Passive Acoustic Monitoring for Marine Mammals in the Gulf of Alaska Temporary Maritime Activities Area 2012-2013

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Blue Whale, photo by Amanda J. Debich

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Executive Summary

Passive acoustic monitoring was conducted in the Gulf of Alaska Temporary Maritime Activities Area from May 2012 to June 2013 to detect the presence of marine mammal and anthropogenic sounds. High-frequency Acoustic Recording Packages (HARPs) recorded sounds between 10 Hz and 100 kHz at a shallow shelf site offshore Kenai Peninsula (200 m depth, site CA), a slope site in deep water as the continental shelf drops off (1000 m depth, site CB), and a deep offshore site at Pratt Seamount (1000 m depth, site PT). At site CA, there were 259 days of recordings. Site CB had 286 days of recordings, while site PT recorded for 275 days. Recordings at sites CA and CB were on a duty cycle of 10 minutes every 12 minutes while the site PT HARP recorded continuously.

Data analysis consisted of detection of sounds by analyst scans of long-term spectral averages and spectrograms, and by automated computer algorithm detection when possible. Representative sounds are presented in this report, as well as details of the computer algorithms used to detect them.

Three baleen whale species were detected: blue whales, fin whales, and humpback whales. Blue whale detections peaked in late fall 2012. There were more blue whale detections at the deep water sites CB and PT than at the shallow site CA. Fin whales were the most commonly detected; their calls were detected throughout the year at each site with a peak in detections between September and December 2012. Humpback whale acoustic encounters occurred primarily in September 2012 through March 2013. Humpbacks were detected at all three sites. No North Pacific right whale up-calls were detected at either site during this monitoring period.

At least seven species of odontocetes were detected: Risso's dolphins, killer whales, sperm whales, Baird's beaked whales, Cuvier's beaked whales, Stejneger's beaked whales, and unidentified porpoises (likely Dall's porpoise). There were very few Risso's dolphin detections, which only occurred at site PT. Killer whale detections occurred sporadically throughout the deployments with a peak in detections in July and August 2012. Most killer whale detections occurred at site CB. Similarly, site CB had more sperm whale detections than the other sites. Sperm whales were the most frequently detected odontocete species. Their calls were detected year-round, but with least detections in January and February 2013. Baird's beaked whale and Stejneger's beaked whale were the most frequently encountered beaked whales. Baird's beaked whale detections occurred at both deep water sites, CB and PT, with a peak in detections at CB in November 2012 and a peak in detections at PT in October 2012. Stejneger's beaked whale detections occurred primarily at site CB and peaked in October 2012. Cuvier's beaked whale detections peaked in January 2013 and occurred primarily at site PT. Porpoise clicks were encountered primarily at the shallow site CA, with peaks in detections in September 2012 and January 2013.

Broadband ship noise was more frequently recorded at sites CB and PT than CA. Echosounder pings, consisting of a variety of frequencies, were more common at sites CA and CB than site PT. Very few explosions were recorded at any of the three sites throughout the monitoring period. These explosions are likely related to fisheries activity rather than naval exercises. No Mid-Frequency Active (MFA) sonar events were detected throughout the recordings.

Project Background

The Navy's Gulf of Alaska Temporary Maritime Activities Area (GATMAA) is an area approximately 300 nautical miles (nm) long by 150 nm wide, situated south of Prince William Sound and east of Kodiak Island (Figure 1). It reaches from the shallow shelf region over the shelf break into deep offshore waters. The region has subarctic climate and is a highly productive marine ecosystem owing to the upwelling linked to the counterclockwise gyre of the Alaska Current. A diverse array of marine mammals is found here, including baleen whales, beaked whales, other toothed whales, and pinnipeds. Endangered marine mammals that are known to inhabit this area include blue, fin, humpback, North Pacific right, and sperm whales. The North Pacific right whales are of particular consideration, as their current abundance estimate is only a few tens of animals, making them the most endangered marine mammal species in U.S. waters. Based on a recent visual sighting, a North Pacific Right Whale Critical Habitat was defined on the shelf along the southeastern coast of Kodiak Island, bordering the GATMAA.

In July 2011, an acoustic monitoring effort was initiated at two sites within the boundaries of the GATMAA with support from the Pacific Fleet under contract to the Naval Postgraduate School. The goal of this effort was to characterize the vocalizations of marine mammal species present in the area, to determine their year-round seasonal presence, and to evaluate the potential for impact from naval operations. In 2012, a new instrument was added to this effort. This report documents the analysis of data recorded by three High-frequency Acoustic Recording Packages (HARPs) that were deployed within the GATMAA, one in shallow water on the shelf (site CA), one in deep water on the slope (site CB), and one on Pratt Seamount (site PT, Figure 1) during the time period May 2012 – April 2013 (Table 1).

