Passive Acoustic Monitoring for Marine Mammals in the SOCAL Range Complex March 2017 – July 2018

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Cuvier's beaked whale, Photo by Jennifer Trickey

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Executive Summary

Passive acoustic monitoring was conducted in the Navy's Southern California Range Complex from March 2017 to July 2018 to detect marine mammal and anthropogenic sounds. High-frequency Acoustic Recording Packages (HARPs) recorded sounds between 10 Hz and 100 kHz at three locations: northwest of San Clemente Island (1,300 m depth, site E), west of San Clemente Island (1,000 m depth, site H), and southwest of San Clemente Island (1200 m depth, site N). In addition, an array of 9 HARPs, sampling at 20 kHz, was deployed in the San Diego Trough during the fall of 2017 to track baleen whale calls. One HARP from this array was analyzed for this report (1,051 m depth, site HP).

While a typical southern California marine mammal assemblage is consistently detected in these recordings (Hildebrand *et al.*, 2012), only a select sub-set of species including blue whales, fin whales, and beaked whales were analyzed for this report. The low-frequency ambient soundscape and the presence of Mid-Frequency Active (MFA) sonar and explosions were also analyzed.

Ambient sound levels were highest at site HP and lowest at site H, likely related to boat activity. Peaks in sound levels at sites E, H, and N during the fall and winter are related to the seasonally increased presence of blue whales and fin whales, respectively.

For marine mammal and anthropogenic sounds, data analysis was performed using automated computer algorithms. Calls of two baleen whale species were detected: blue whale B calls and D calls, and fin whale 20 Hz calls. Both species were present at all sites: B calls occurred in high numbers at sites E, H, and N; D calls were highest at sites H and N; and the fin whale acoustic index, representative of 20 Hz calls, was high at sites E, H, and N. Site HP had the lowest call detection levels for both species. Blue whale B call detections peaked from September to December 2017 at sites E and N, and in September at site H. Very few B calls were detected after January 2018. Blue whale D calls peaked in July 2017 at sites H and N and in July 2018 at site N. The fin whale acoustic index was highest from October 2017 to March 2018.

Frequency modulated (FM) echolocation pulses from Cuvier's beaked whales were regularly detected at sites E, H, and N but were detected in much higher numbers at site E, where peaks in detections occurred during spring 2017, winter 2018, and spring 2018. A new beaked whale FM pulse type, BW35, thought to be produced by Hubbs' beaked whale (Griffiths *et al.*, 2018), was detected on only 2 days; once at site E and once at site H. The beaked whale-like FM pulse type, BW43, thought to be produced by Perrin's beaked whale (Baumann-Pickering *et al.*, 2014), was detected intermittently throughout the recording period, only at site N. No other beaked whale signal types were detected.

Two anthropogenic pulsed signals were detected: MFA sonar and explosions. MFA sonar was detected at all sites with a peak in August 2017. Site N had the most MFA sonar packet detections normalized per year and highest cumulative sound exposure levels, including events concurrent with a major naval exercise during August 2017. Sites E and H both had fewer packets detected and lower cumulative sound exposure levels, though site E had the highest received level. Site HP had the lowest number of sonar packet detections, as well as the lowest cumulative sound exposure level.

Explosions were detected at all sites, but were highest in July 2017 at site H. Temporal and spectral parameters, as well as received levels of these explosive events suggest association with fishing, specifically the use of seal bombs.

Project Background

The Navy's Southern California (SOCAL) Range Complex is located in the Southern California Bight and the adjacent deep waters to the west. This region has a highly productive marine ecosystem due to the southward flowing California Current, and associated coastal current system. A diverse array of marine mammals is found here, including baleen whales, beaked whales and other toothed whales and pinnipeds.

In January 2009, an acoustic monitoring effort was initiated within the SOCAL Range Complex with support from the U.S. Pacific Fleet. The goal of this effort was to characterize the vocalizations of marine mammal species present in the area, determine their seasonal presence, and evaluate the potential for impact from naval training. In this current effort, the goal was to explore the seasonal presence of a subset of species of particular interest, including blue whales, fin whales, and beaked whales. In addition, the low-frequency ambient soundscape, as well as the presence of Mid-Frequency Active (MFA) sonar and explosions were analyzed.

This report documents the analysis of data recorded by High-frequency Acoustic Recording Packages (HARPs) that were deployed at three sites within the SOCAL Range Complex and collected data between March 2017 and July 2018. The three recording sites include one to the northwest (site E), one to the west (site H) and one to the southwest (site N) of San Clemente Island (Figure 1; Figure 2). Data from site E were analyzed for March 2017 to February 2018 and March to July 2018 (Table 1). Data from site H were analyzed for June to November 2017 (Table 1), when recording ended prematurely due to a hydrophone malfunction. Data from site N were analyzed for June to December 2017 and again February to July 2018 (Table 1). In addition, an array of HARPs, sampling at 20 kHz (Table 2), was deployed in the San Diego Trough (Figure 3) during summer and fall 2017 to provide localization capability for baleen whale calls. In order to determine which species and anthropogenic signals of interest were recorded by this array, we analyzed site HP (Figure 1; Figure 2; Figure 3) from August to November 2017 (Table 2).

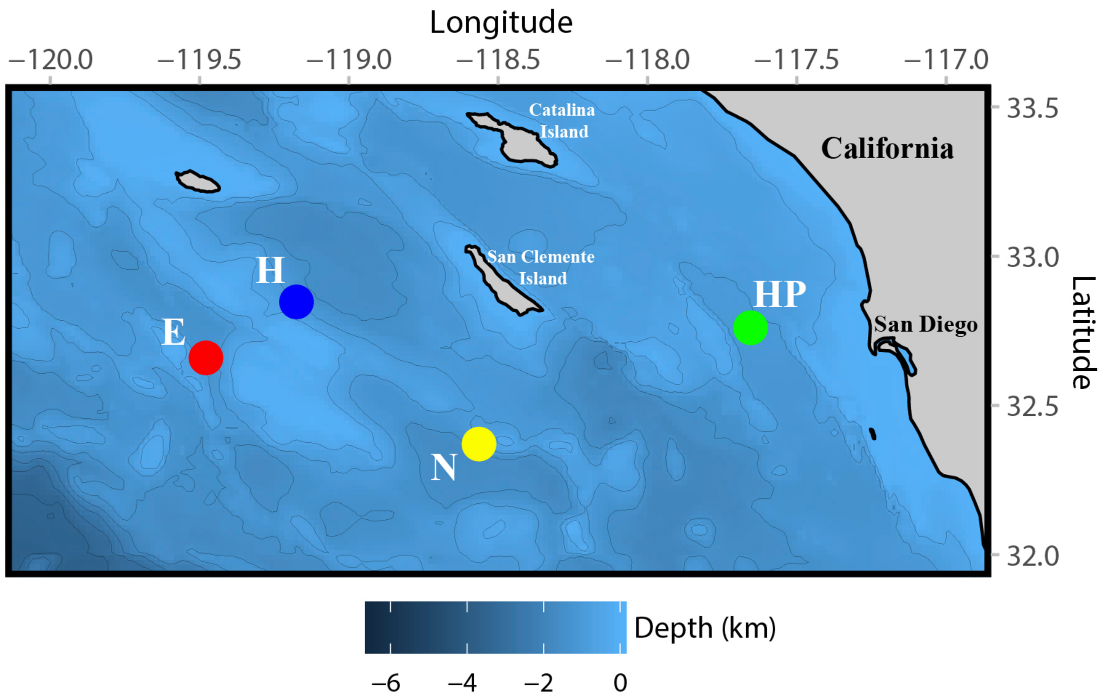

Figure 1. Locations of High-frequency Acoustic Recording Package (HARP) deployment sites E, H, N, and HP (circles) in the SOCAL study area from March 2017 through July 2018. Color indicates bathymetric depth. Contour lines represent 500 m depth increments.

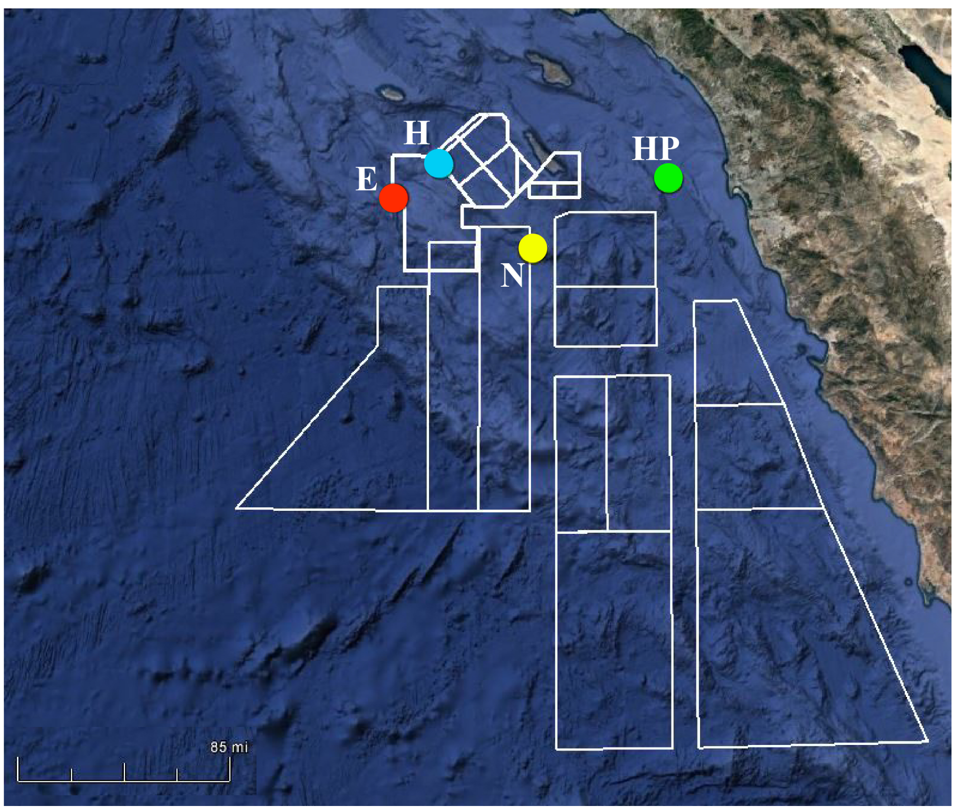

Figure 2. Locations of High-frequency Acoustic Recording Package (HARP) deployments in the SOCAL study area (colored circles) and SCORE operating areas (white boxes).

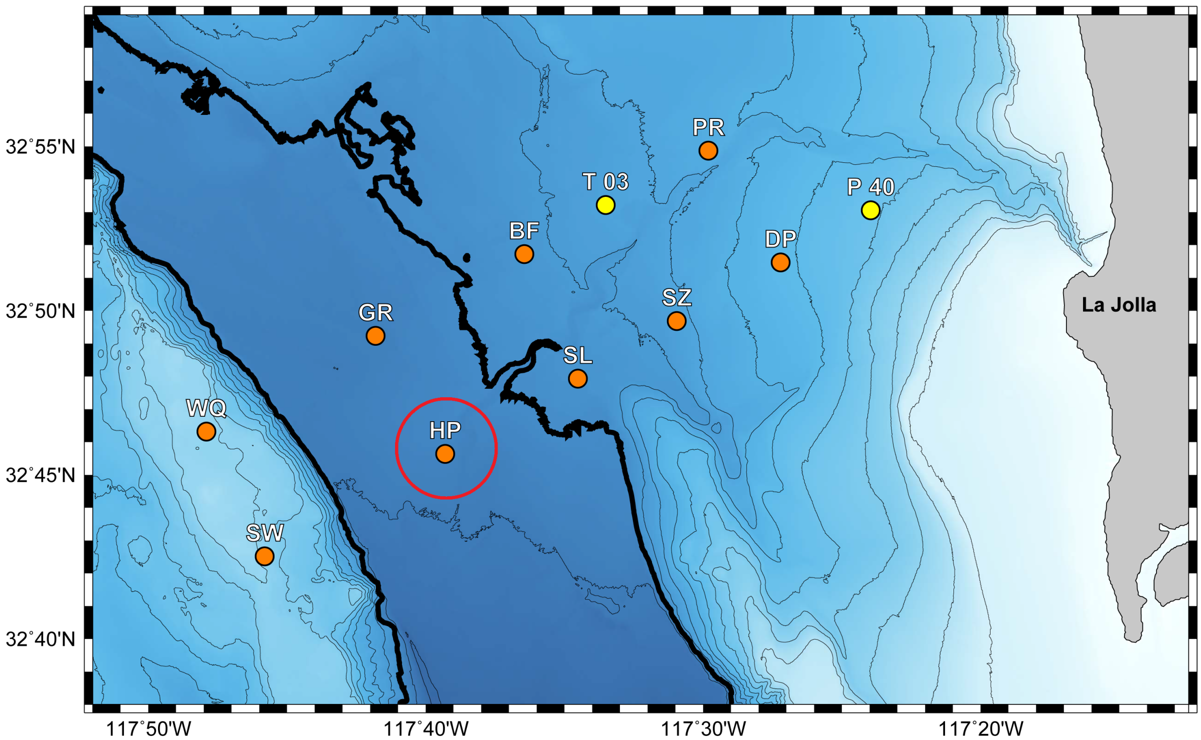

Figure 3. Deployment locations of HARP array sampling at 20 kHz (orange circles) and those sampling at 200 kHz (yellow circles) in the San Diego Trough region.
Red circled site indicates instrument analyzed in this report. Contour lines are at 100 m intervals (thick black contour line represents 1000 m).

Table 1. SOCAL Range Complex acoustic monitoring since January 2009.
Periods of instrument deployment analyzed in this report are shown in bold. Dates in italics were only used for high frequency analysis.

Deployment Name	Site E Monitoring Period	# Hours	Site H Monitoring Period	# Hours	Site N Monitoring Period	# Hours
SOCAL 31	-	-	1/13/09 – 3/08/09	1320	1/14/09 – 3/09/09	1296
SOCAL 32	-	-	3/14/09 – 5/07/09	1320	3/14/09 – 5/07/09	1320
SOCAL 33	-	-	5/19/09 – 6/13/09	600	5/19/09 – 7/12/09	1296
SOCAL 34	-	-	7/23/09 – 9/15/09	1296	7/22/09 – 9/15/09	1320
SOCAL 35	-	-	9/25/09 – 11/18/09	1320	9/26/09 – 11/19/09	1296
SOCAL 36	-	-	12/6/09 – 1/29/10	1296	12/6/09 – 1/26/10	1224
SOCAL 37	-	-	1/30/10 – 3/22/10	1248	1/31/10 – 3/26/10	1296
SOCAL 38	-	-	4/10/10 – 7/22/10	2472	4/11/10 – 7/18/10	2352
SOCAL 40	-	-	7/23/10 – 11/8/10	2592	7/23/10 – 11/8/10	2592
SOCAL 41	-	-	12/6/10 – 4/17/11	3192	12/7/10 – 4/09/11	2952
SOCAL 44	-	-	5/11/11 – 10/12/11	2952	5/12/10 – 9/23/11	3216
SOCAL 45	-	-	10/16/11 – 3/5/12	3024	10/16/11 – 2/13/12	2904
SOCAL 46	-	-	3/25/12 – 7/21/12	2856	3/25/12 – 8/5/12	3216
SOCAL 47	-	-	8/10/12 – 12/20/12	3192	8/10/12 – 12/6/12	2856
SOCAL 48	-	-	12/21/12 – 4/30/13	3140	12/20/12 – 5/1/13	3155
SOCAL 49	-	-	-	-	5/2/13 – 9/11/13	3156
SOCAL 50	-	-	9/10/13 – 1/6/14	2843	-	-
SOCAL 51	-	-	1/7/14 – 4/3/14	2082	1/7/14 – 2/16/14	956
SOCAL 52	-	-	4/4/14 – 7/30/14	2814	4/4/14 – 7/30/14	2817
SOCAL 53	-	-	7/30/14 – 11/5/14	2340	7/30/14 – 11/5/14	2342
SOCAL 54	-	-	11/5/14 – 2/4/15	2198	11/4/14 -2/5/15	2196
SOCAL 55	-	-	2/5/15 – 6/1/15	2800	2/5/15 – 2/23/15	433
SOCAL 56	-	-	6/2/15 – 10/3/15	2952	6/2/15 – 10/3/15	2966
SOCAL 57	-	-	-	-	10/3/15 – 11/21/15	1168
SOCAL 58	-	-	11/21/15 – 4/25/16	3734	*11/21/15 – 4/18/16*	*3578*
SOCAL 59	-	-	7/6/16 – 11/9/16	3011	7/7/16 – 11/8/16	2999
SOCAL 60	-	-	-	-	11/9/16 – 2/21/17	2457
SOCAL 61	**3/5/17 – 7/10/17**	**3063**	2/22/17 – 6/6/17	2518	2/21/17 – 6/7/17	2528
SOCAL 62	**7/11/17 – 2/10/18**	**5148**	**6/7/17 – 10/4/17**	**2879**	**6/7/17 – 12/21/17**	**4723**
SOCAL 63	**3/15/18 – 7/11/18**	**2843**	**10/5/17 – 11/3/17**	**707**	**2/4/18 – 7/9/18**	**3722**

Table 2. HARP array deployments in the San Diego Trough from May 2017 to January 2018. Periods of instrument deployment analyzed in this report are shown in bold.

