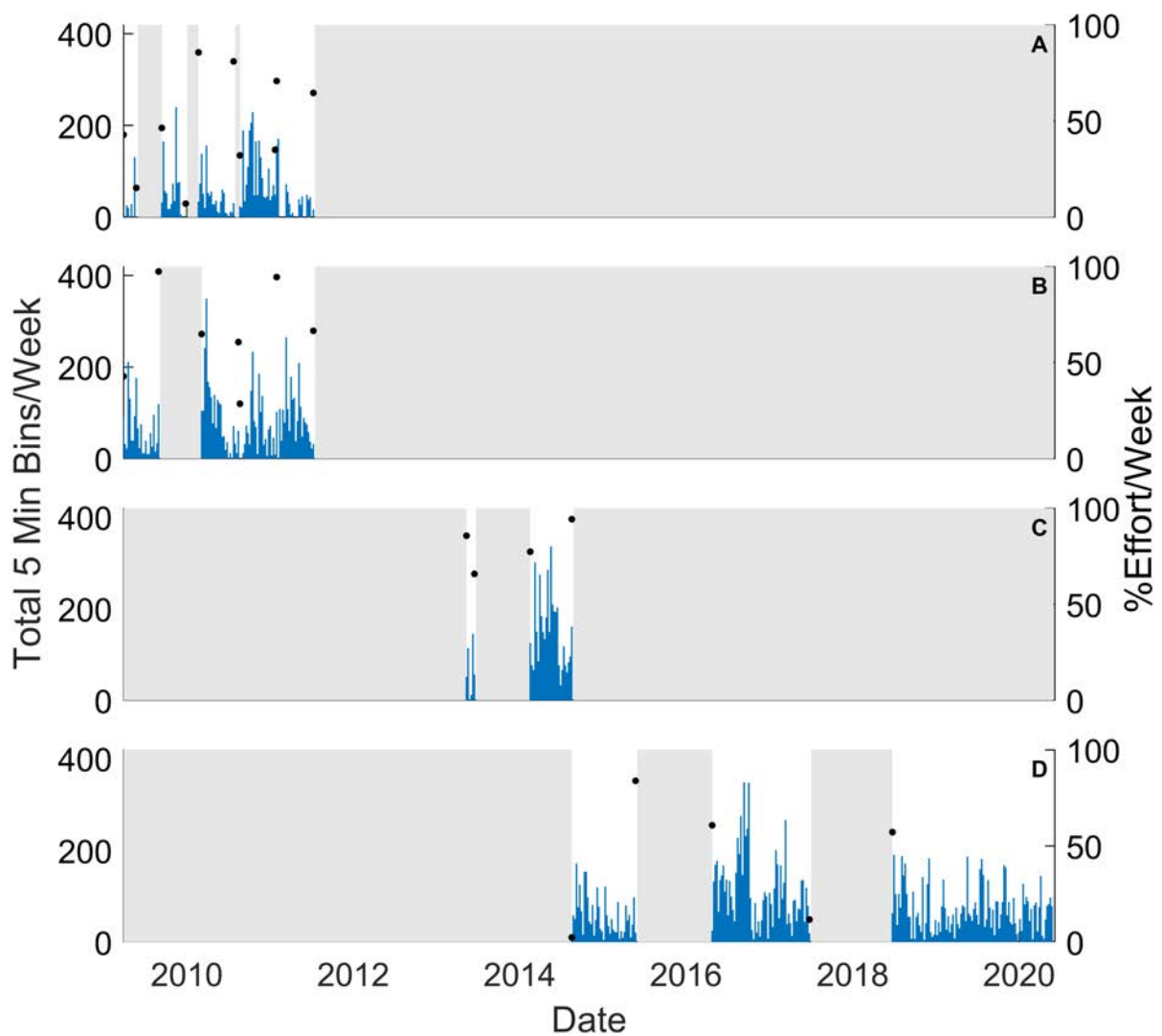


Figure 62: Cumulative hours/week of broadband ships at all Jacksonville sites. Gray bars indicate times of no effort and black dots represent weeks with partial effort.