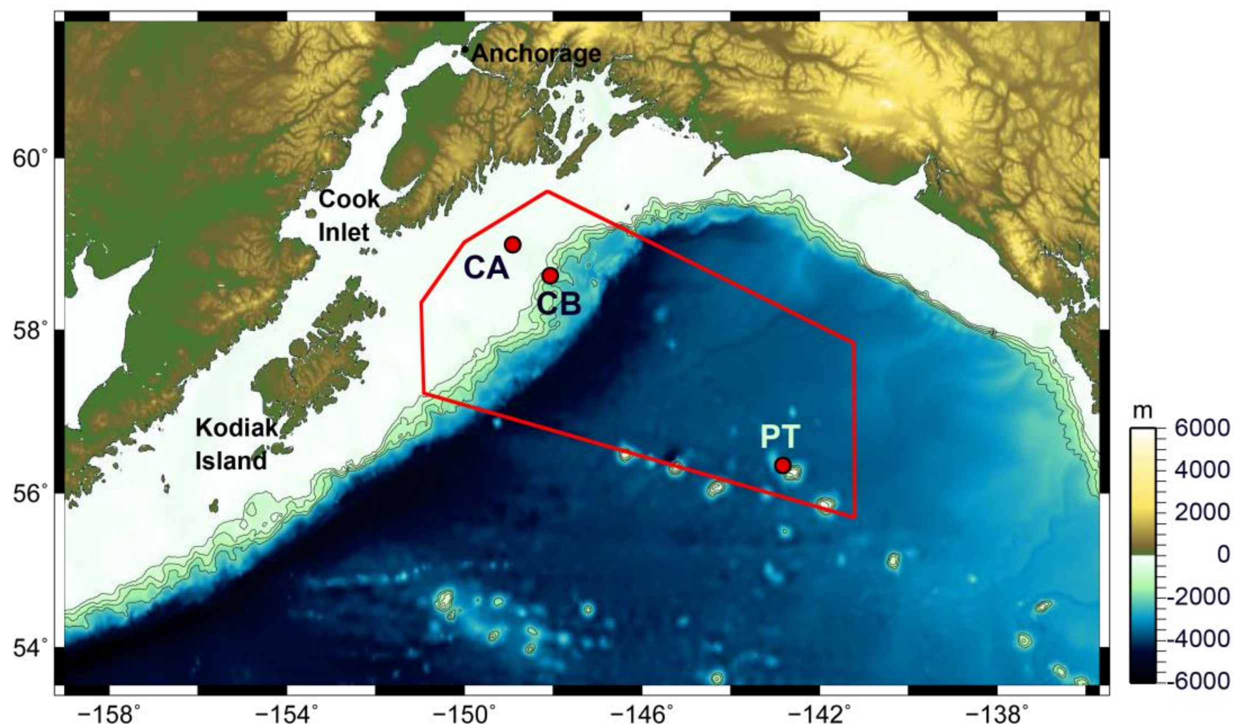


Figure 1. Locations of High-frequency Acoustic Recording Packages (CA, CB, and PT) in the GATMAA (red line). Color is bathymetric depth (scale bar at right in meters) with contour lines every 500 m.

Methods

High-frequency Acoustic Recording Packages

High-frequency Acoustic Recording Packages, HARPs (Wiggins & Hildebrand 2007) were used to detect marine mammal species and characterize ambient noise in the GATMAA. HARPs record underwater sounds from 10 Hz to 100 kHz and are capable of approximately 300 days of continuous data storage. For the GATMAA deployments, the HARPs were in a seafloor mooring configuration with the hydrophones suspended about 30 m above the seafloor. Each HARP is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones have also been calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations.

Data Collected to Date

Acoustic data have been collected within the GATMAA using autonomous HARPs sampling at 200 kHz since July 2011. The sites are designated CA (59° 0.51N, 148° 54.50W, depth 200 m), CB (58° 38.74N, 148° 04.13W, depth 1000 m), and PT (56° 14.61N, 142° 45.44W, depth 990m) (Table 1).

Table 1. GATMAA acoustic monitoring periods since July 2011. Periods of deployment analyzed in this report are shown in bold. Dates marked with * indicate time periods when some of the data quality was compromised and could have resulted in masking of biological signals.

Designation	Deployment Period	Duration (days)
CA01	7/13/2011 – 7/31/2011 8/1/2011 – 12/17/2011*	153*
CB01	7/13/2011 – 2/19/2012	221
PT01	**9/9/2012 – 6/10/2013**	**275**
CA02	**5/3/2012 – 9/17/2012** **9/17/2012 – 1/16/2013***	**259***
CB02	**5/3/2012 – 6/13/2012** **6/13/2012 – 2/12/2013***	**286***

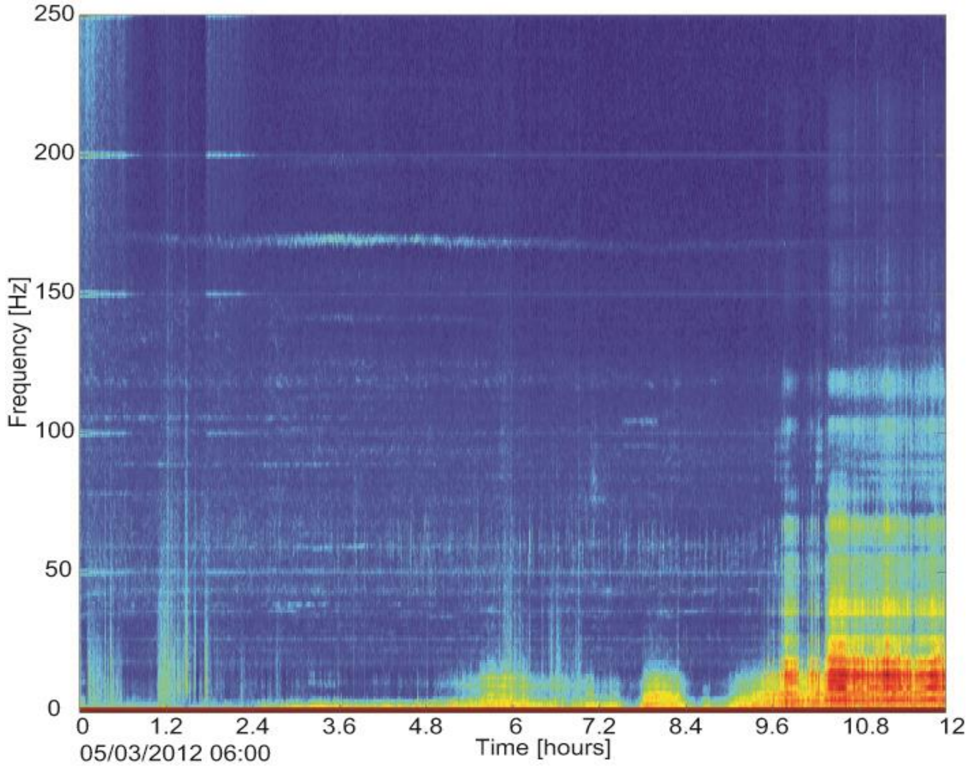
Data Quality

Hardware issues that were discovered upon recovery of HARPs at sites CA and CB complicated data analysis. These site-specific complications are described below. The HARP data from site PT were in good condition upon recovery.