Deployment Name	Monitoring Period	Latitude (N)	Longitude (W)	Depth (m)	# Hours
LJ 40-P	5/30/2017 – 9/29/2017	32˚ 53.053	117˚ 23.954	517	2933
SOCAL 03-T	7/8/2017 – 1/17/2018	32˚ 53.199	117˚ 33.496	814	4632
SDT 01-BF	7/27/2017 –11/13/2017	32˚ 51.721	117˚ 36.446	915	2636
SDT 01-DP	8/3/17 – 11/15/17	32˚ 51.467	117˚ 27.204	609	2514
SDT 01-GR	7/31/17 – 11/13/17	32˚ 49.231	117˚ 41.802	1068	2539
SDT 01-HP	**8/1/17 – 11/13/17**	**32˚ 45.640**	**117˚ 39.295**	**1051**	**2511**
SDT 01-PR	8/03/17 – 11/15/17	32˚ 54.867	117˚29.805	725	2513
SDT 01-SL	7/27/17 – 11/15/17	32˚ 47.930	117˚ 34.513	943	2667
SDT 01-SW	7/31/17 – 11/13/17	32˚ 42.512	117˚ 45.805	295	2537
SDT 01-SZ	8/3/2017 – 11/15/2017	32˚ 49.685	117˚ 30.951	823	2512
SDT 01-WQ	7/31/2017 – 11/13/2017	32˚ 46.317	117˚ 47.905	285	2537

Methods

High-frequency Acoustic Recording Package (HARP)

HARPs were used to record the low-frequency ambient soundscape as well as marine mammal and anthropogenic sounds in the SOCAL area. HARPs can autonomously record underwater sounds from 10 Hz up to 160 kHz and are capable of approximately 300 days of continuous data storage. The HARPs were deployed in a seafloor mooring configuration with the hydrophones suspended at least 10 m above the seafloor. Each HARP hydrophone is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones were also calibrated at the Navy's Transducer Evaluation Center facility to verify the laboratory calibrations (Wiggins and Hildebrand, 2007).

Data Collected

Acoustic recordings have been collected within the SOCAL Range Complex near San Clemente Island since 2009 (Table 1) using HARPs sampling at 200 kHz. The sites analyzed in this report are designated site E (32° 39.54N, 119° 28.71W, depth 1,300 m) site H (32° 50.76N, 119° 10.57W, depth 1,000 m), and site N (32° 22.21N, 118° 33.85W, depth 1,200 m). Additionally, an array of HARPs was deployed in the San Diego Trough (SDT) during the summer and fall of 2017 (Table 2). A total of 9 instruments were deployed, sampling at 20 kHz, and these were supplemented by two additional instruments that sampled at 200 kHz, to yield a total array of 11 instruments. The instruments were deployed in a northeast-to-southwest trending array with dimensions of 20 nm x 5 nm. The only site from the array analyzed in this report is site HP (32° 45.64N, 117° 39.3W, depth 1,051 m)

Site E yielded data from March 5, 2017 to February 10, 2018 and also from March 15 to July 11, 2018. Site H yielded data from June 7 to November 3, 2017. Analysis could not be conducted on data beyond November 3 due to a hydrophone malfunction. Site N yielded data from June 7, 2017 to December 21, 2017 and also from February 4 to July 9, 2018. Site HP yielded data from August 3, 2017 to November 13, 2017. For all four sites, a total of 25,596 hours, covering 1,066 days of acoustic data were recorded in the deployments analyzed in this report.

Data Analysis

Recording over a broad frequency range of 10 Hz to 100 kHz allows detection of the low-frequency ambient soundscape, baleen whales (mysticetes), toothed whales (odontocetes), and anthropogenic sounds. All analyses were conducted using appropriate automated detectors for whale and anthropogenic sound sources. Analysis was focused on the following species: blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), and Cuvier's beaked whales (*Ziphius cavirostris*). In addition, signals from Blainville's (*Mesoplodon densirostris*) and Stejneger's (*M. stejnegeri*) beaked whales were also analyzed. Other beaked whale signals screened for include FM pulses known as BW43 and BW70, which may belong to Perrin's (*M. perrini*) and pygmy beaked whales (*M.peruvianus*), respectively (Baumann-Pickering *et al.*, 2014). A recently identified beaked whale signal type, possibly belonging to Hubbs' beaked whale (*M. carlhubbsi*), was found at some sites during this reporting period and is referred to as BW35. A description of this signal type can be found below. Individual blue whale B calls, D calls, and beaked whale echolocation clicks, as well as MFA and explosion occurrence and levels were detected automatically using computer algorithms. Presence of fin whale 20 Hz calls was detected using an energy detection method and is reported as a daily average, termed the ‘fin whale acoustic index’ (Širović *et al.*, 2015). Details of all automatic detection methods are described below.

We summarize results of the acoustic analysis on data collected between March 2017 and July 2018 at sites E, H, N, and HP. We discuss seasonal occurrence and relative abundance of calls for different species and anthropogenic sounds that were consistently identified in the data. There was no beaked whale analysis conducted for data from site HP, as this site had a lower sampling frequency and beaked whales would not have been recorded.

Low-frequency Ambient Soundscape

To determine ambient sound levels, HARP recordings were decimated by a factor of 100 to provide an effective bandwidth of 10 Hz to 1 kHz from which LTSAs were constructed with 1 Hz frequency and 5 s temporal resolution. Daily spectra were computed by averaging 5, 5 s sound pressure spectrum levels calculated from each 75 s acoustic record. System self-noise was excluded from these averages.

Blue Whales

Blue whales produce a variety of calls worldwide (McDonald *et al.*, 2006). Calls recorded in the eastern North Pacific include the Northeast Pacific blue whale B call (Figure 4) and the D call (Figure 5). Northeast Pacific blue whale B calls are geographically distinct and potentially associated with mating functions (McDonald *et al.*, 2006; Oleson *et al.*, 2007). They are low-frequency (fundamental frequency <20 Hz), long duration (> 10 s) calls that are often regularly repeated. D calls are downswept in frequency (approximately 100-40 Hz) with a duration of several seconds. These calls are similar worldwide and are assocaited with feeding animals; they may be produced as call-counter call between multiple animals (Oleson *et al.*, 2007).

Northeast Pacific blue whale B calls

Blue whale B calls (Figure 4) were detected automatically using spectrogram correlation (Mellinger and Clark, 1997). The detection kernel was based on frequency and temporal characteristics measured from 30 calls recorded in the data set, each call separated by at least 24 hours. The kernel was comprised of four segments, three 1.5 s and one 5.5 s long, for a total duration of 10 s. Since blue whale calls change over time (McDonald *et al.*, 2009; Širović, 2016), separate kernels were measured for summer and fall periods. The summer 2017 kernel was defined as sweeping from 45.9 to 45.4 Hz; 45.4 to 44.6 Hz, 44.6 to 44.1 Hz, and 44.1 to 43.4 Hz during these predefined periods. The fall 2017 kernel was defined as 45.3 to 45 Hz; 45 to 44.3 Hz, 44.3 to 43.8 Hz, and 43.8 to 43 Hz. The summer 2018 kernel was defined as 45.6 to 45 Hz; 45 to 44.4 Hz, 44.4 to 43.8 Hz, and 43.8 to 42.8 Hz. The kernel bandwidth was 2 Hz. The total number of detections are reported for this call type.

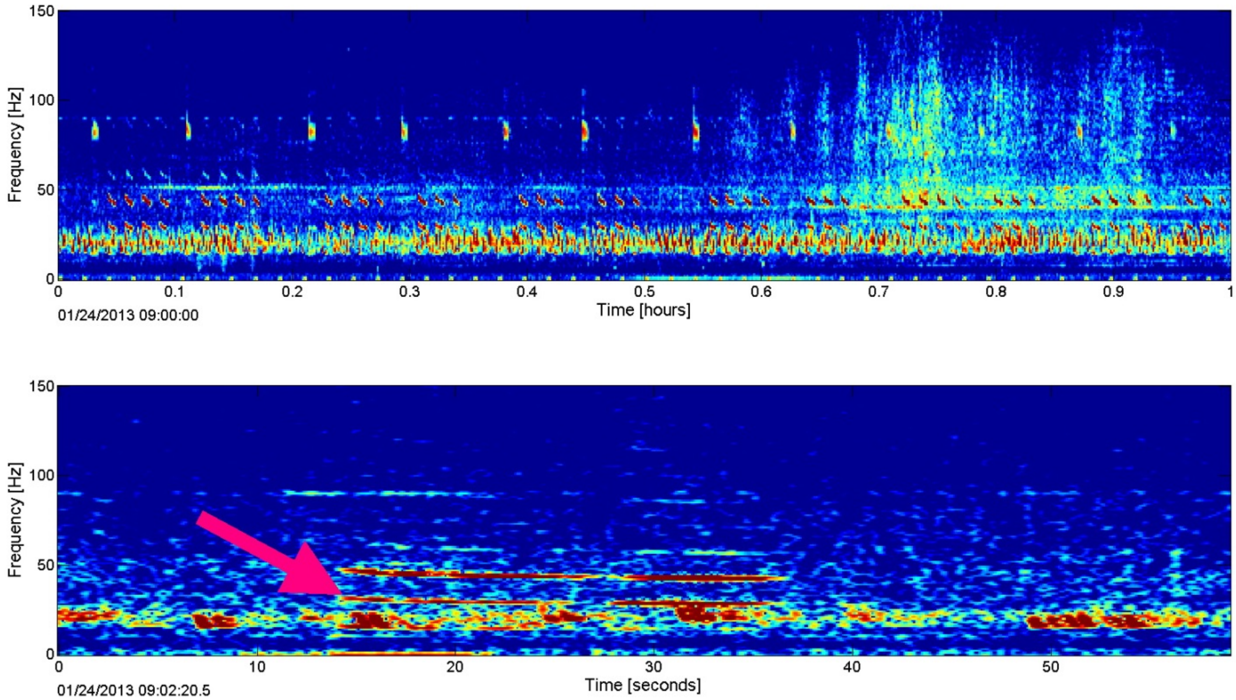

Figure 4. Blue whale B calls (just below 50 Hz) in Long-term Spectral Average (LTSA; top) and an individual call shown in a spectrogram (bottom) recorded at site N.

Blue whale D calls

Blue whale D calls (Figure 5) were detected using an automatic algorithm based on the generalized power law (Helble *et al.*, 2012). This algorithm was adapted for the detection of D calls by modifying detection parameters that included the frequency space over which the detector operates. A trained analyst subsequently verified the detections (Figure 5).

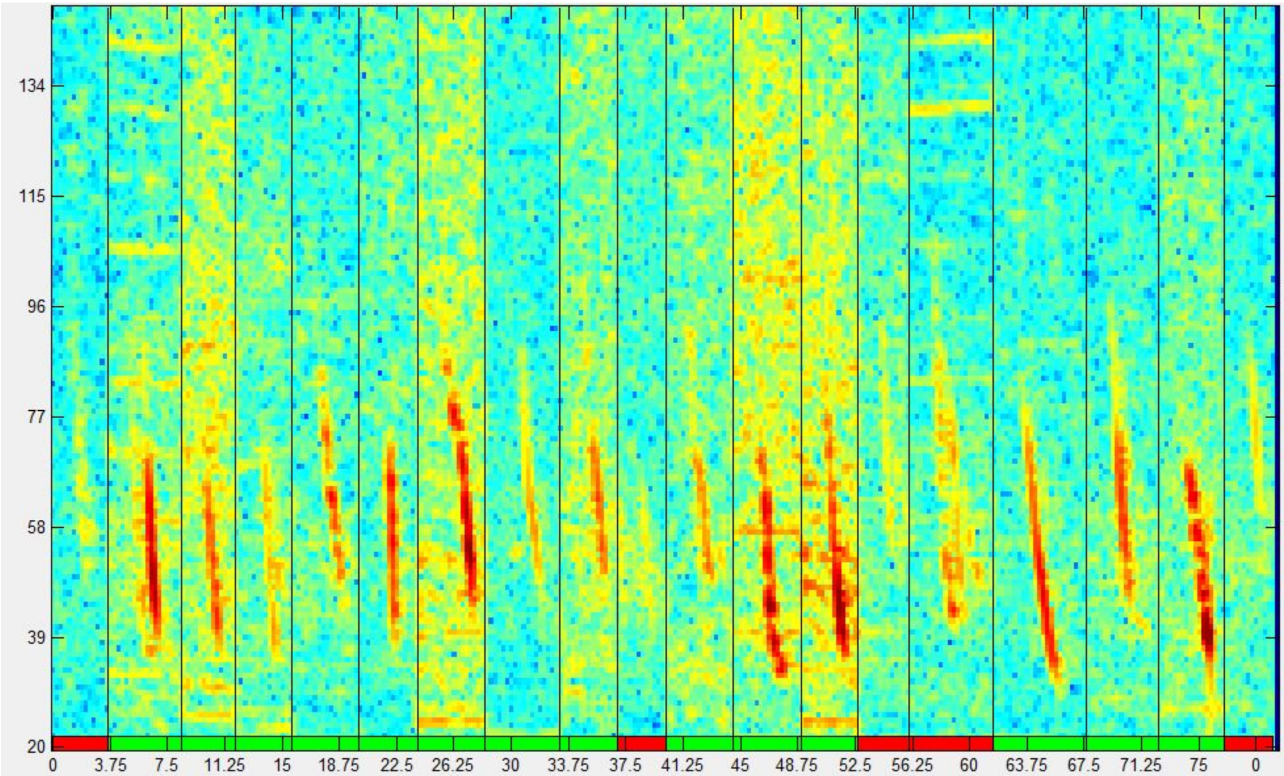

Figure 5. Blue whale D calls from site H in the analyst verification stage of the detector. Green along the bottom evaluation line indicates true detections and red indicates false detections.

Fin Whales

Fin whales produce short (~ 1 s duration), low-frequency calls. The most common is a frequency downsweep from 30-15 Hz called the 20 Hz call (Watkins, 1981; Figure 6). 20 Hz calls can occur at regular intervals as song (Thompson *et al.*, 1992), or irregularly as call counter-calls among multiple, traveling animals (McDonald *et al.*, 1995).

Fin whale 20 Hz calls

In the SOCAL study area, fin whale 20 Hz calls are so abundant that it is often impossible to distinguish, and therefore detect, individual calls (Watkins *et al.*, 2000; Širović *et al.*, 2015). Therefore, fin whale 20 Hz calls (Figure 6) were detected automatically using an energy detection method (Širović *et al.*, 2015). The method uses a difference in acoustic energy between signal and noise, calculated from a long-term spectral average (LTSA) calculated over 5 s with 1 Hz frequency resolution. The frequency at 22 Hz was used as the signal frequency (Nieukirk *et al.*, 2012; Širović *et al.*, 2015), while noise was calculated as the average energy between 10 and 34 Hz. The resulting ratio is termed 'fin whale acoustic index' and is reported as a daily average. All calculations were performed on a logarithmic scale.

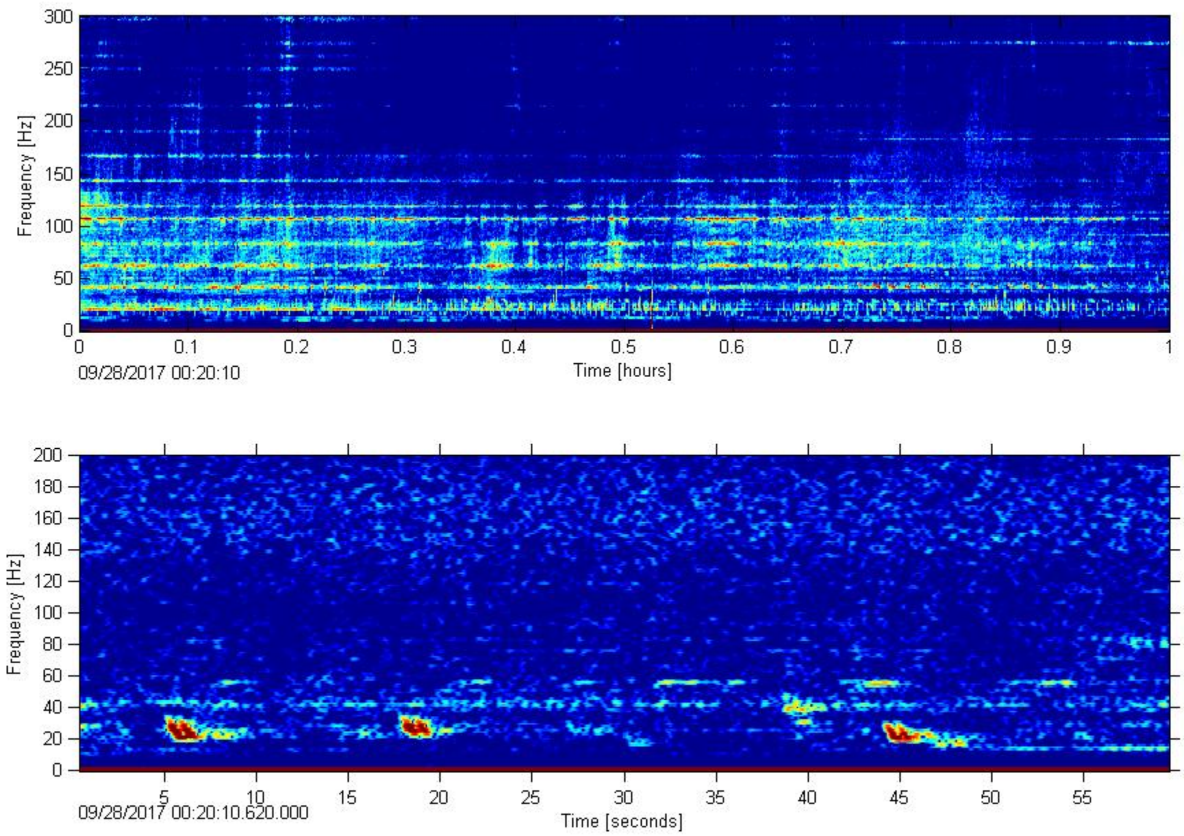

Figure 6. Fin whale 20 Hz calls in an LTSA (top) and spectrogram (bottom) recorded at site H.

Beaked Whales

Beaked whales found in the Southern California Bight include Baird's (*Berardius bairdii*), Cuvier's, Blainville's, Stejneger's, Hubbs', Perrin's, and pygmy beaked whales (Jefferson *et al.*, 2008; Jefferson *et al.*, 2015).

Beaked whales can be identified acoustically by their echolocation signals (Baumann-Pickering *et al.*, 2014). These signals are frequency-modulated (FM) upswept pulses, which appear to be species specific and are distinguishable by their spectral and temporal features. Identifiable signals are known for Baird's, Blainville's, Cuvier's, and likely Stejneger's beaked whales (Baumann-Pickering *et al.*, 2013b).