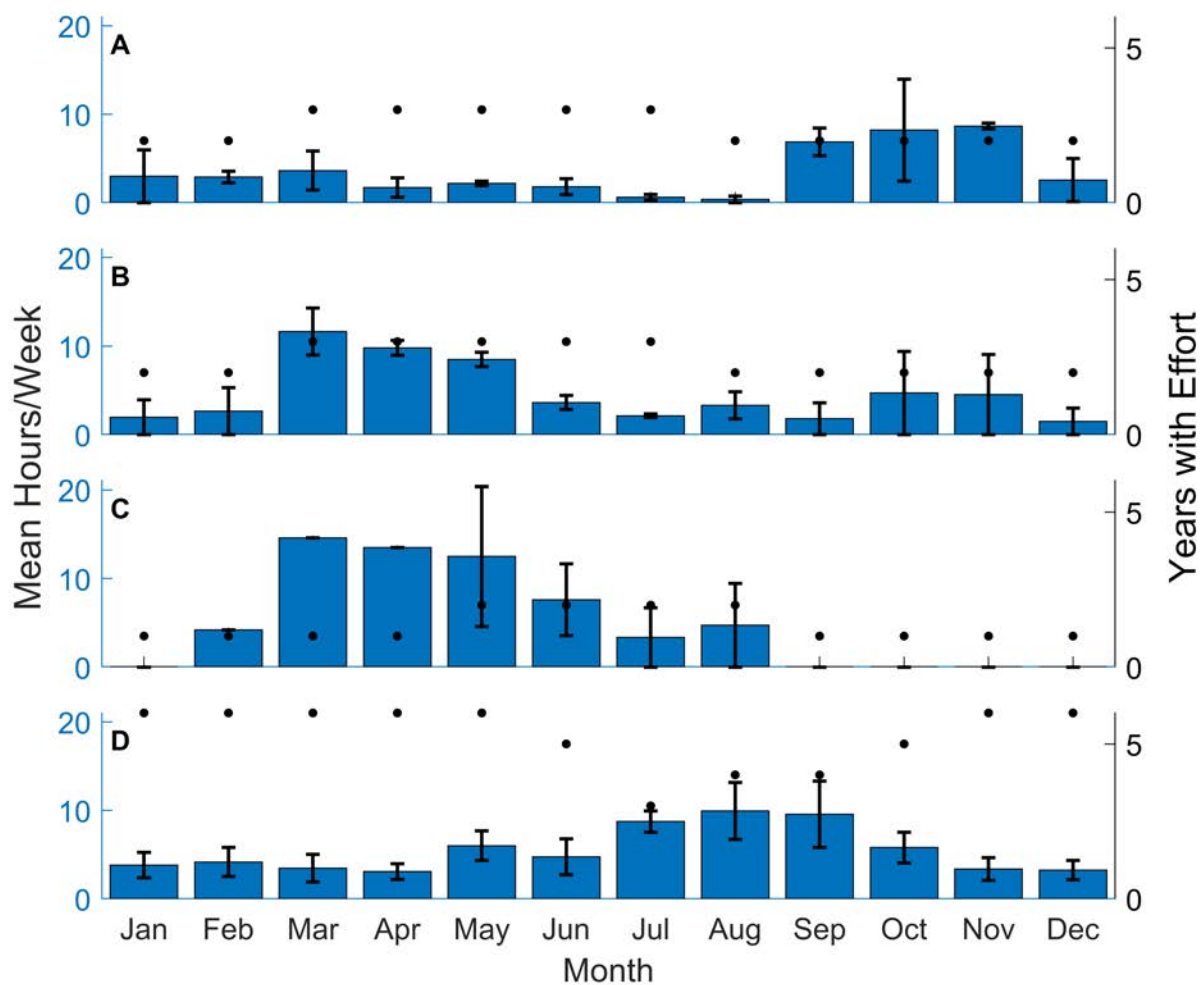


Figure 63: Monthly mean hours per week of broadband ships at all Jacksonville sites. Bars indicate the monthly mean (left y-axis), and error bars represent standard error of the mean across years. Years with effort for each month (right y-axis) are represented by the black dots.