Site CA

Upon recovery of the HARP at the shallow site CA, HARP technicians noticed that the electrical contacts between the hydrophone and the cable that runs to the data logger were corroded and broken. This suggests that the seal at the hydrophone and cable connection had been comprised, allowing saltwater to intrude and create a short circuit between the power and hydrophone signal lines. Since site CA is in shallow water and because the data show large amounts of strumming (likely from strong tidal flows, see Figure 2), it is reasonable to assume that the strumming caused the connector seal failure and hence the loss of data signal. The failure caused broadband spikes that occurred increasingly over time as the wire corroded. The tidal strumming affected primarily the low- and mid-frequency data analysis. The broadband spikes were affecting all frequencies. Data from site CA were divided into quality categories: “good”, “mediocre”, and “poor” where good data were acceptable in quality and mediocre data contained high-intensity strumming as well as broadband spikes that over time increasingly affected detection probabilities for marine mammal vocalizations. Category “poor” was used in high-frequency analysis where data was increasingly compromised by broadband spikes but some signals were still detectable.

Strumming caused masking in large parts of low-frequency data, and thus hampered our analysis effort. Percent of data without strumming is reported in low frequency plots, as additional measure of overall possible effort. Broadband spikes additionally compromised the overall possible effort, which increasingly occurred starting in mid-September as can be seen in low-frequency plots as continuously decreasing effort. By November 17, strumming and hydrophone failure degraded low-frequency data quality beyond the point where analysis was feasible. For mid- and high-frequency bands, data at site CA were considered “good” from May 3 – September 17, 2012. Data were considered to be “mediocre” for mid- and high-frequency analysis from September 17, 2012 – January 16, 2013 (Figure 3). Data after January 16 were considered too degraded for mid-frequency analysis. Data in high-frequency analysis were considered “poor” until April 11, 2013 with some detectability of signals (Figure 4).



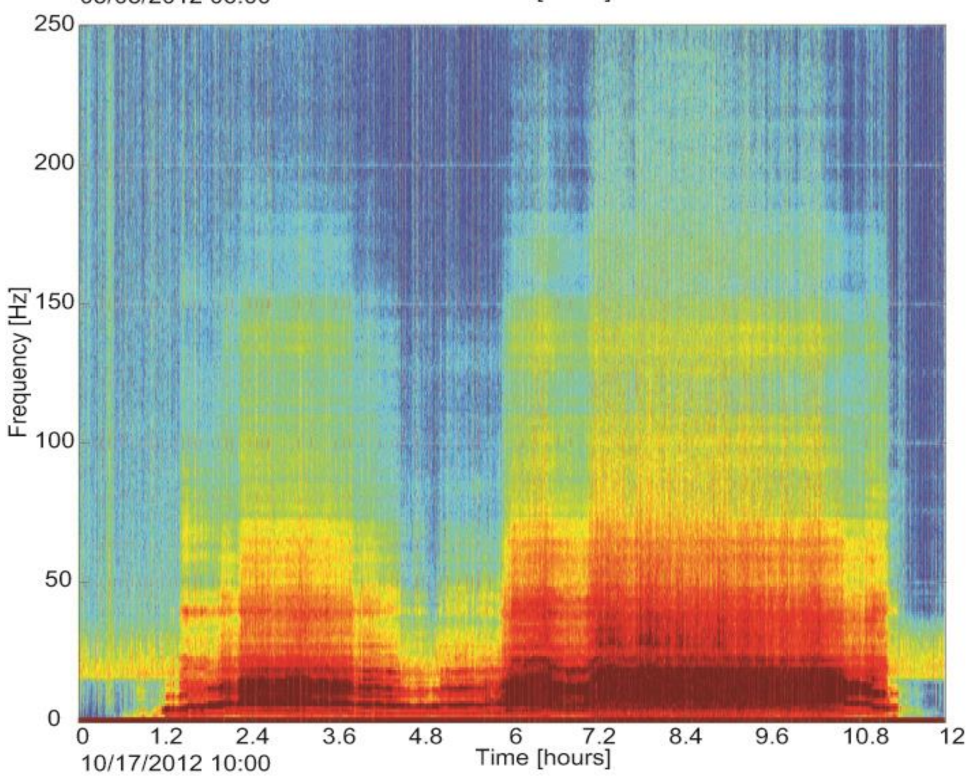


Figure 2. Example of low-intensity strumming (top, category "good") and high-intensity strumming (bottom, category "mediocre") in the LTSA in low-frequency data at site CA.