Other beaked whale signals detected in the Southern California Bight include FM pulses known as BW43 and BW70, which may belong to Perrin's and pygmy beaked whales, respectively (Baumann-Pickering *et al.*, 2013a; Baumann-Pickering *et al.*, 2014). A new signal type, BW35, possibly belonging to Hubbs' beaked whales (Griffiths *et al.*, 2018), was searched for. Only Cuvier's, BW43, and BW35 signals were detected during this recording period. These signals are described below in more detail.

Beaked whale FM pulses were detected with an automated method. This automated effort was for all identifiable signals found in Southern California except Baird's beaked whales since they produce a signal with a lower frequency content than is typical of other beaked whales and therefore is not reliably identified by the detector used. After all echolocation signals were identified with a Teager Kaiser energy detector (Soldevilla *et al.*, 2008; Roch *et al.*, 2011b), an expert system discriminated between delphinid clicks and beaked whale FM pulses based on the parameters described below.

A decision about presence or absence of beaked whale signals was based on detections within a 75 second segment. Only segments with more than seven detections were used in further analysis. All echolocation signals with a peak and center frequency below 32 and 25 kHz, respectively, a duration less than 355 μs, and a sweep rate of less than 23 kHz/ms were deleted. If more than 13% of all initially detected echolocation signals remained after applying these criteria, the segment was classified to have beaked whale FM pulses. This threshold was chosen to obtain the best balance between missed and false detections. A third classification step, based on computer assisted manual decisions by a trained analyst, labeled the automatically detected segments to pulse type and rejected false detections (Baumann-Pickering *et al.*, 2013a). The rate of missed segments was approximately 5%. The start and end of each segment containing beaked whale signals was logged and their durations were added to estimate cumulative weekly presence.

Cuvier's Beaked Whales

Cuvier's beaked whale echolocation signals are well differentiated from other species' acoustic signals as polycyclic, with a characteristic FM pulse upsweep, peak frequency around 40 kHz, and uniform inter-pulse interval of about 0.4 – 0.5 s (Johnson *et al.*, 2004; Zimmer *et al.*, 2005; Figure 7). An additional feature that helps with the identification of Cuvier's FM pulses is that they have characteristic spectral peaks around 17 and 23 kHz.

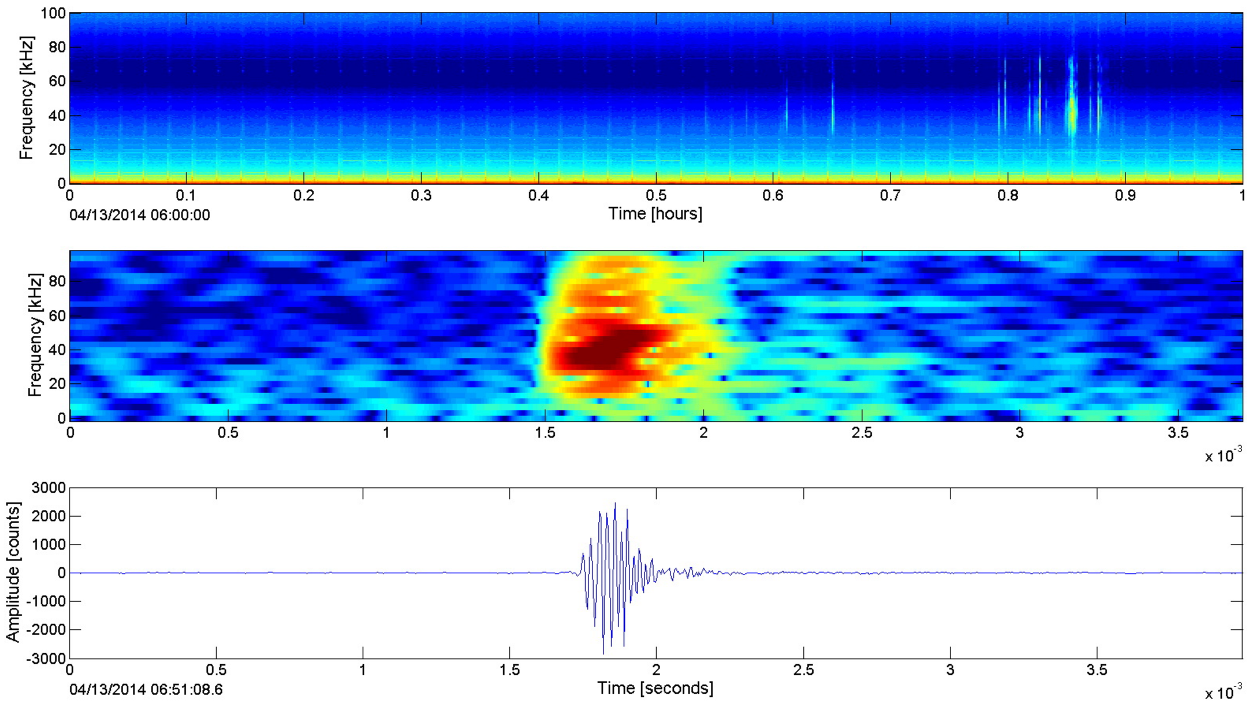

Figure 7. Echolocation sequence of Cuvier's beaked whale in an LTSA (top) and example FM pulse in a spectrogram (middle) and corresponding time series (bottom) recorded at site N.

BW35

The BW35 FM pulse has yet to be positively linked to a specific species. These FM pulses are distinct from other beaked whale species' signals in their bimodal frequency distribution, which shows a prominent spectral peak around 35 kHz, a spectral notch at 37 kHz, and an upper peak at 48 kHz (Griffiths *et al.*, 2018; Figure 8). This signal type has a stable inter-pulse interval of approximately 0.13 s. A candidate species for producing this FM pulse type may be Hubbs' beaked whale (Griffiths *et al.*, 2018).

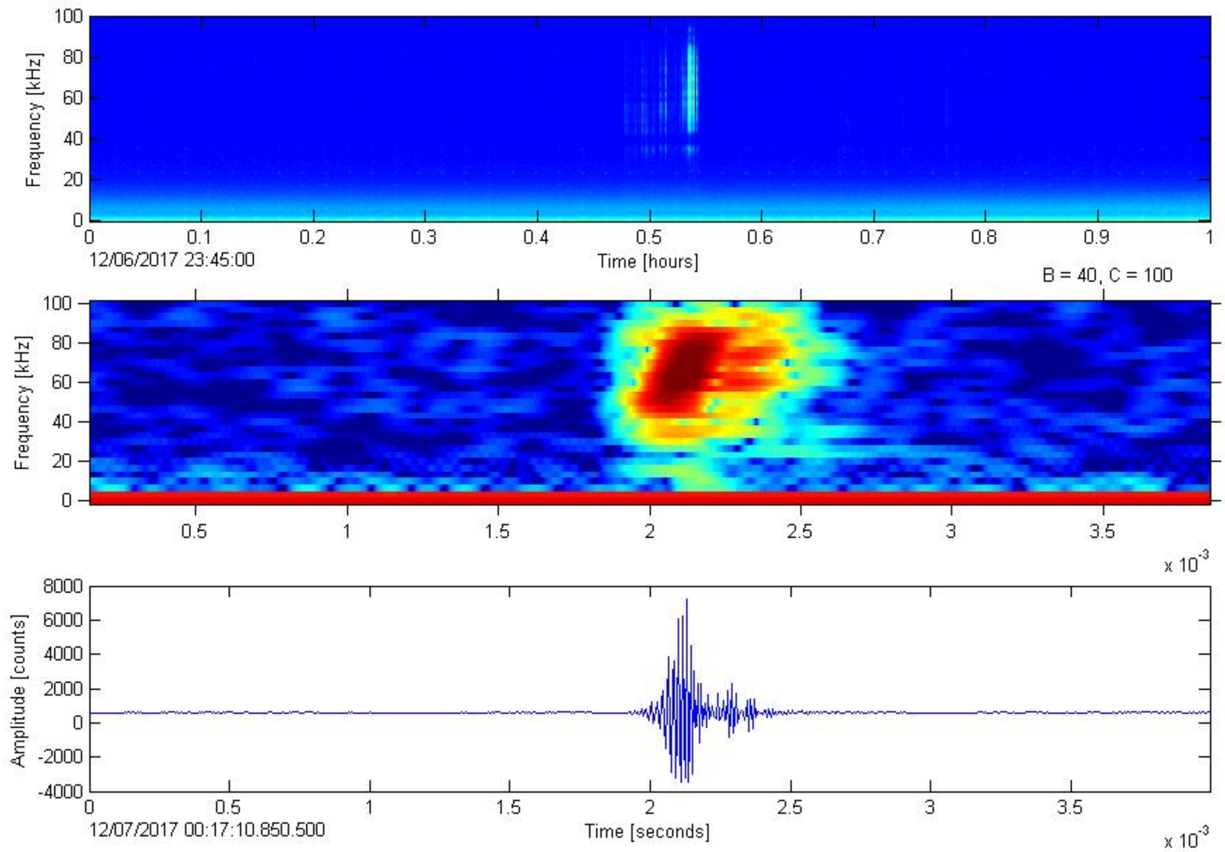

Figure 8. Echolocation sequence of BW35 in an LTSA (top) and example FM pulse in a spectrogram (middle) and corresponding time series (bottom) recorded at site E.

BW43

The BW43 FM pulse has yet to be positively linked to a specific species. These FM pulses are distinguishable from other species' signals by their peak frequency around 43 kHz and uniform inter-pulse interval around 0.2 s (Baumann-Pickering *et al.*, 2013a; Figure 9). A candidate species for producing this FM pulse type may be Perrin's beaked whale (Baumann-Pickering *et al.*, 2014).

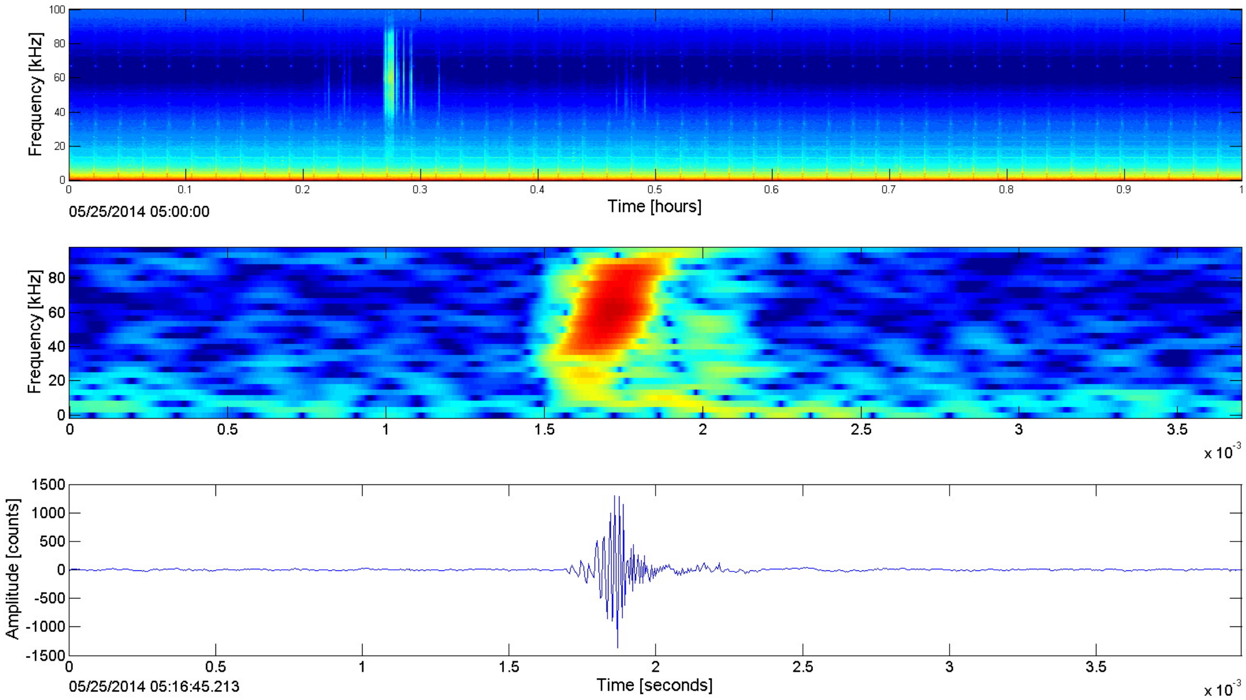

Figure 9. Echolocation sequence of BW43 in an LTSA (top) and example FM pulse in a spectrogram (middle) and corresponding time series (bottom) recorded at site N.

Anthropogenic Sounds

Two anthropogenic sounds were monitored for this report: Mid-Frequency Active (MFA) sonar and explosions. Both sounds were detected by computer algorithms. The start and end of each sound or session was logged and their durations were added to estimate cumulative weekly presence.

Mid-Frequency Active Sonar

Sounds from MFA sonar vary in frequency (1 – 10 kHz) and are composed of pulses of both frequency modulated (FM) sweeps and continuous wave (CW) tones that have durations ranging from less than 1 s to greater than 5 s. Groups of pulses, or pings, constitute a packet while a wave train, or an event, is a group of packets that are separated from other MFA sonar packets by at least 1 h. Packets are transmitted repetitively as wave trains with inter-packet-intervals typically greater than 20 s (Figure 10). In the SOCAL Range Complex, the most common MFA sonar signals are between 2 and 5 kHz and are more generically known as '3.5 kHz' sonar.

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

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

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

Various filters were applied to the detections to limit the MFA sonar detection range to ~20 km for off-axis signals from an AN/SQS 53C source, which resulted in a received level detection threshold of 130 dB pp re 1 μPa (Wiggins, 2015). Instrument maximum received level was ~162 dB pp re 1 μPa, above which waveform clipping occurred. Packets were grouped into wave trains separated by more than 1 hour. Packet received levels were plotted along with the number of packets and cumulative SEL (CSEL) in each wave train over the study period. Wave train duration and total packet duration were also calculated. Wave train duration is the difference between the first and last packet detections in an event. The total packet duration of for a wave train is the sum of the individual packet (i.e., group of pings) durations, which is measured as the period of the waveform that is 0 to 10 dB less than the maximum peak-to-peak received level of the ping group.

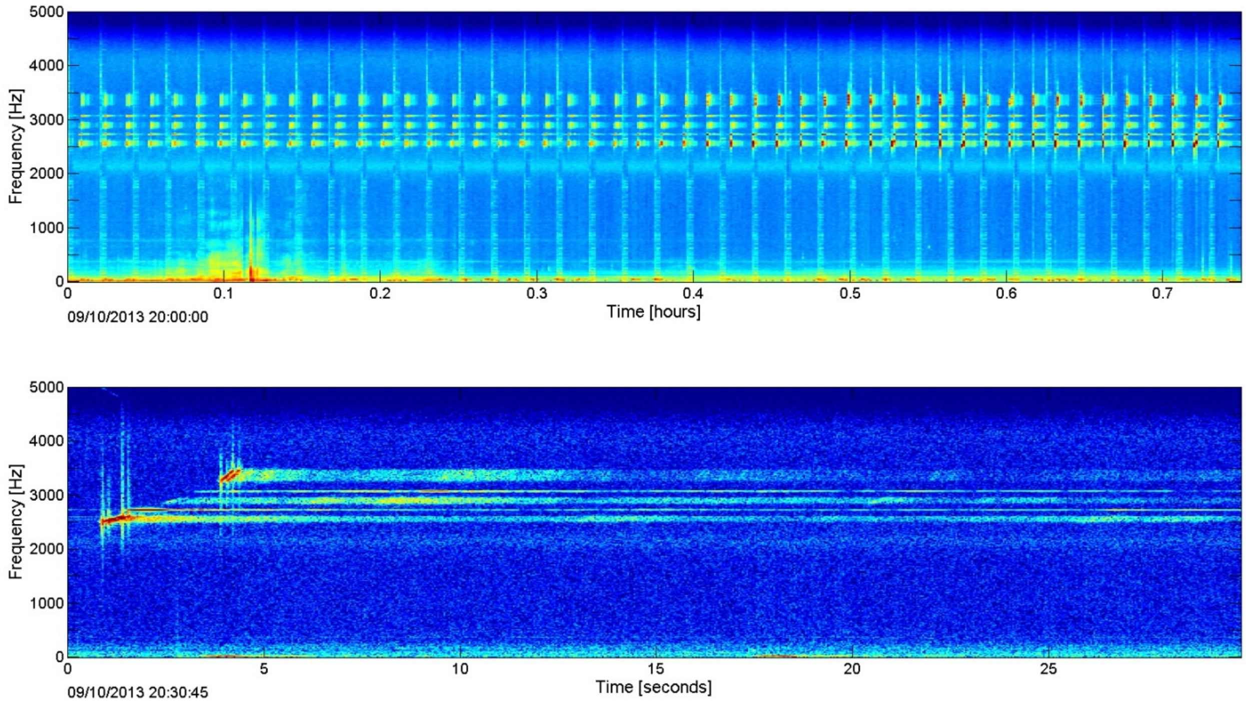

Figure 10. MFA sonar recorded at site H and shown as a wave train event in a 45 minute LTSA (top) and as a single packet with multiple pulses in a 30 second spectrogram (bottom).

Explosions

Effort was directed toward finding explosive sounds in the recordings including military explosions, shots from sub-seafloor exploration, and seal bombs used by the fishing industry. An explosion appears as a vertical spike in the LTSA that, when expanded in the spectrogram, has a sharp onset with a reverberant decay (Figure 11). Explosions were detected automatically for all deployments using a matched filter detector on data decimated to a 10 kHz sampling rate.

The time series was filtered with a 10^{th} order Butterworth bandpass filter between 200 and 2,000 Hz. Cross-correlation was computed between 75 seconds of the envelope of the filtered time series and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the matched filter signal. The cross correlation was squared to 'sharpen' peaks of explosion detections. A floating threshold was calculated by taking the median cross correlation value over the current 75 seconds of data to account for detecting explosions within noise, such as shipping. A cross-correlation threshold of above the median was set. When the correlation coefficient reached above threshold, the time series was inspected more closely.