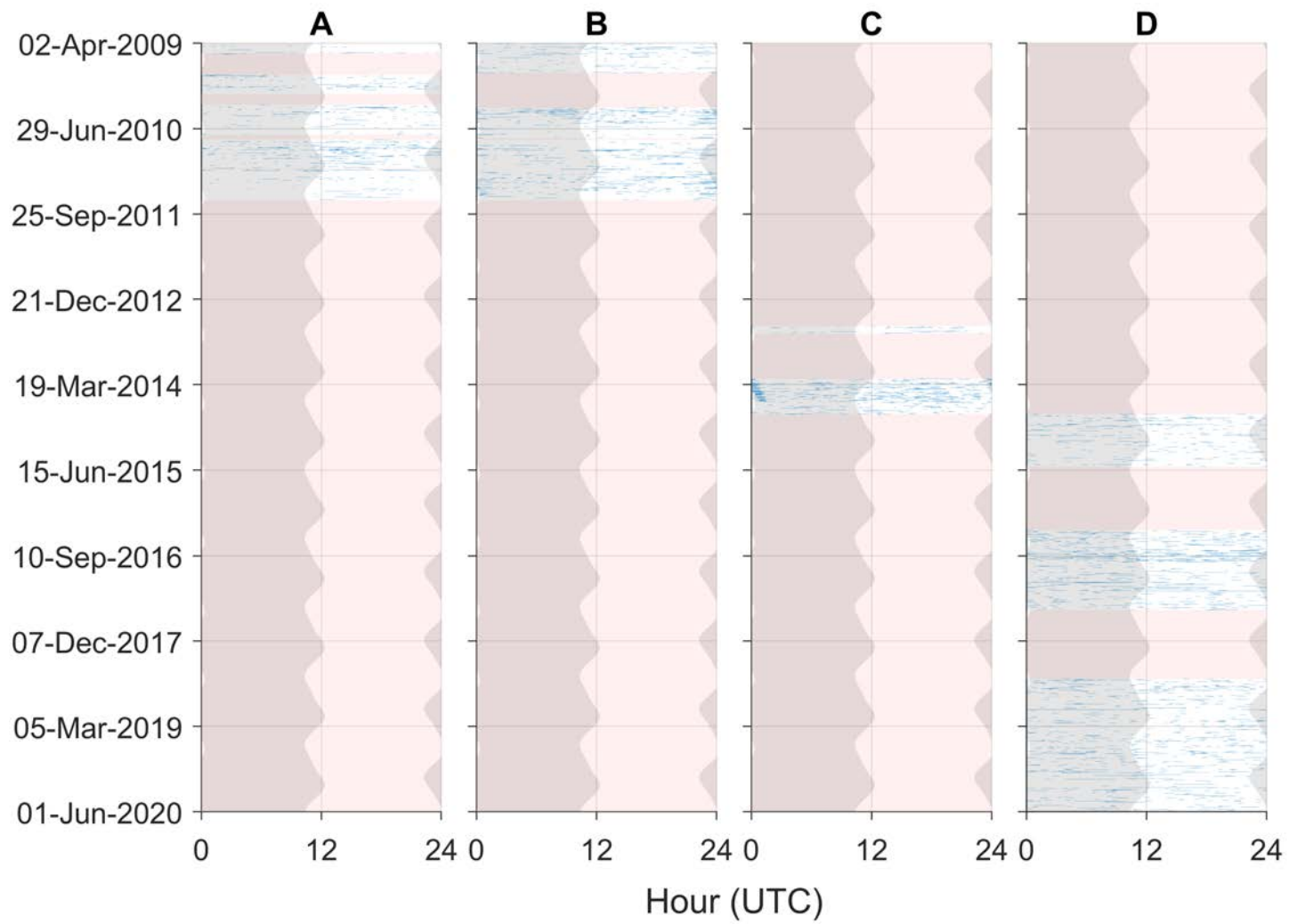


Figure 64: Broadband ships in 5-min bins at all Jacksonville sites. Gray vertical shading denotes nighttime and light red horizontal shading indicates times of no effort.

6 Acknowledgments

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