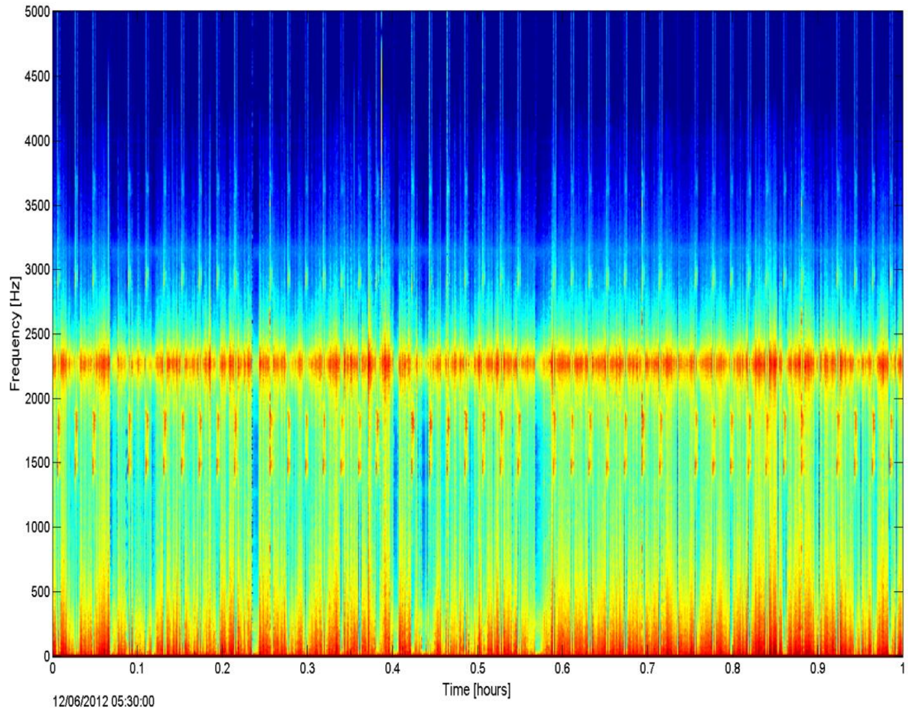


Figure 3. Example of high-intensity strumming and broadband spikes in the LTSA in mid-frequency data at site CA (category "mediocre").

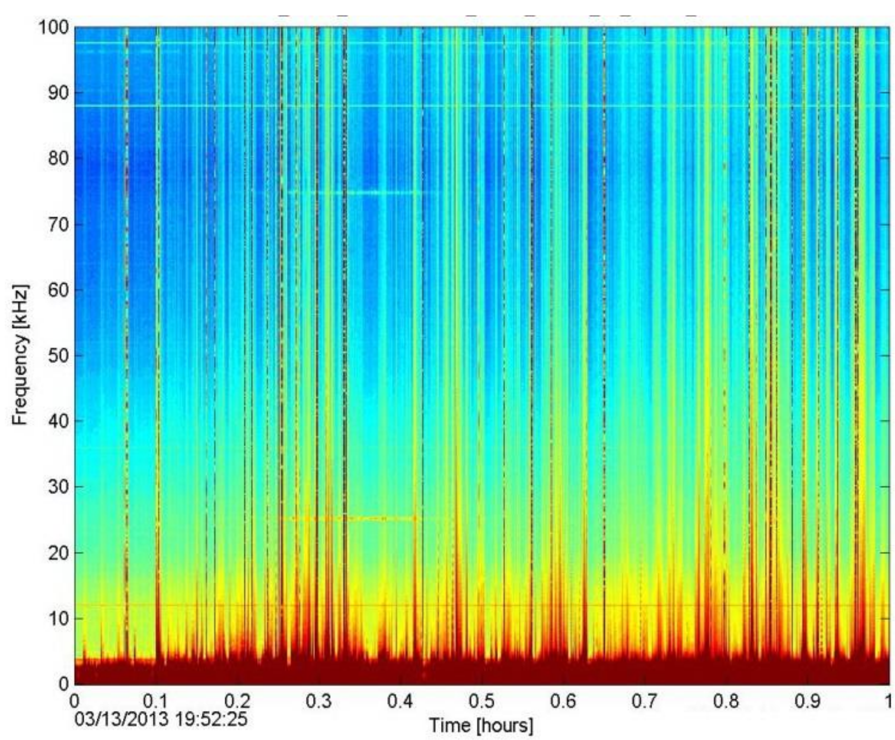


Figure 4. Example of high-intensity strumming and broadband spikes in the LTSA in full-frequency data at site CA (category "poor").

Site CB

There were no obvious physical signs of failure for the hydrophone at site CB, and deck and laboratory tests of this hydrophone did not show any indications of poor performance. However, the long-term recordings from this deployment show data quality degradation starting about six weeks into the deployment. The hydrophone has since been removed from use and is currently under investigation as to its poor performance.

Data at site CB were considered “good” from May 3 – June 20, 2012 for mid- and high-frequency analysis. The low-frequency data at site CB were considered “good” from May 3 – June 13, 2013 (Figure 5 top). Data between June 13, 2012 and February 12, 2013 were considered “mediocre” for low-frequency analysis (Figure 5 bottom). For mid- and high-frequency bands data were considered “poor” for analysis from June 20 – July 6, 2012 (Figure 6, Figure 7). Data from July 6, 2012 through February 12, 2013 were considered “mediocre” for analysis of mid- and high-frequency bands. Data after February 12, 2013 were considered too degraded for any analyses.