Consecutive explosions were required to have a minimum time distance of 0.5 seconds to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end of the detection above threshold was determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and RMS RL were computed over the potential detection period and a time series of the length of the explosion template before and after the detection.

The potential detection was classified as false and deleted if: 1) the dB difference pp and RMS between signal and time AFTER the detection was less than 4 dB or 1.5 dB, respectively; 2) the dB difference pp and RMS between signal and time BEFORE signal was less than 3 dB or 1 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 0.55 seconds. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. A trained analyst subsequently verified the remaining detections for accuracy. Explosions have energy as low as 10 Hz and often extend up to 2,000 Hz or higher, lasting for a few seconds including the reverberation.

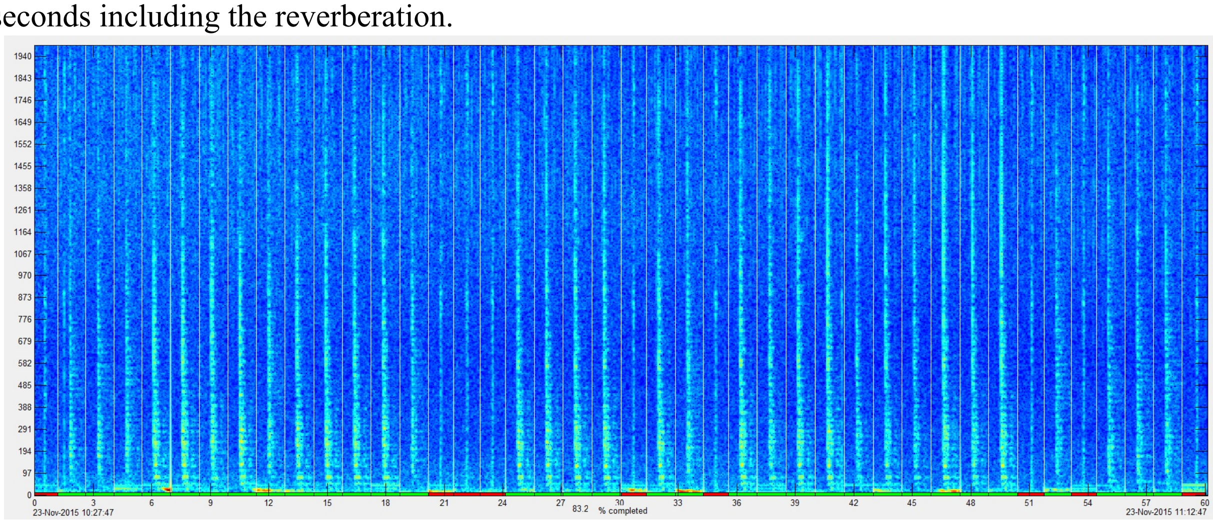

Figure 11. Explosions from site H in the analyst verification stage where events are concatenated into a single spectrogram.
Green along the bottom indicates true and red indicates false detections.

Results

The results of acoustic data analysis at sites E, H, N, and HP from March 2017 to July 2018 are summarized below.

We describe the low-frequency ambient soundscape, the seasonal occurrence, and relative abundance of marine mammal acoustic signals and anthropogenic sounds of interest.

Low-frequency Ambient Soundscape

- The underwater ambient soundscape at all sites had spectral shapes with higher levels at low frequencies, owing to the dominance of ship noise at frequencies below 100 Hz and local wind and waves above 100 Hz (Hildebrand, 2009; Figure 12).
- Site H had the lowest spectrum levels below 100 Hz (Figure 12). This is expected owing to the fact that site H is away from shipping routes and is located in a basin shielded from the deep ocean (McDonald *et al.*, 2008).
- Sites E and N had spectrum levels about 5 dB higher than site H at 10-100 Hz, owing to greater exposure to shipping noise (Figure 12).
- Site HP had overall elevated spectrum levels in comparison to sites E, H, and N, particularly in frequencies above 30 Hz, likely due to increased local small boat activity closer to shore (Figure 12).
- Prominent peaks in sound spectrum levels observed in the frequency band 15-30 Hz during fall and winter at sites E, H, and N are related to seasonally increased presence of fin whale calls, with highest levels at sites E and N (Figure 12).
- Spectral peaks around 45-47 Hz from July to December at sites E, H, and N are related to blue whale B calls (Figure 12).
- Spectral peaks around 500 Hz occur during summer 2017 at site HP and again in late winter and spring at sites E and N (Figure 12). These peaks are believed to be from a currently unidentified biological source, likely a fish chorus.

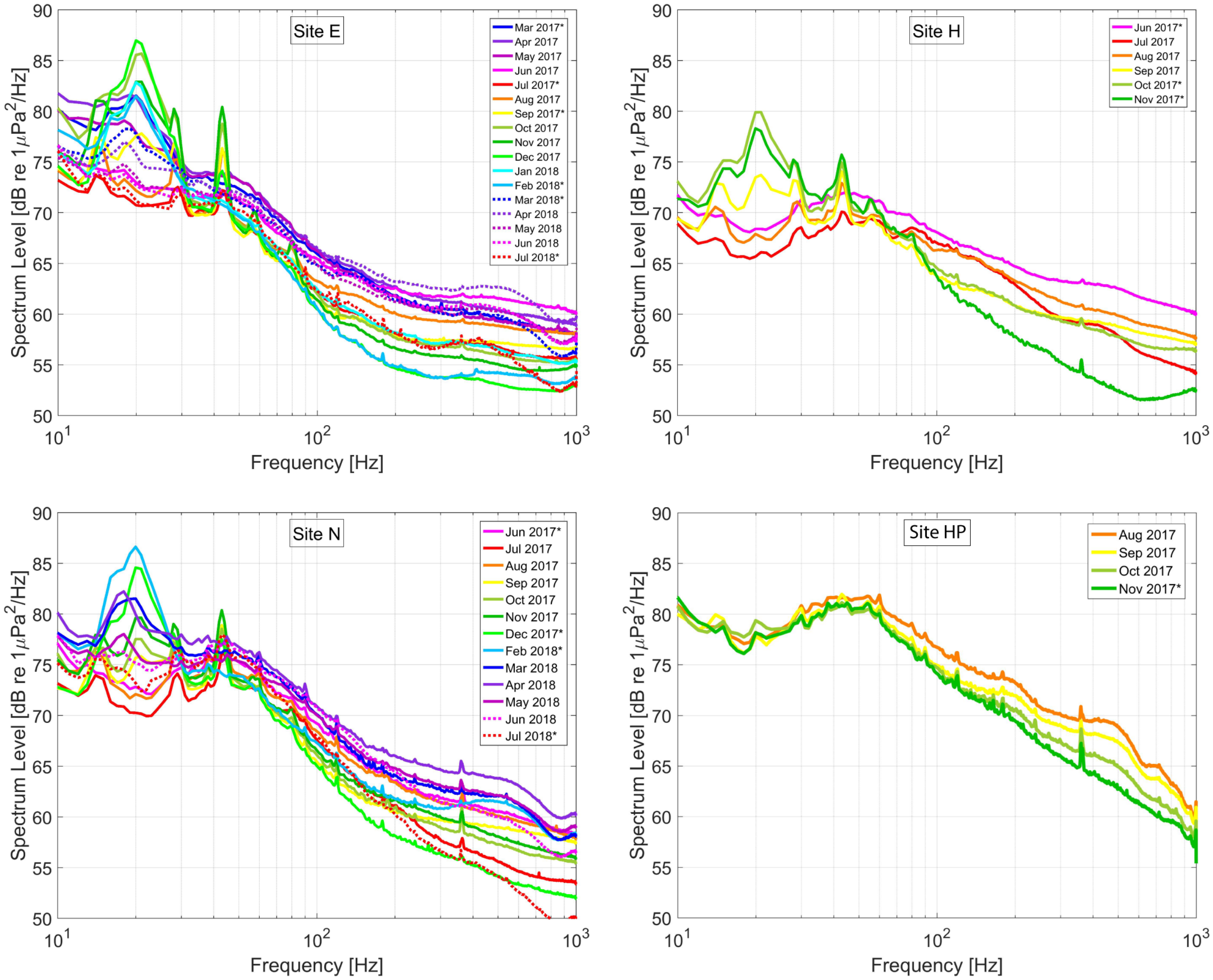

Figure 12. Monthly averages of sound spectrum levels at sites E, H, N, and HP. Legend gives color-coding by month. * denotes months with partial (< 90%) effort.

Mysticetes

Blue and fin whales were detected using automated methods between March 2017 and July 2018. In general, fewer baleen whale vocalizations were detected at site HP. More details of each species' presence are given below.

Blue Whales

Blue whale calls were detected at all sites and were most prevalent during the summer and fall.

- Northeast (NE) Pacific blue whale B calls were typically detected from summer through early winter with a peak in September at all sites. Though site E had a peak in September, there was an additional, larger peak in November (Figure 13).
- Site HP had a substantially lower number of NE Pacific B call detections than sites E, H, and N (Figure 13).
- There was no discernable diel pattern for the NE Pacific B calls (Figure 14).
- The fall peak in NE Pacific B calls is consistent with earlier recordings at these sites (Kerosky *et al.*, 2013; Debich *et al.*, 2015a; Debich *et al.*, 2015b; Širović *et al.*, 2016; Rice *et al.*, 2017; Rice *et al.*, 2018)
- D call detections occurred between March and December but were highest during June and July 2017 at sites H and N. D calls were detected in low numbers throughout most of the year at site E. The lowest number of detections occurred at site HP (Figure 15).
- There was no clear D call diel pattern at any site, though in the spring of 2017 at site N there appears to be an increase in D calls around sunset and sunrise, with decreased calling during the night (Figure 16)
- The spring/summer peak in D calls is consistent with earlier recordings at these sites, though there were a higher number of D calls at site N than in previous recordings (Debich *et al.*, 2015b; Rice *et al.*, 2017; Rice *et al.*, 2018).

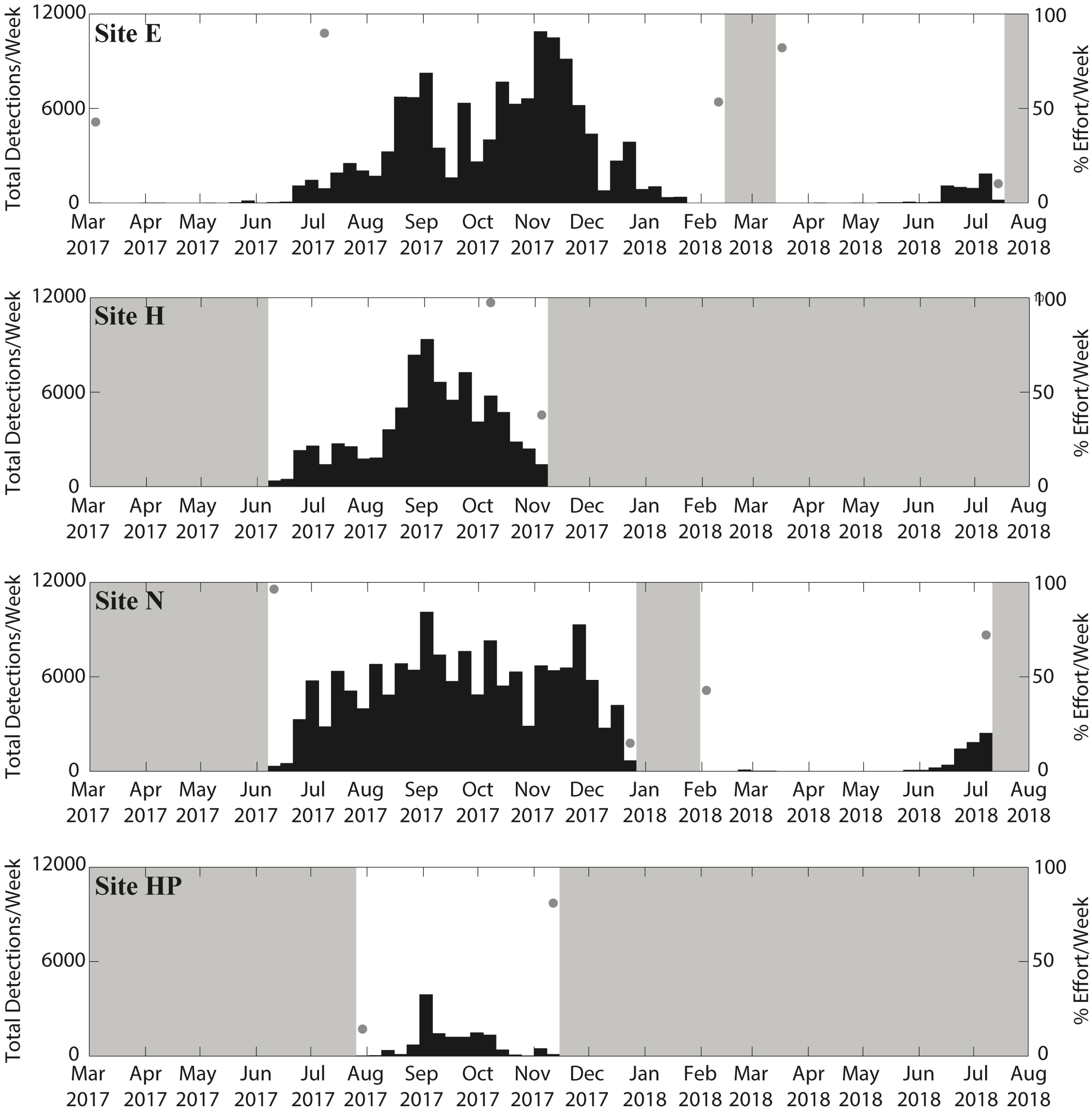

Figure 13. Weekly presence of NE Pacific blue whale B calls between March 2017 and July 2018 at sites E, H, N, and HP.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

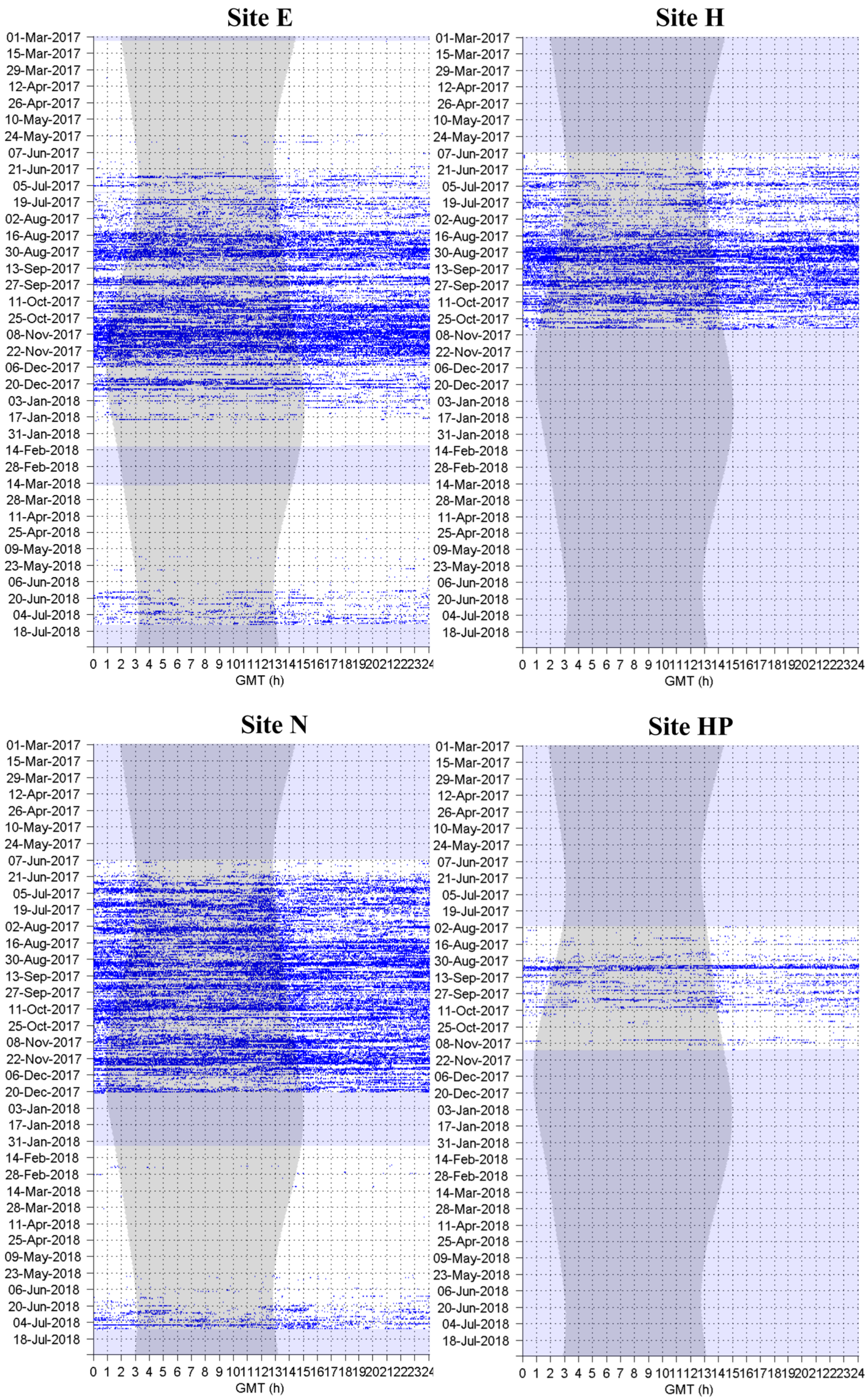

Figure 14. Diel presence of NE Pacific blue whale B calls, indicated by blue dots, in one-minute bins at sites E, H, N, and HP.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