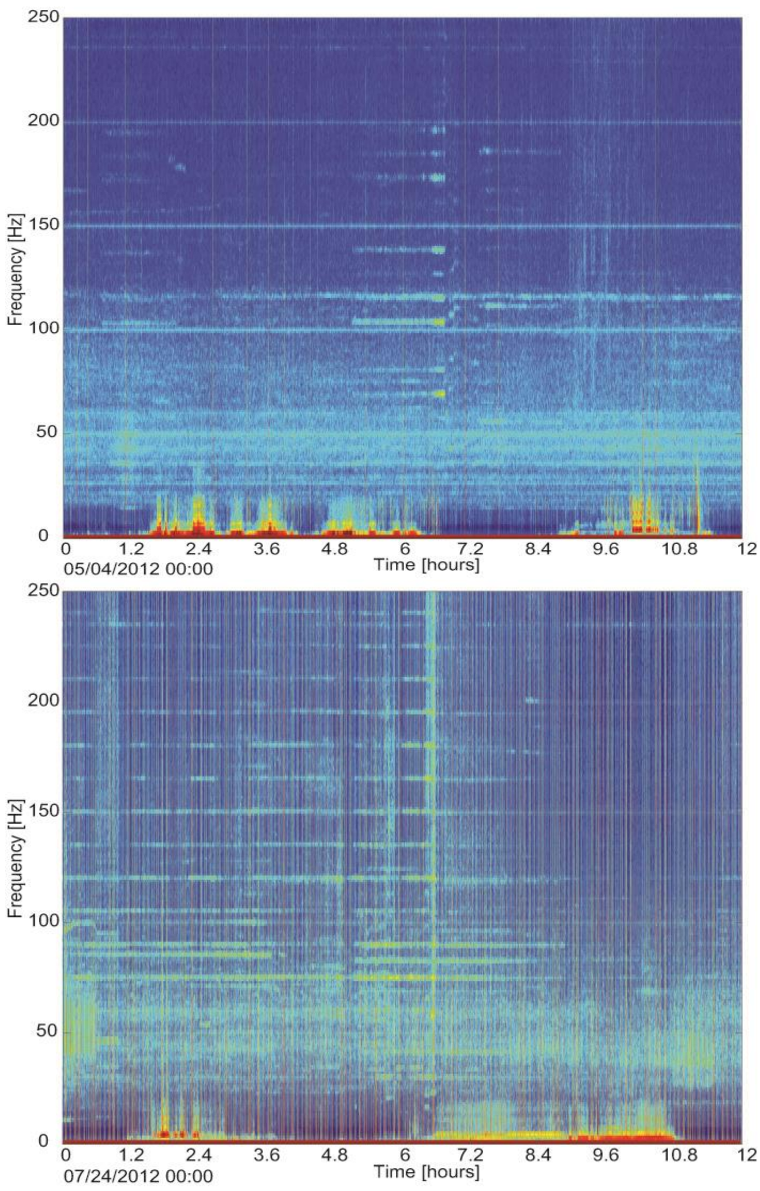


Figure 5. Example of low-intensity (top) and high-intensity (bottom) electronic noise in the LTSA in low-

frequency data.

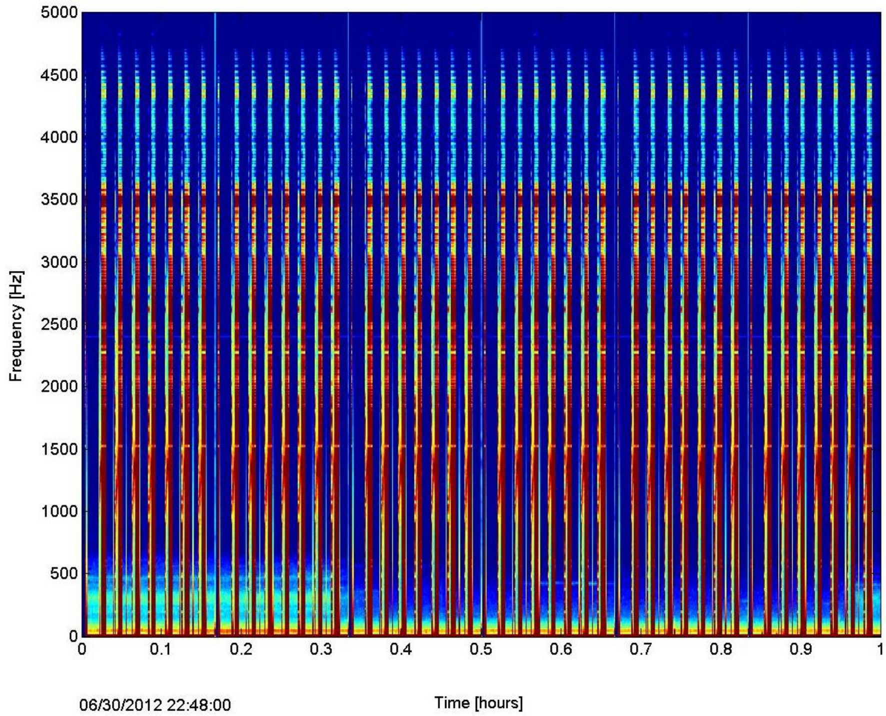


Figure 6. Example of the LTSA in mid-frequency data, showing “poor” data quality.

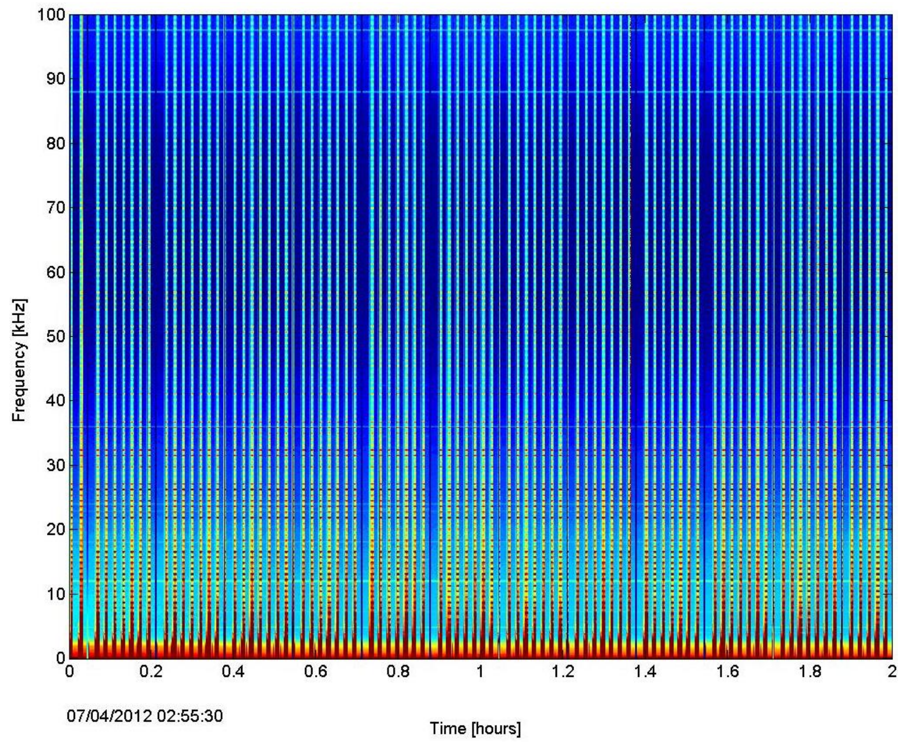


Figure 7. Example of the LTSA in full-frequency data, showing “poor” data quality.

Data Analysis

To visualize the acoustic data, frequency spectra were calculated for all data using a time average of 5 seconds and variable size frequency bins (1, 10, and 100 Hz). These data, called Long-Term Spectral Averages (LTSAs) were then examined both for characteristics of ambient noise and as a means to detect marine mammal and anthropogenic sounds in the data set. Recording a broad frequency range up to 100 kHz allows detection of baleen whales (mysticetes), toothed whales (odontocetes) and seal/sea lion (pinniped) species. The presence of sounds from marine mammal species was analyzed, along with the presence of anthropogenic noise such as sonar, explosions, and shipping. Data were analyzed by visually scanning LTSAs in source-specific frequency bands and, when appropriate, using automatic detection algorithms (described in detail below).

During visual analysis, when a sound of interest was identified in the LTSA but its origin was unclear, the waveform or spectrogram of the sound was examined to further classify the sounds to species or source. Acoustic classification was carried out from comparison to known species-specific spectral and temporal characteristics.

To document the data analysis process, we describe the marine mammal calls and anthropogenic sounds in the Gulf of Alaska region, and the procedures used to detect them in the HARP data. For effective analysis, the data were divided into three frequency bands and each band was analyzed for the sounds of an appropriate subset of species or sources. The three frequency bands were as follows:

(1) low-frequency, between 10 – 500 Hz,

(2) mid-frequency, between 500 – 5000 Hz, and

(3) high-frequency, between 1 – 100 kHz.

Blue, fin, and grey whale sounds were classified as low-frequency; humpback, minke, pinniped, nearby shipping, explosions, and mid-frequency active sonar were classified as mid-frequency; while the remaining odontocete and sonar sounds were considered high-frequency.

Blue whale B calls and fin whale 20 Hz calls were detected using automatic computer algorithms (described in detail below). Likewise, odontocete echolocation clicks were detected using a Teager energy detector (Roch et al. 2011). Beaked whale frequency-modulated pulses were detected both manually and automatically and the results were compared (see detailed description below).

We describe the calls and procedures separately for each frequency band.

Low-Frequency Marine Mammals

The Gulf of Alaska is inhabited at least for a portion of the year by blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), gray whales (*Eschrichtius robustus*), and North Pacific right whales (*Eubalaena japonica*) producing low frequency calls. For the low frequency data analysis, the 200 kHz sampled raw-data were decimated by a factor of 100 for an effective bandwidth of 1 kHz. Long-term spectral averages (LTSAs) of these data were created using a time average of 5 seconds and frequency bins of 1 Hz. The Central Pacific tonal blue whale calls, blue whale D calls, fin whale 40 Hz calls, and gray whale M3 calls were detected manually by logging presence of calls in hourly bins. Analysis effort was also kept for North Pacific right whale up-calls. For manual detection, the LTSA frequency was set to display up to 500 Hz. To observe individual calls, spectrogram window sizes were typically set to 120 seconds by 200 Hz. The fast Fourier transform (FFT) window was generally set between 1500 and 2000 data points (yielding about 1 Hz resolution), with an 85-95% window overlap. At site PT, Northeast Pacific blue whale B calls and fin whale 20 Hz calls were detected automatically (described below). At site CB, only fin whale 20 Hz calls were detected automatically and the Northeast Pacific blue whale B calls were detected manually. All detections were manual at site CA.

Blue Whale Northeast Pacific B Call Detector

Blue whale Northeast Pacific B calls were detected automatically using spectrogram correlation (Mellinger & Clark, 2000). The kernel for automatic detection was made of four segments, first three 1.5 s and the last one 5.5 s long, for a total 10 s duration. The frequency ranged over those time periods from 48.03 to 47.28; 47.28 to 46.75; 46.75 to 46.45; and 46.45 to 45.98 Hz. The kernel bandwidth was 2 Hz. The performance of the detector was tested against 10 days of manual hourly-presence picks of blue whale B calls in November and 10 days in January. We found that average hourly false alarm and missed detection rates were 4.78% and 5.82%, respectively, though they varied across seasons. Automatic detections during January and February, when blue whales are not common in this area, were manually reviewed and false alarms were removed from further analysis. Detections were binned into 1 hour bins for consistent reporting with other detections. The automatic detector was only run on data from site PT; data from site CA and CB were analyzed manually.