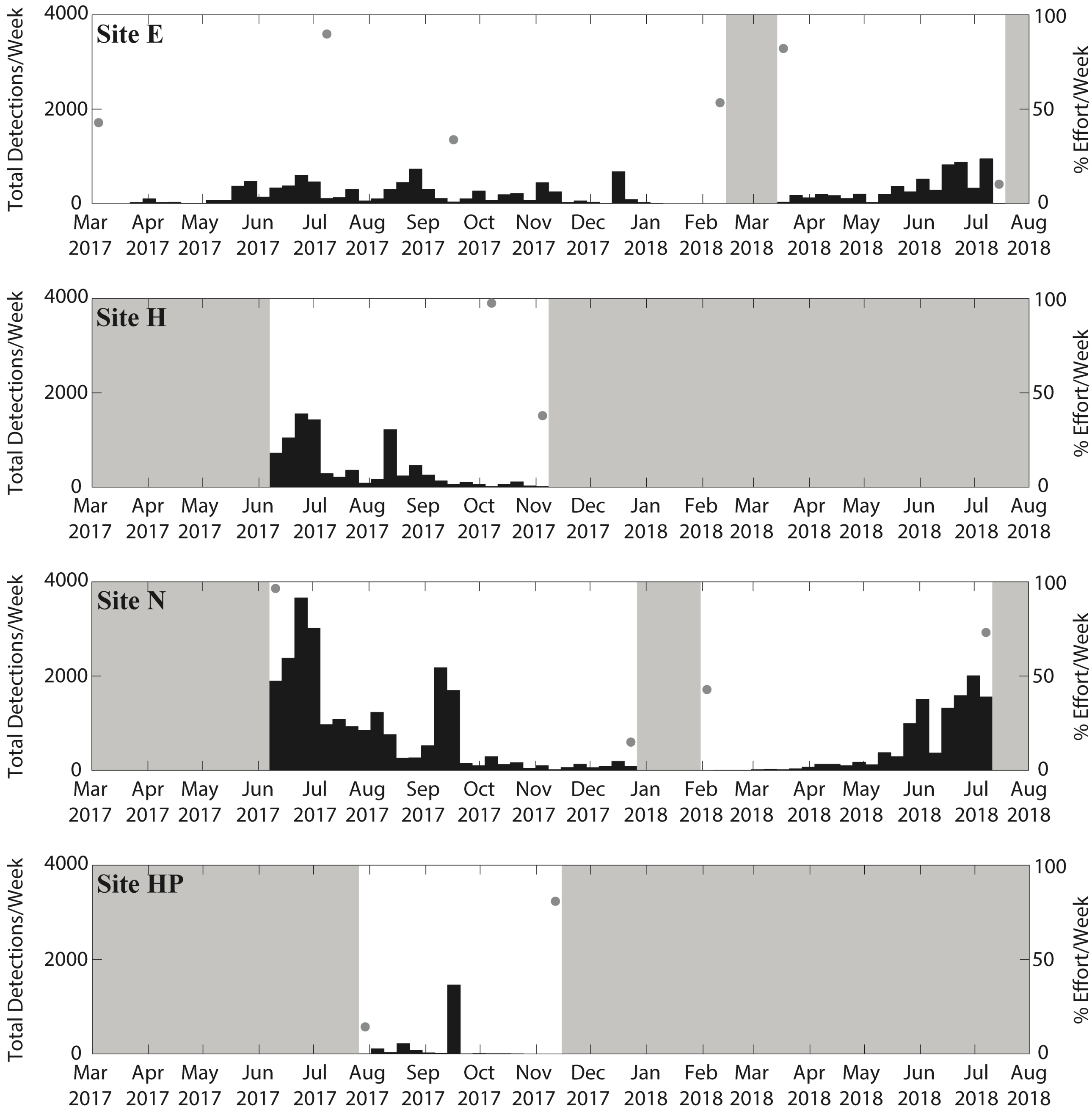

Figure 15. Weekly presence of NE Pacific blue whale D calls between March 2017 and July 2018 at sites E, H, N, and HP.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

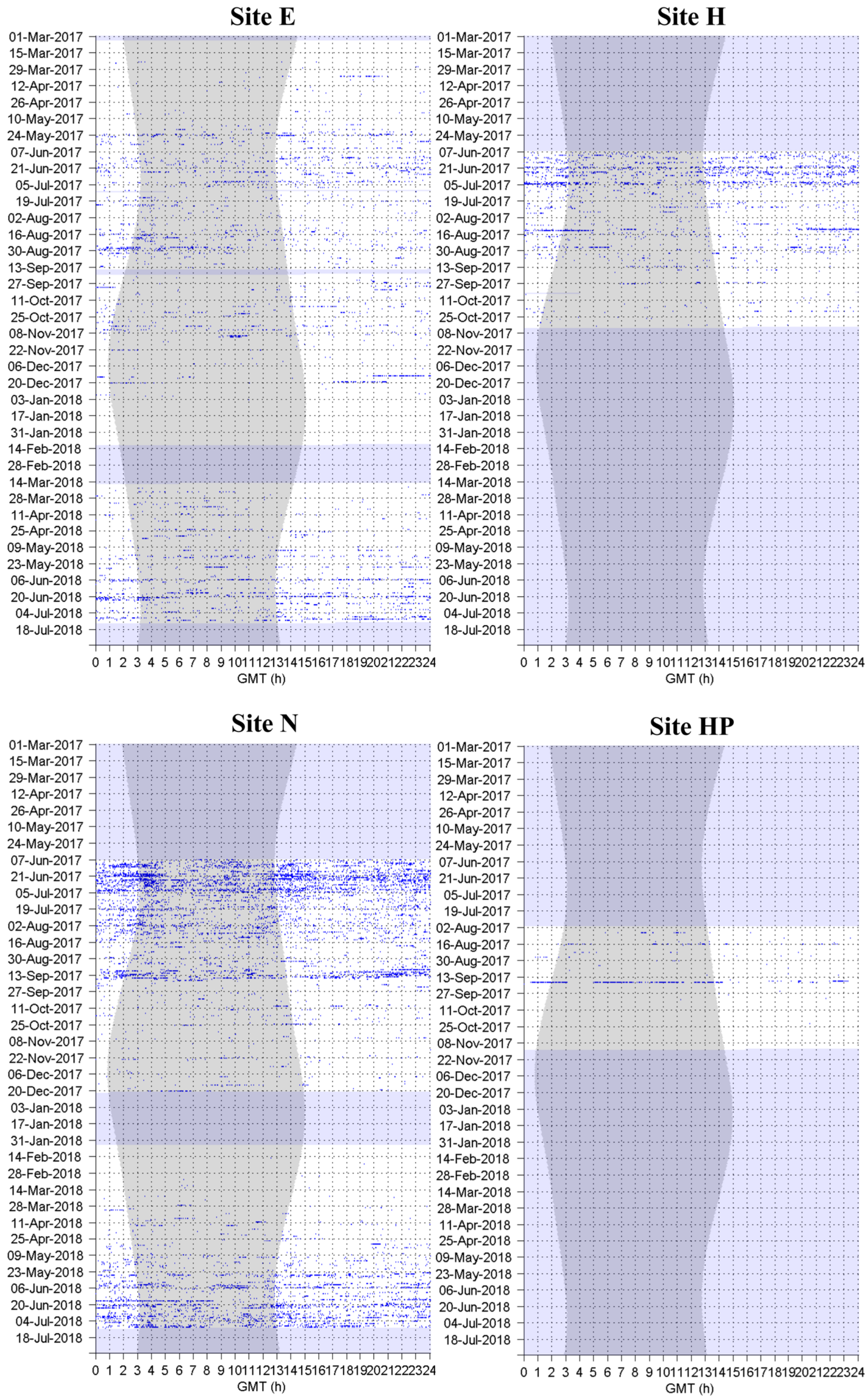

Figure 16. Diel presence of NE Pacific blue whale D calls, indicated by blue dots, in one-minute bins at sites E, H, N and HP.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

Fin Whales

Fin whales were detected throughout the recordings at all sites.

- The highest values of the fin whale acoustic index (representative of 20 Hz calls) were measured at site E (Figure 17).
- A peak in the fin whale acoustic index occurred in December 2017 at sites E and N. At site H, the acoustic index increased from September to November, when recording ended. Site HP had low acoustic index values overall (Figure 17).
- The winter peak in the fin whale acoustic index is consistent with earlier recordings (Debich *et al.*, 2015a; Debich *et al.*, 2015b; Širović *et al.*, 2016; Rice *et al.*, 2017; Rice *et al.*, 2018)

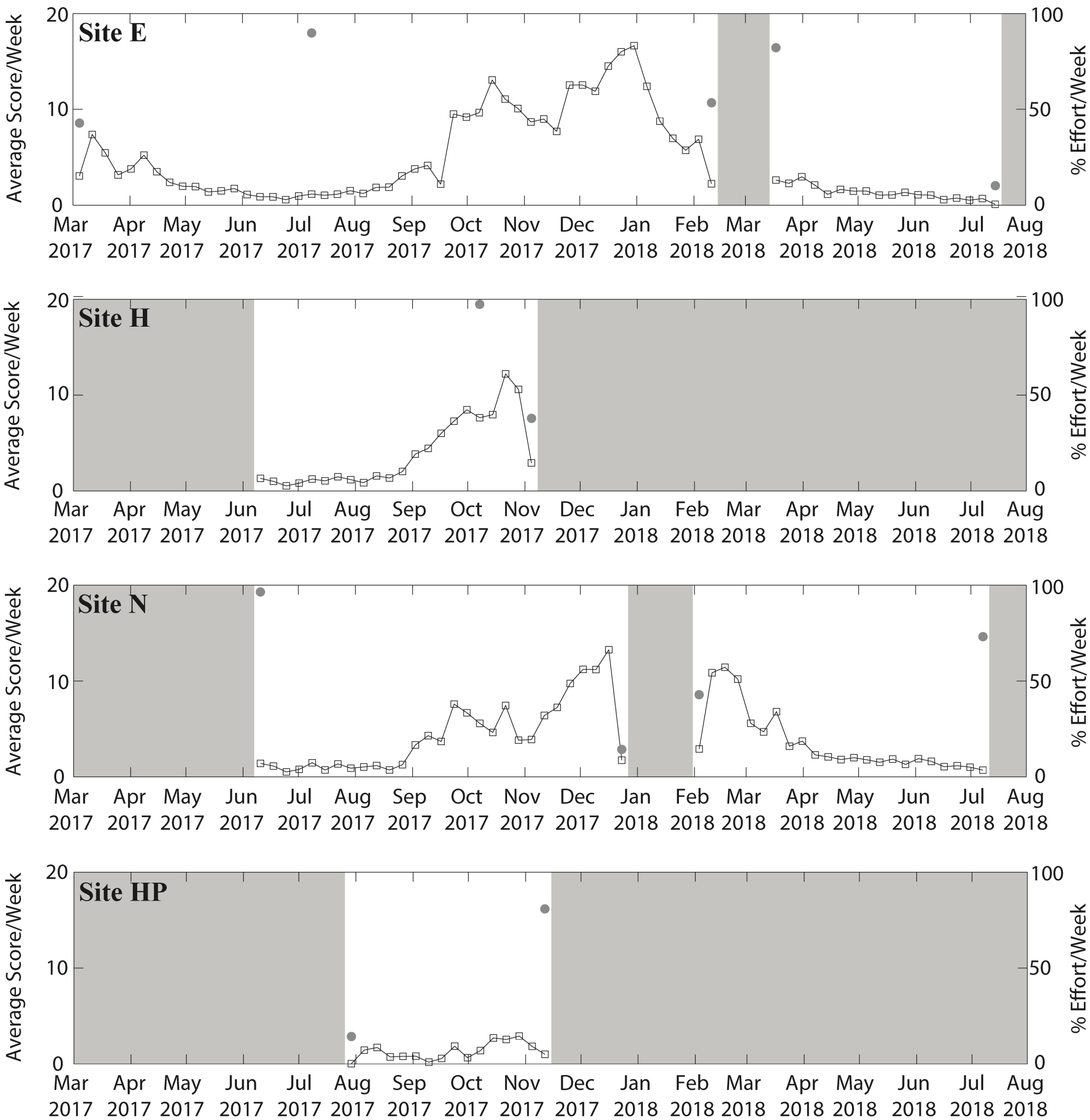

Figure 17. Weekly value of fin whale acoustic index (proxy for 20 Hz calls) between March 2017 and July 2018 at sites E, H, N, and HP.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

Beaked Whales

Cuvier's beaked whales were detected throughout the deployment period. The FM pulse type, BW35, possibly produced by Hubbs' beaked whales (Griffiths *et al.*, 2018) was detected only once at site E and once at site H. The FM pulse type, BW43, possibly produced by Perrin's beaked whales (Baumann-Pickering *et al.*, 2014) was detected only occasionally at site N. No other beaked whale species were detected during this recording period. More details of each species' presence at the three sites are given below (there was no effort for beaked whales at site HP due to the lower sampling rate of the instrument).

Cuvier's Beaked Whales

Cuvier's beaked whale was the most commonly detected beaked whale.

- Cuvier's beaked whale FM pulses were detected in high numbers at site E and in much lower number at sites H and N (Figure 18).
- Detections peaked during spring 2017, winter 2018, and again in spring 2018 at site E. Smaller peaks during these periods can also be seen at sites H and N (Figure 18).
- There was no discernable diel pattern for Cuvier's beaked whale detections (Figure 19).
- Overall the results were consistent with pervious monitoring periods (Kerosky *et al.*, 2013; Debich *et al.*, 2015a; Debich *et al.*, 2015b; Širović *et al.*, 2016), though there were fewer detections at site H and N than during recent monitoring periods (Rice *et al.*, 2017; Rice *et al.*, 2018).

BW35

There were very few detections of BW35 FM pulses with only 3 detections on 2 days between March 2017 and July 2018.

- BW35 FM pulses were only detected at site E on December 7, 2017 and on August 10, 2017 at site H. There were no detections at site N (Figure 20).
- There were not enough BW35 detections to determine if there was a diel pattern (Figure 21).
- This is the first time this FM pulse type has been recorded during a SOCAL monitoring period.

BW43

Detections of BW43 FM pulses were intermittent throughout the recording period at site N.

- BW43 FM pulses were only detected at site N and detections occurred intermittently throughout the year. The majority of detections occurred during spring 2018 (Figure 22). There were no detections at sites E or H.
- There was no discernable diel pattern for BW43 detections (Figure 23).
- There were no detections at site H as there were during some previous monitoring periods (Širović *et al.*, 2016; Rice *et al.*, 2017) but the overall results are consistent with previous reports (Kerosky *et al.*, 2013; Debich *et al.*, 2015a; Debich *et al.*, 2015b; Rice *et al.*, 2018).

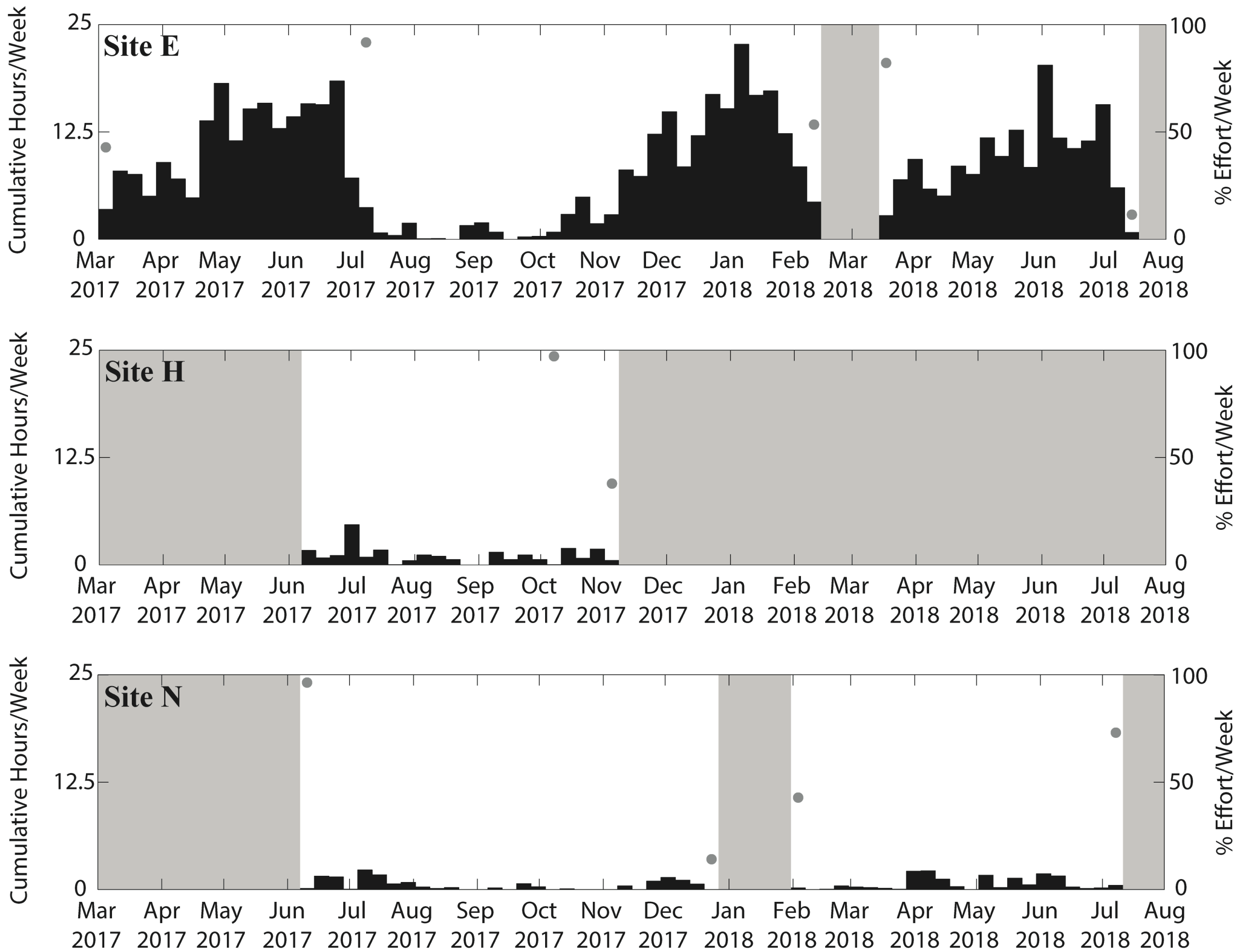

Figure 18. Weekly presence of Cuvier's beaked whale FM pulses between March 2017 and July 2018 at sites E, H, and N.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