Fin Whale 20 Hz Call Detector

Fin whale 20 Hz calls were detected automatically using an energy detector. We used a difference in acoustic energy between signal and noise at different frequencies, calculated from 5 s LTSA with 1 Hz resolution as an indicator of the presence of 20 Hz calls. The frequency bin at 20 Hz was used for the signal energy, while noise energy was calculated as the average of the acoustic energies at 8 and 32 Hz. All energy calculations were performed on the logarithmic scale. The optimal threshold was determined by comparing the performance of the detector against 7 days in December and March of manual hourly-presence picks of fin whale 20 Hz calls. The average rate of false positives and missed detections were 10.75% and 9.55%, respectively. Detections were binned into 1 hour bins for consistent reporting with other detections. The automatic detector was run on data from sites PT and CB; data from site CA were analyzed manually.

Low-Frequency Call Types

Blue Whale Calls

Blue whale calls recorded in the Gulf of Alaska included the Northeast Pacific blue whale B call (Figure 8) and the Central Pacific tonal call (Figure 9), which are geographically distinct calls possibly associated with mating functions (McDonald et al. 2006, Oleson et al. 2007). They are low-frequency (fundamental frequency <20 Hz), have long duration, and often are regularly repeated. Also detected were blue whale D calls (Figure 10), which have been recorded across regions (Thode et al. 2000, Rankin et al. 2005). They are produced by blue whale males and females and are likely associated with foraging animals (Oleson et al. 2007).

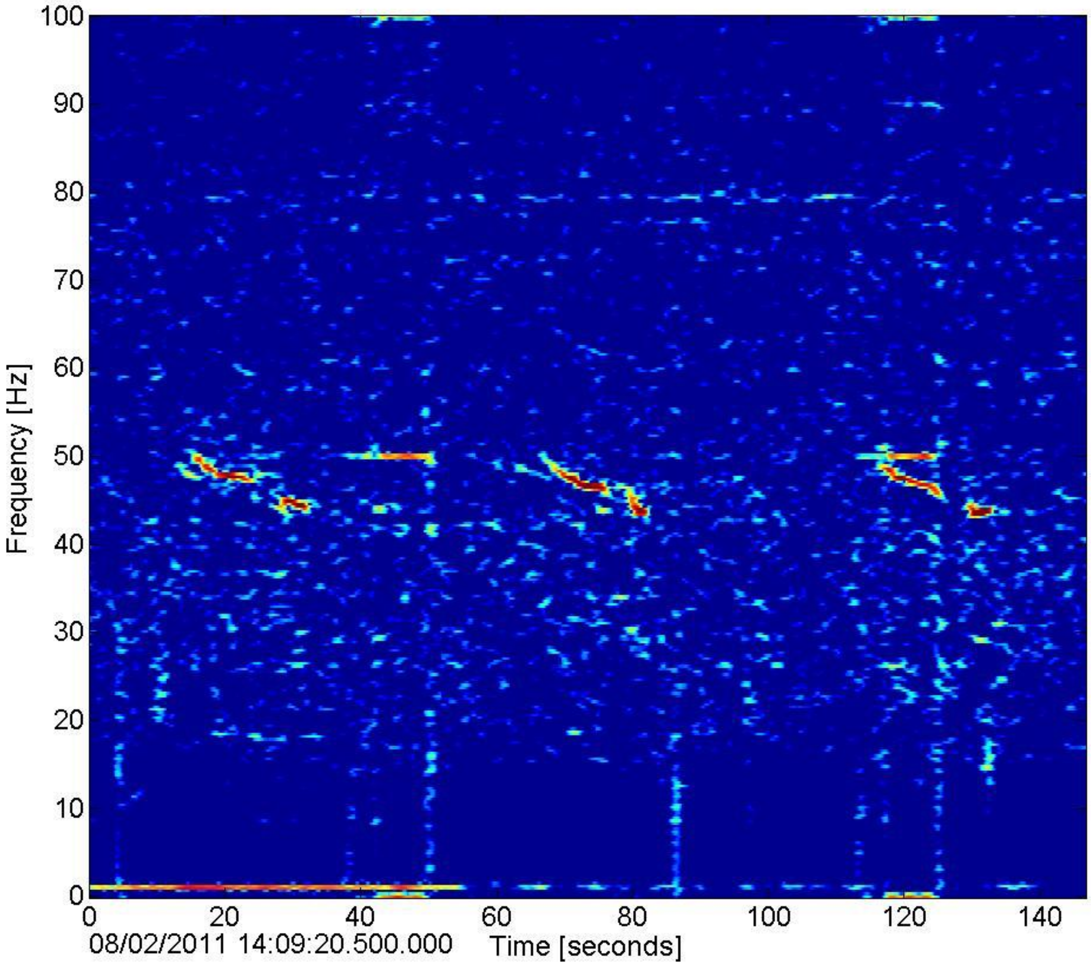


Figure 8. Spectrogram of three Northeast Pacific blue whale B calls (6,500-point FFT, 95% overlap, Hanning window) recorded at site CB. The third harmonic seen here is often the most energetic component in this call type. Pure tones at 50 Hz are related to electronic (disk) noise.

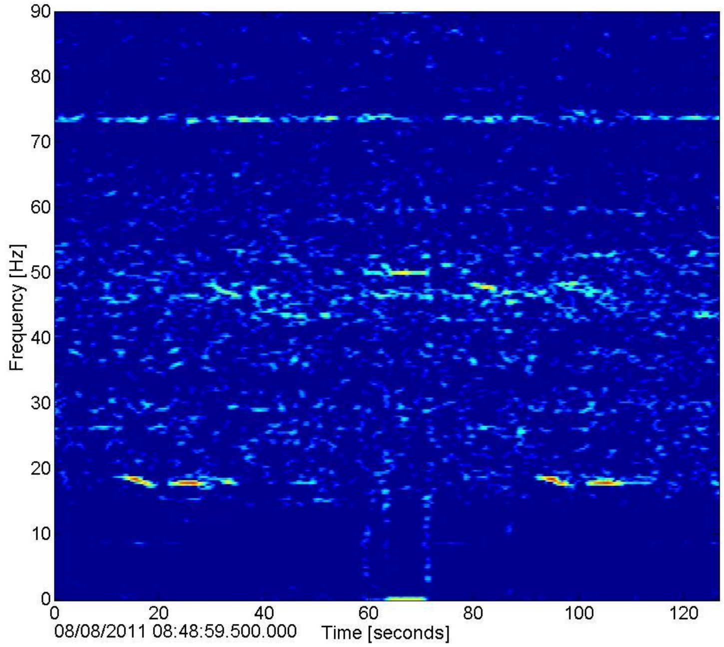


Figure 9. Spectrogram of two Central Pacific blue whale tonal calls (6,500-point FFT, 95% overlap, Hanning window) recorded at site CB.