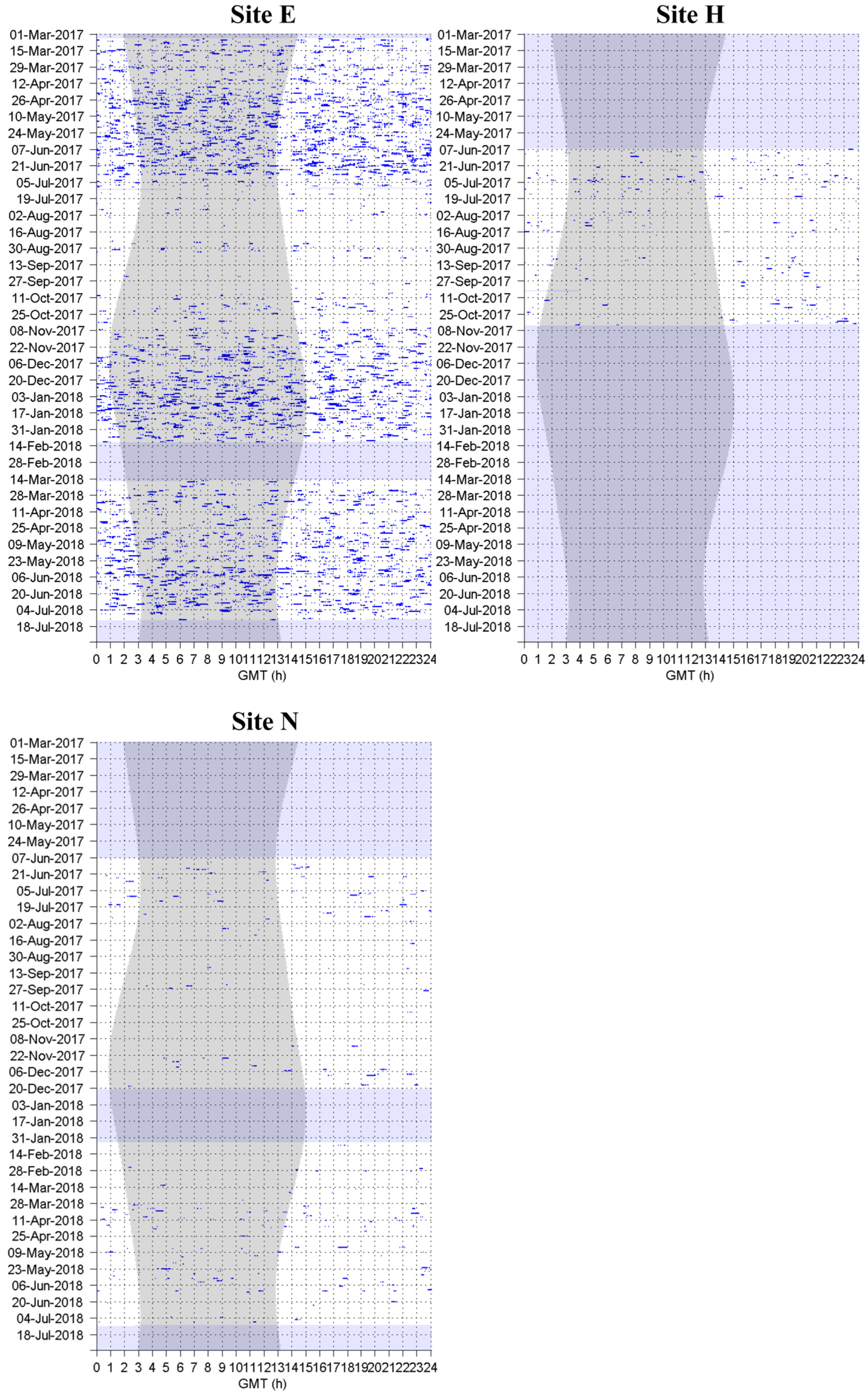

Figure 19. Cuvier's beaked whale FM pulses, indicated by blue dots, in one-minute bins at sites E, H, and N.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

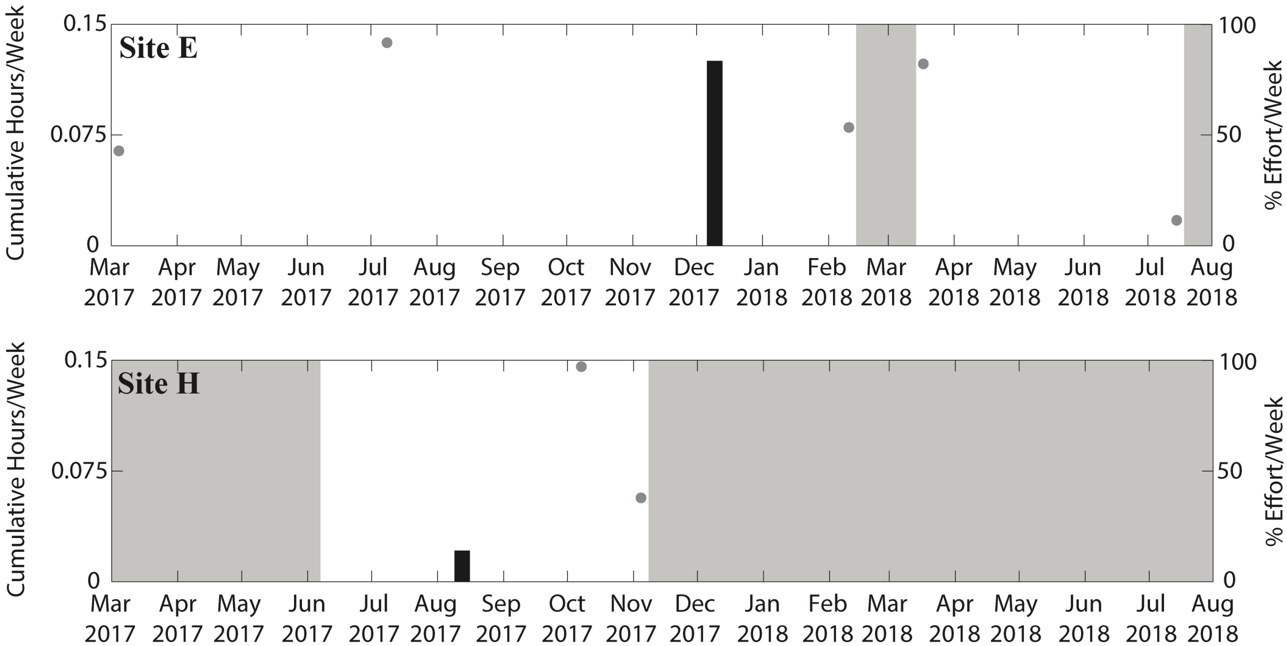

Figure 20. Weekly presence of BW35 FM pulses between March 2017 and July 2018 at sites E and H. There were no detections at site N.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

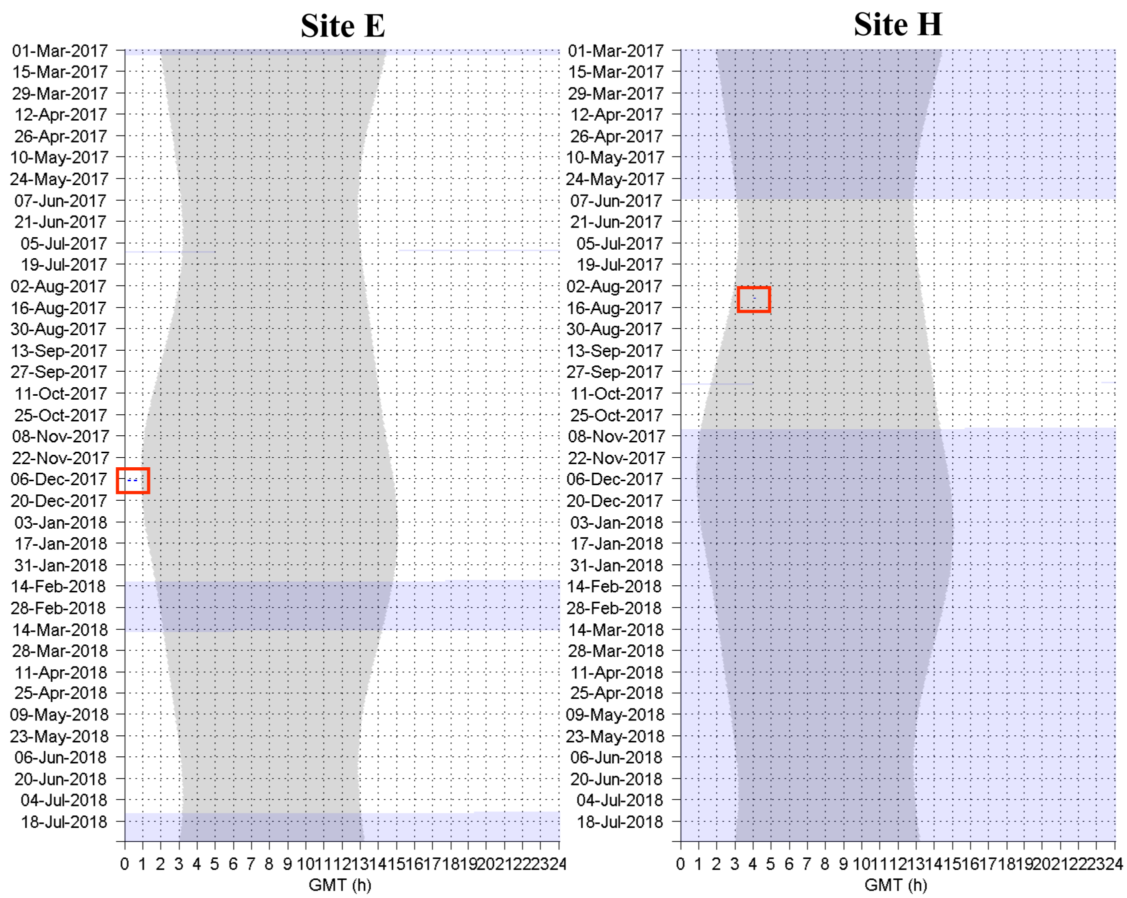

Figure 21. BW35 FM pulses, indicated by blue dots, in ten-minute bins at sites E and H. There were no detections at sites N.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

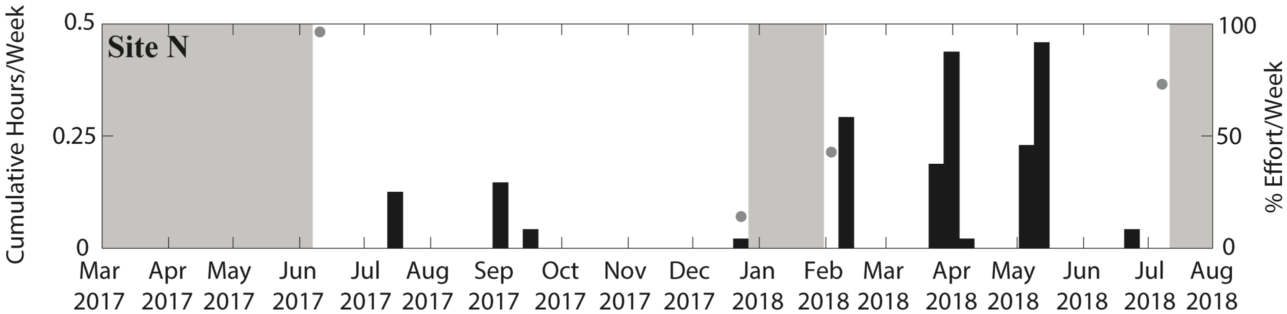

Figure 22. Weekly presence of BW43 FM pulses between June 2017 and July 2018 at site N. There were no detections at sites E and H.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

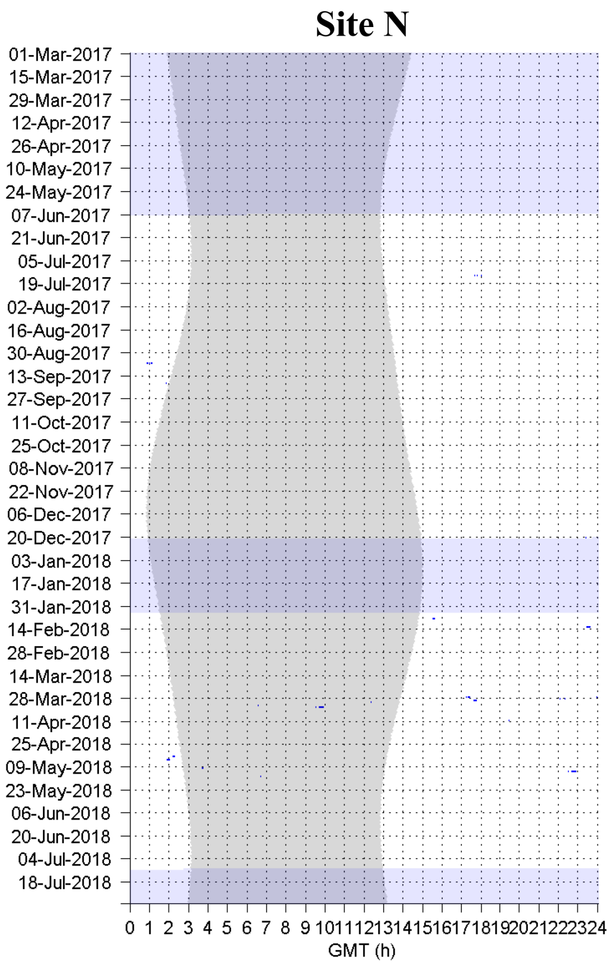

Figure 23. BW43 FM pulses, indicated by blue dots, in one-minute bins at site N. There were no detections at sites E and H.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

Anthropogenic Sounds

Anthropogenic sounds from MFA sonar (2.4 – 4.5 kHz) and explosions, between March 2017 and July 2018, were analyzed for this report.

Mid-Frequency Active Sonar

MFA sonar was a commonly detected anthropogenic sound. The dates of major naval training exercises that were conducted in the SOCAL region between March 2017 and July 2018 are listed in Table 3 (C. Johnson, personal communication). Sonar usage outside of designated major exercises is likely attributable to unit-level training. The automatically detected packets and wave trains show the highest level of MFA sonar activity (>130 dB_{pp} re 1 µPa) when normalized per year at site N, followed by site H, site E, and then site HP (Table 4).

- MFA sonar was detected at all four sites. Detections occurred throughout the recordings at all sites, but peaked in August 2017 at sites E and N (Figure 24).
- During periods without major naval training exercises, bouts of MFA sonar seem to typically begin an hour or so following sunrise, but they could persist throughout the night (Figure 25).
- At site E, a total of 773 packets were detected, with a maximum received level of 169 dB_{pp} re 1 µPa (Figure 26). Total wave train duration was around 17 h (Figure 29) but the total packet duration was only about 0.5 h (1,773 s; Table 4; Figure 30).
- At site H, a total of 3,102 packets were detected, with a maximum received level of 163 dB_{pp} re 1 µPa (Figure 26). Total wave train duration was around 68 h (Figure 29) but the total packet duration was only about 1.6 h (5,694 s; Table 4; Figure 30).
- At site N, a total of 8,401 packets were detected, with a maximum received level of 165 dB_{pp} re 1 µPa (Figure 26). Total wave train duration was around 180 h (Figure 29) but the total packet duration was only about 5.8 h (20,976 s; Table 4; Figure 30).
- At site HP, a total of 50 packets were detected, with a maximum received level of 152 dB_{pp} re 1 µPa (Figure 26). Total wave train duration was around 0.5 h (Figure 29) but the total packet duration was only about 0.03 h (99 s; Table 4; Figure 30).
- Maximum cumulative sound exposure levels of wave trains occurred during August 2017 at site N and were greater than 170 dB re 1 μPa^2-s. At site E, maximum levels were also above 170 dB re 1 μPa^2-s and occurred in April 2017. At site H, maximum levels were around 167 dB re 1 μPa^2-s and occurred in September 2017. At site HP maximum levels were around 150 dB re 1 μPa^2-s and occurred during November 2017 (Figure 27).
- Most MFA sonar wave trains occurred at site N in August 2017 during a major training exercise (Figure 28).

Table 3. Major naval training exercises in the SOCAL region between March 2017 and July 2018.

Exercise Dates
28 March to 24 April 2017
1 to 17 May 2017
1 to 31 August 2017
13 to 27 October 2017
17 May to 15 June 2018

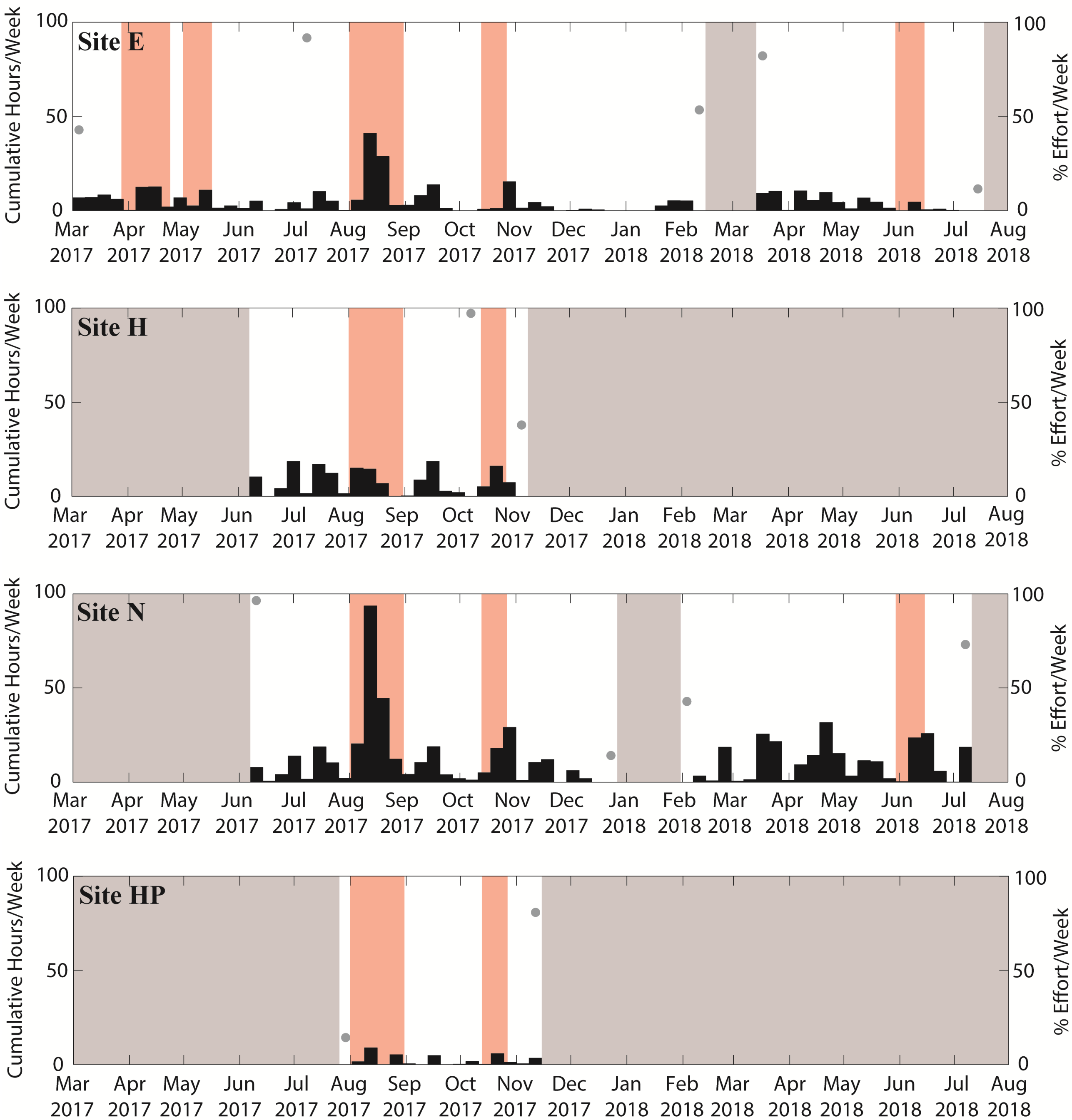

Figure 24. Major naval training events (shaded pink, from Table 3) overlaid on weekly presence of MFA sonar <5kHz between March 2017 and July 2018 at sites E, H, N, and HP.
Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

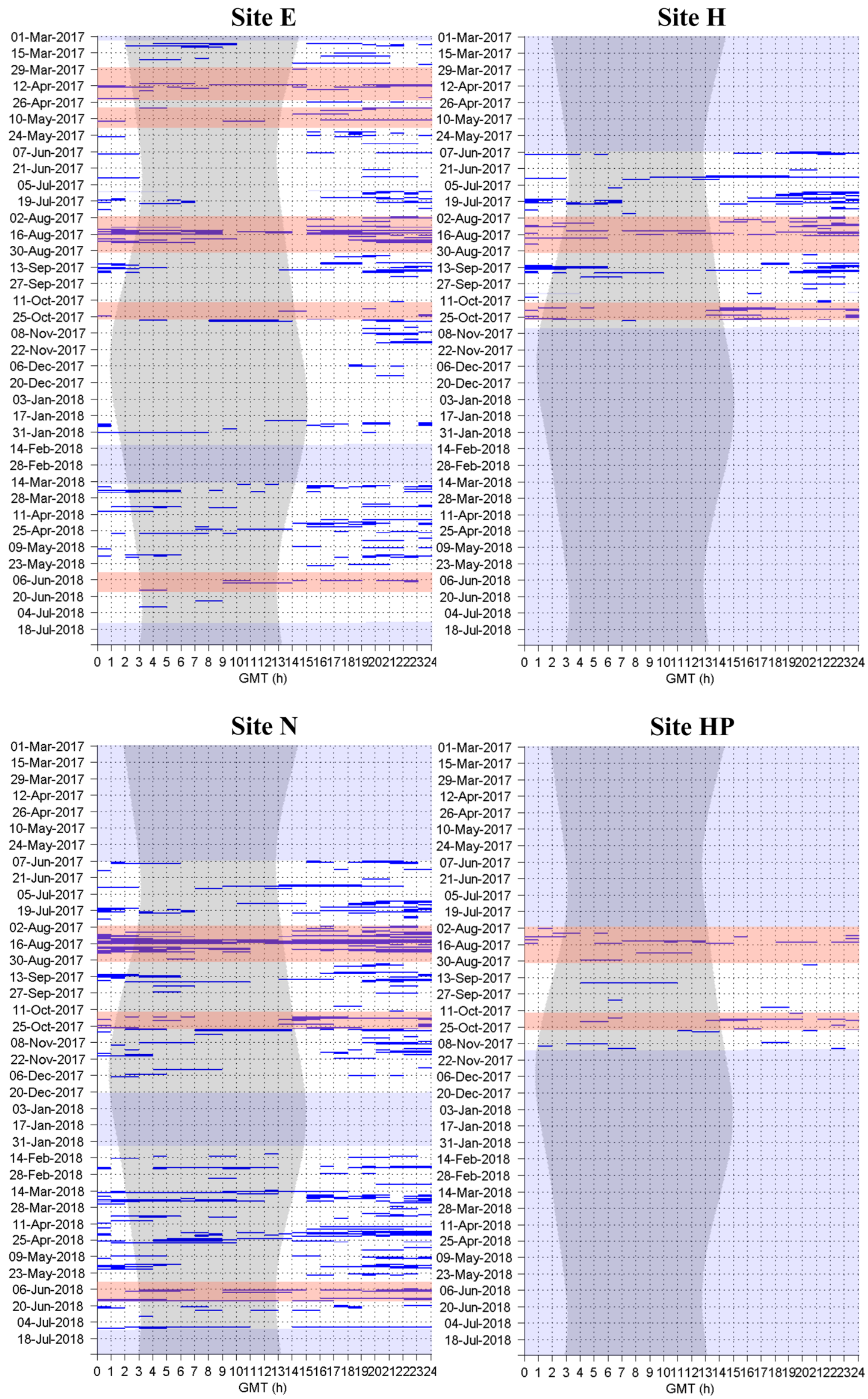

Figure 25. Major naval training events (shaded pink, from Table 3) overlaid on MFA sonar <5kHz signals, indicated by blue dots, in one-hour bins at sites E, H, N, and HP.
Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

Table 4. MFA sonar automated detector results for sites E, H, N, and HP.
Total effort at each site in days (years), number of and extrapolated yearly estimates of wave trains and packets at each site (> 130 dB_{pp} re 1 µPa), total wave train duration, and total packet duration.

Site	Period Analyzed Days (Years)	Number of Wave Trains	Wave Trains per year	Number of Packets	Packets per year	Total Wave Train Duration (h)	Total Packet Duration (s)
E	461 (1.26)	13	10	773	613	17.3	1,773
H	149 (0.41)	37	90	3,102	7,566	68	5,694
N	352 (0.96)	97	101	8,401	8,751	179.5	20,976
HP	105 (0.28)	2	7	50	179	0.46	99

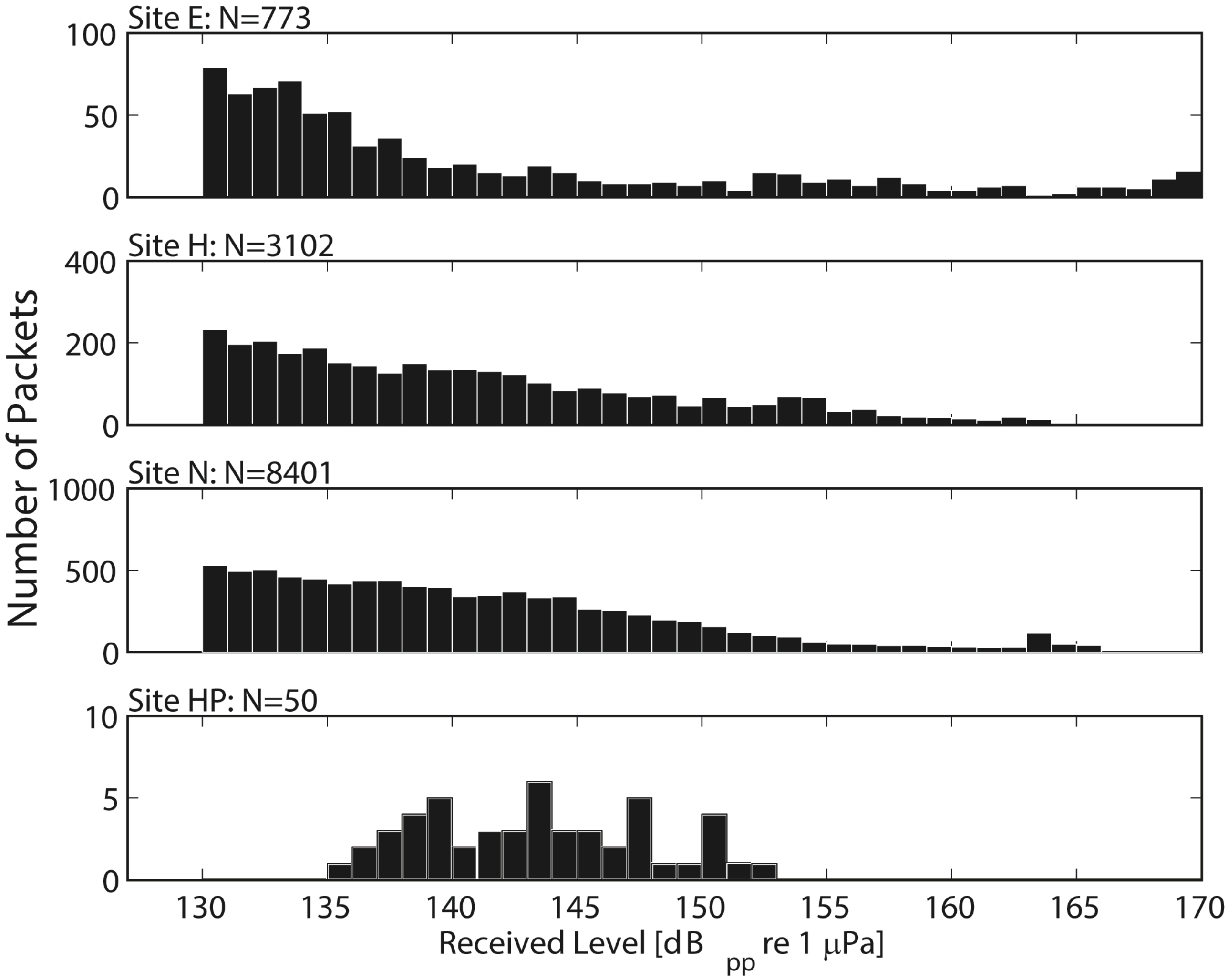

Figure 26. MFA sonar packet peak-to-peak received level distributions for sites E, H, N, and HP. The total number of packets detected at each site is given in the upper left corner of each panel. Instrument clipping levels are reached around 161-169 dBpp re 1 µPa, depending on hydrophone configuration. Note the vertical axes are at different scales.

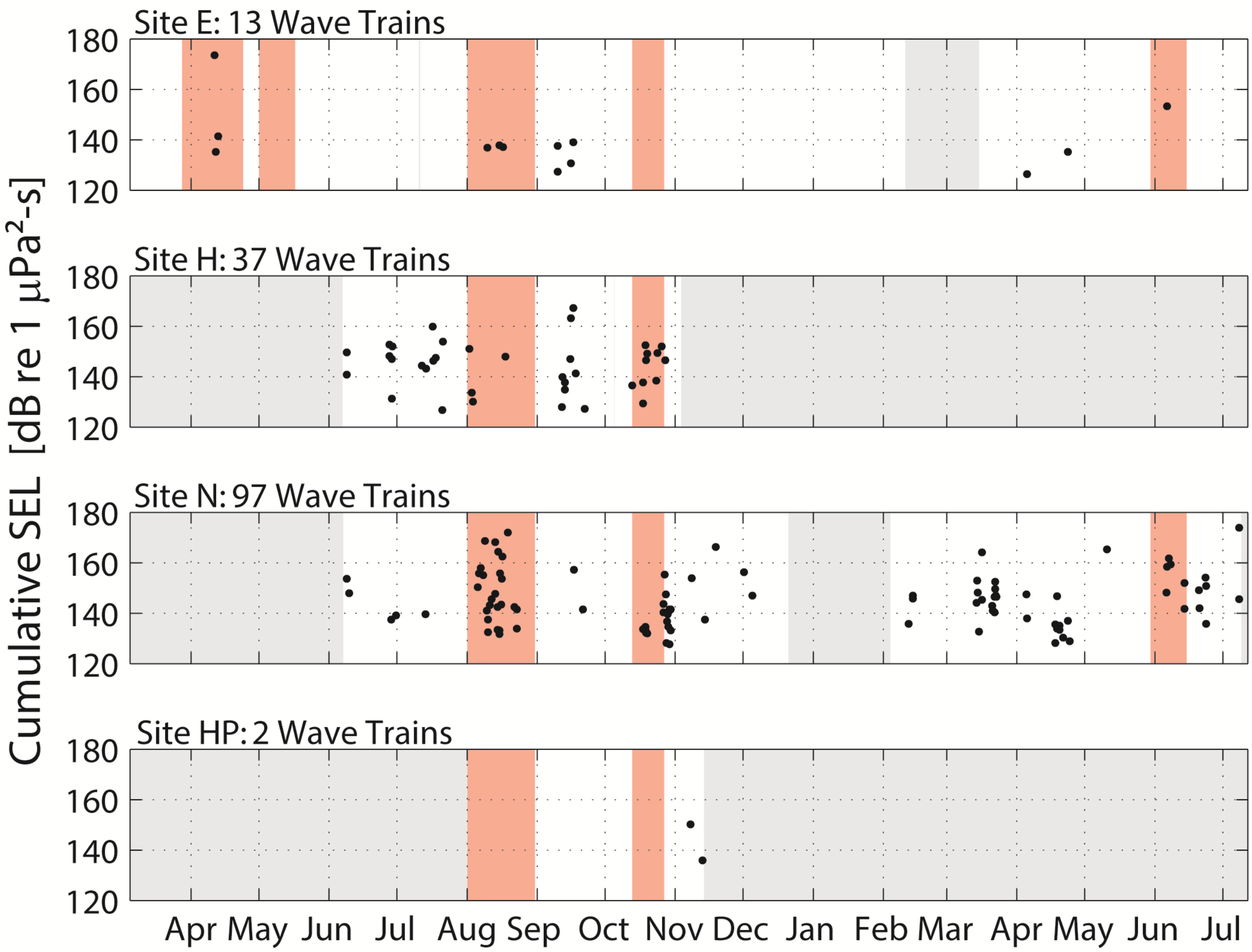

Figure 27. Cumulative sound exposure level for each wave train at sites E, H, N, and HP.

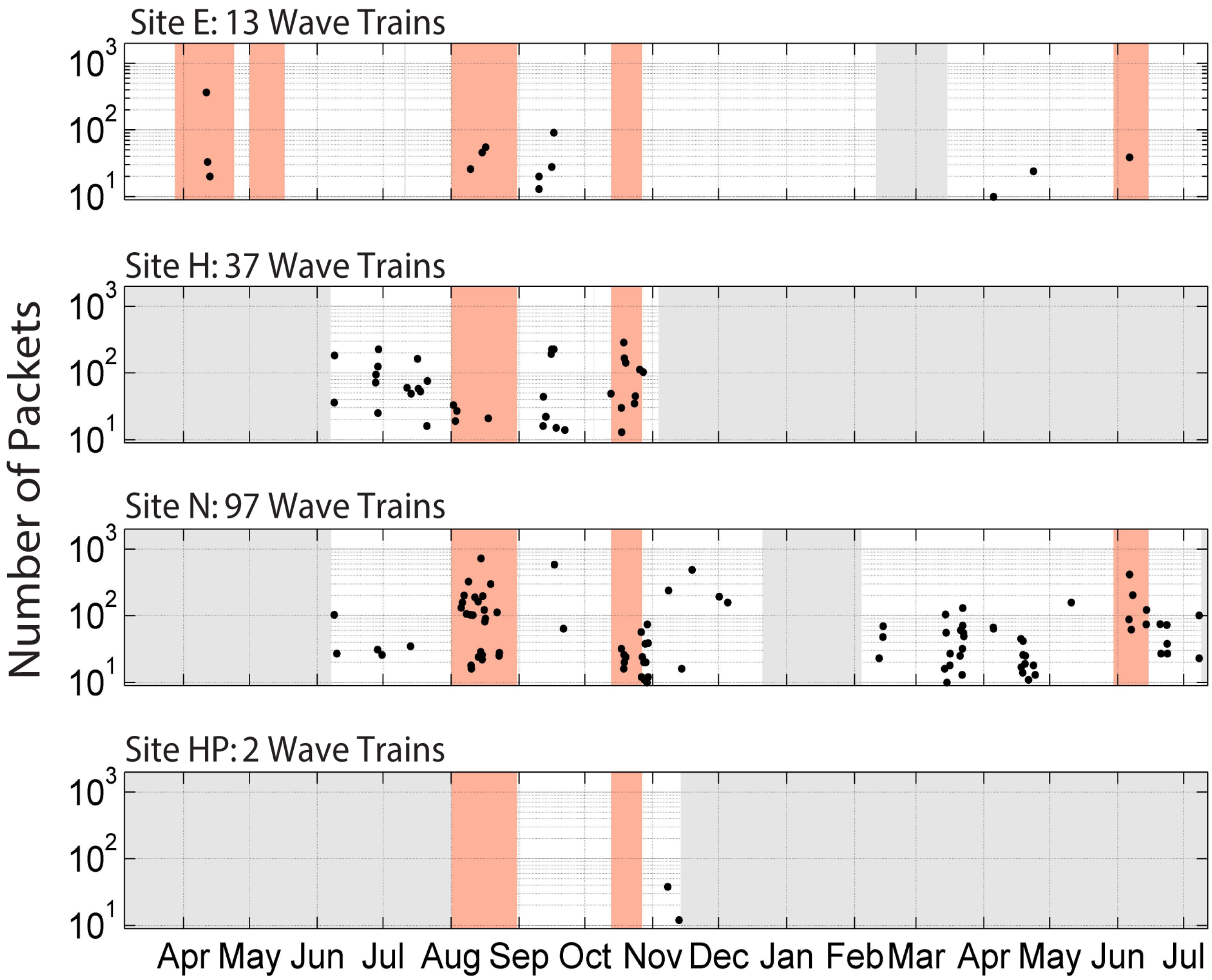

Figure 28. Number of MFA sonar packets for each wave train at sites E, H, N, and HP. Note the vertical axes are logarithmic base-10.

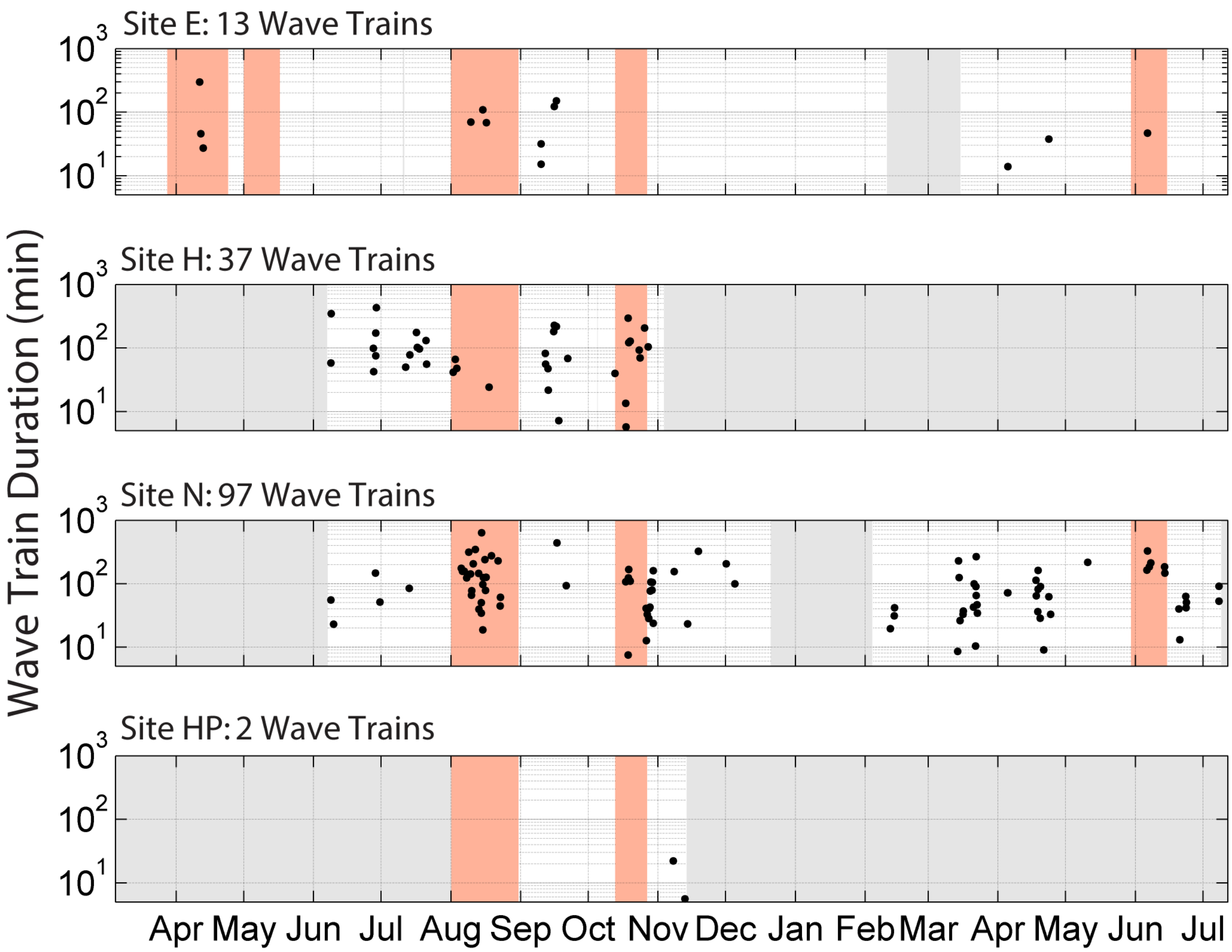

Figure 29. Wave train duration at sites E, H, N, and HP.
Note the vertical axes are logarithmic base-10.

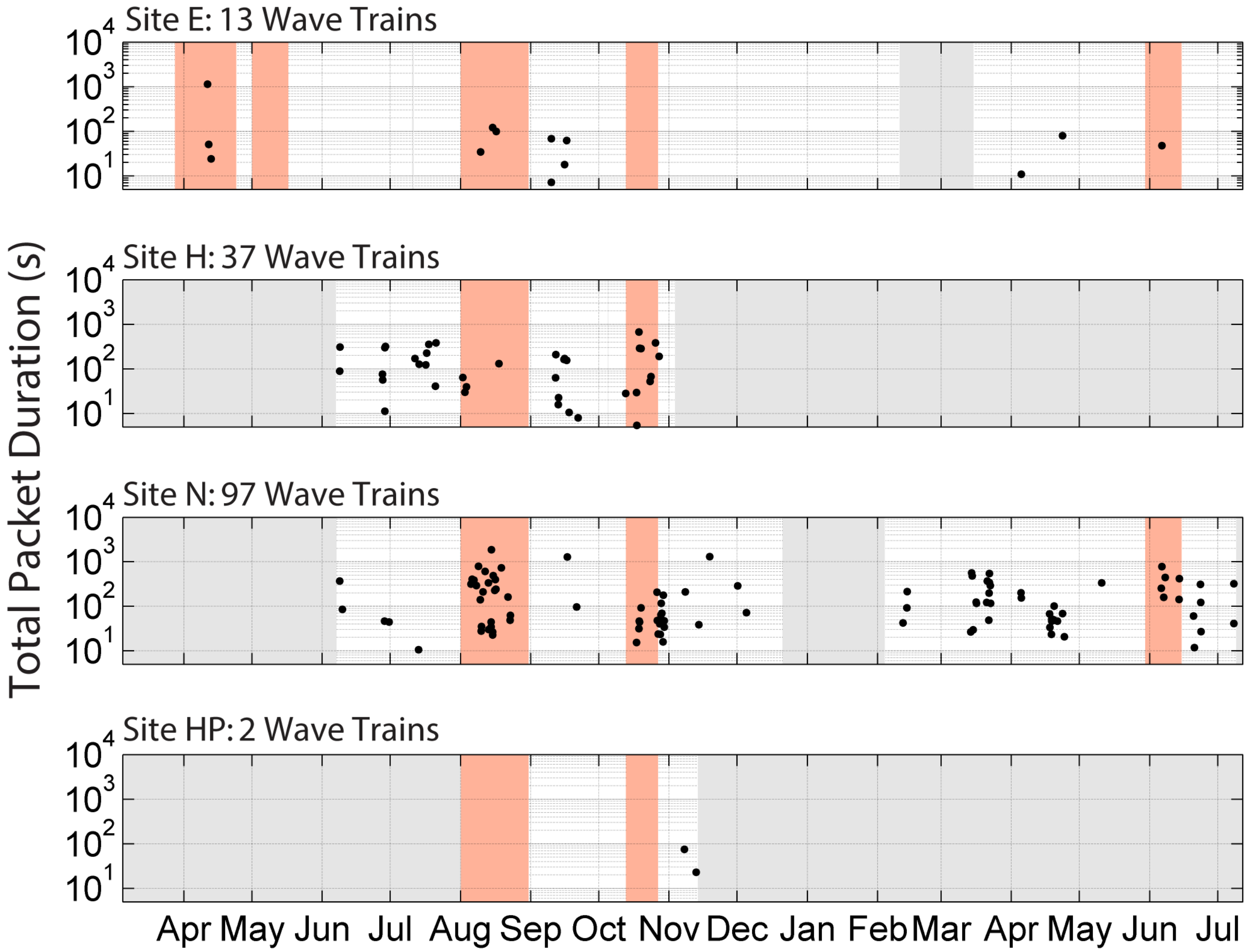

Figure 30. Total packet duration for each wave train at sites E, H, N, and HP. Note the vertical axes are logarithmic base-10.

Explosions

Explosions were detected at all four sites.

- Explosions occurred throughout the monitoring period at all sites. The highest number of explosions occurred at site H, with a peak in July 2017, and the lowest number of detections occurred at site E (Figure 31).
- Total explosion counts at each site were as follows:
    - 45 at site E
    - 4,331 at site H
    - 415 at site N
    - 134 at site HP
- There were more explosions at night at site H in 2017, but overall there was no clear diel pattern present at any site (Figure 32).
- The relatively short duration of the explosion reverberations, and moderate received levels suggest these explosions may be seal bombs related to fishing activity.
- The lack of diel pattern may indicate a shift in the use of seal bombs to a fishery other than squid.
- The overall number of detections at sites H and N has decreased compared to earlier reports (Debich *et al.*, 2015a; Debich *et al.*, 2015b; Širović *et al.*, 2016; Rice *et al.*, 2017; Rice *et al.*, 2018) which could be due to a geographic shift in fishing effort.

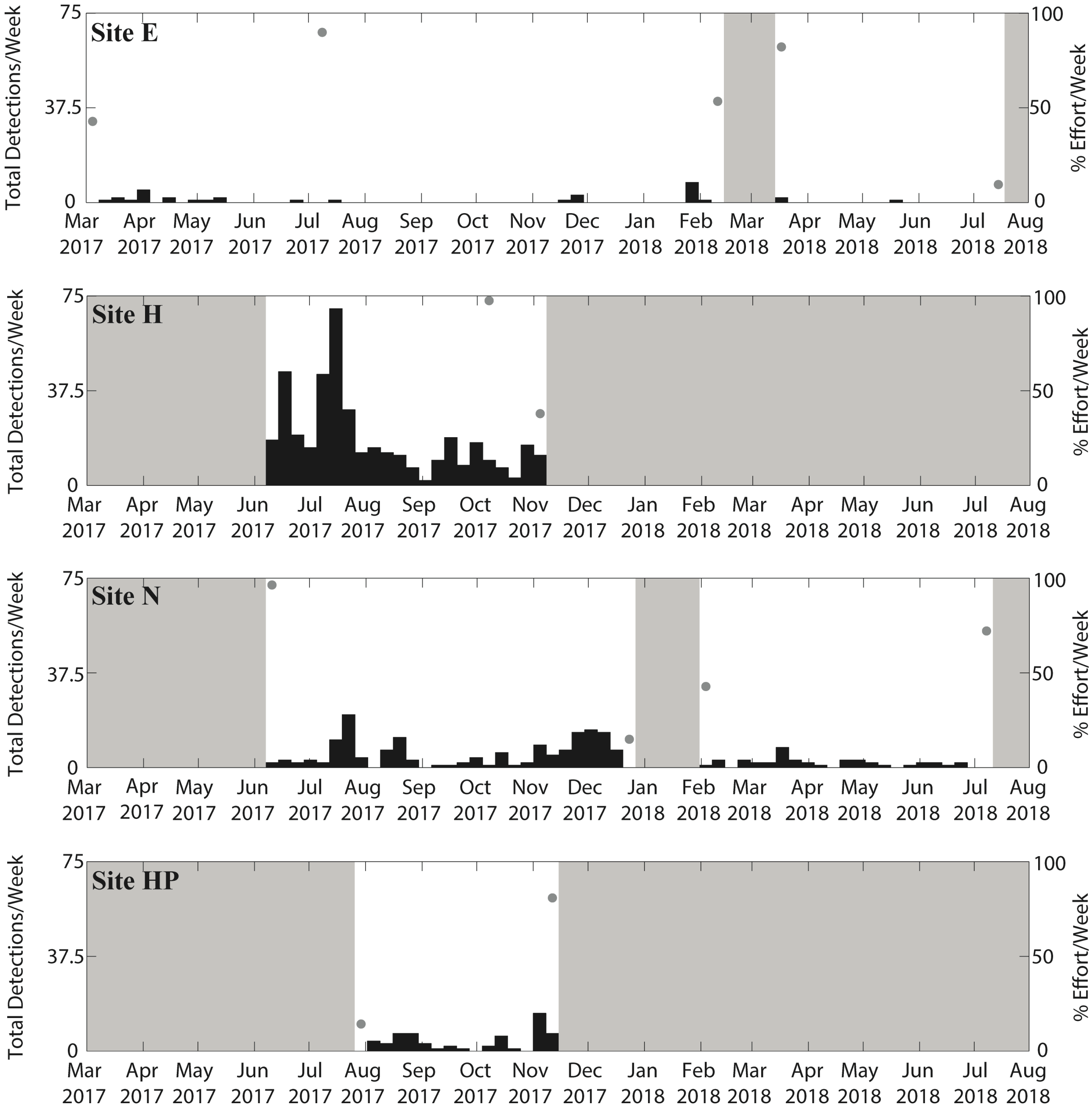

Figure 31. Weekly presence of explosions between March 2017 and July 2018 at sites E, H, N, and HP. Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

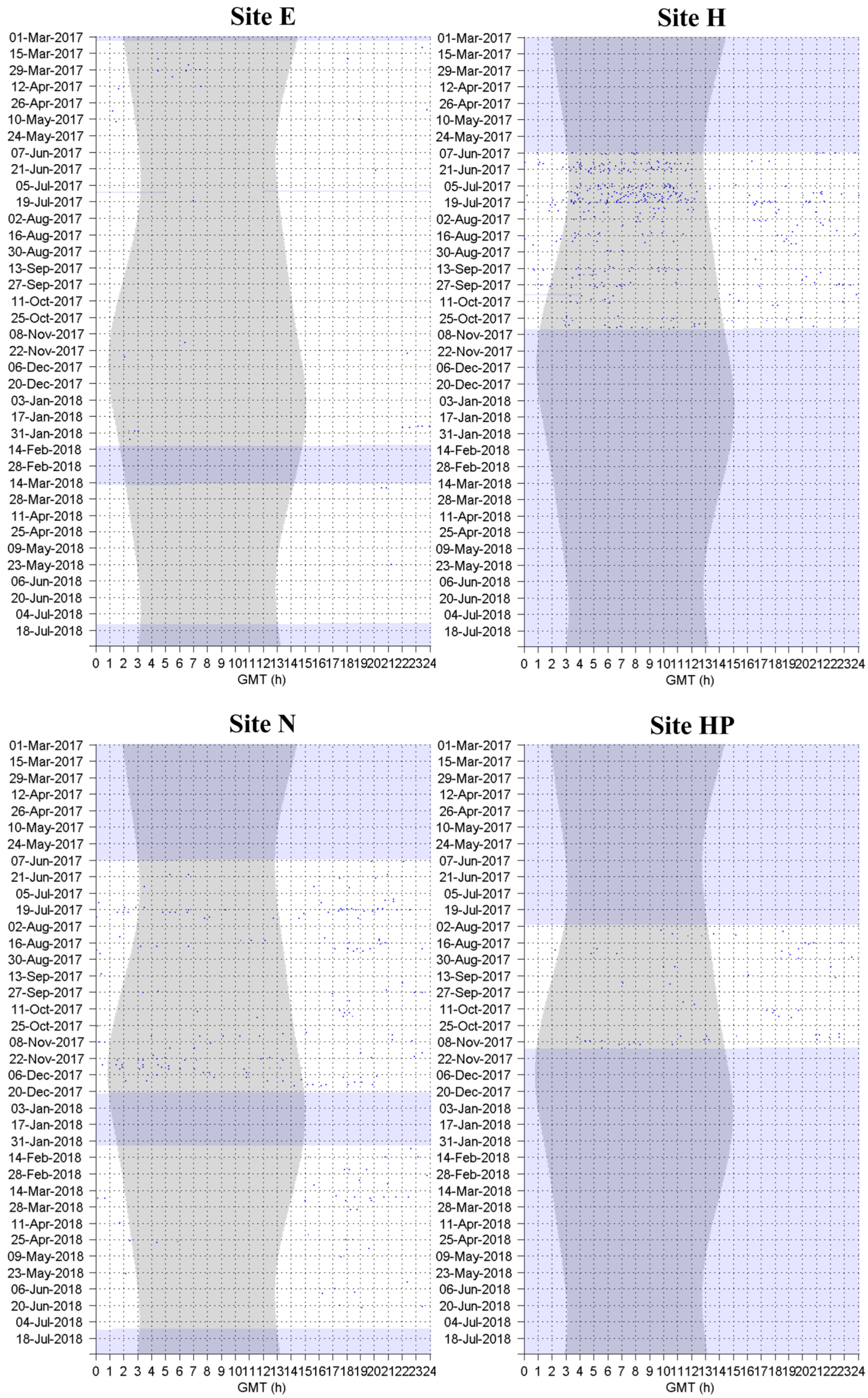

Figure 32. Explosion detections, indicated by blue dots, in five-minute bins at sites E, H, N, and HP. Gray vertical shading denotes nighttime and light purple horizontal shading denotes absence of acoustic data.

Conclusion

The results from this report are generally consistent with previous reports on the SOCAL region. The main differences are the presence of the new BW35 signal at sites E and H, as well as the lower number of explosions detected at all sites. The decrease in explosions could signal a continued geographic shift in fishing effort. Monitoring will continue in the SOCAL range in an effort to document the seasonal presence of this subset of marine mammal species and to record anthropogenic activity as well as the low-frequency ambient soundscape.

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