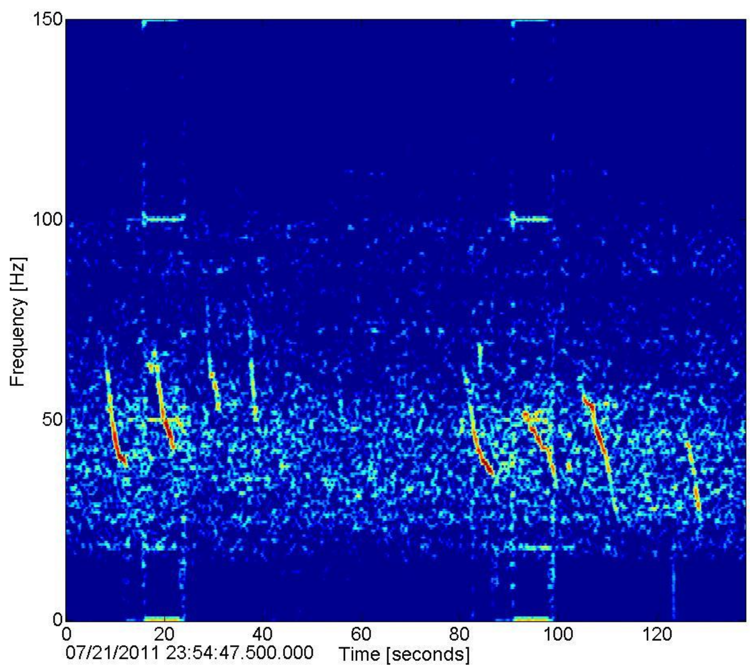


Figure 10. Spectrogram of multiple blue whale D calls (3,500-point FFT, 95% overlap, Hanning window recorded at site CB.

Fin Whale Calls

Two types of fin whale calls were recorded in the Gulf of Alaska: the 20 Hz (Figure 11) and the 40 Hz calls (Figure 12). Both call types are short pulses (~1 s duration), but they cover different frequency bands (Watkins et al. 1987, Širović et al. 2013). 20 Hz calls are usually regularly repeated, and 40 Hz calls occur more irregularly. When fin whale 20 Hz calls are produced by a large number of animals, they can create "bands" of noise in the 15-34 Hz range, which is often seen in the Gulf of Alaska region (Figure 13).

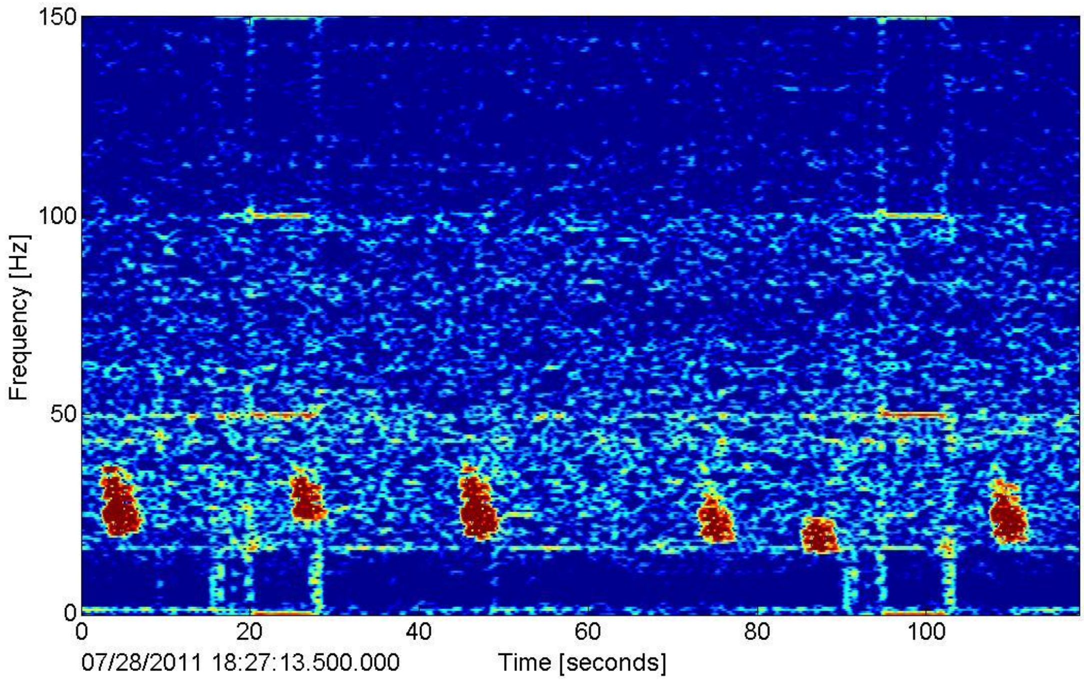


Figure 11. Spectrogram of fin whale 20 Hz calls (3,800-point FFT, 99% overlap, Hanning window) recorded at site CB.

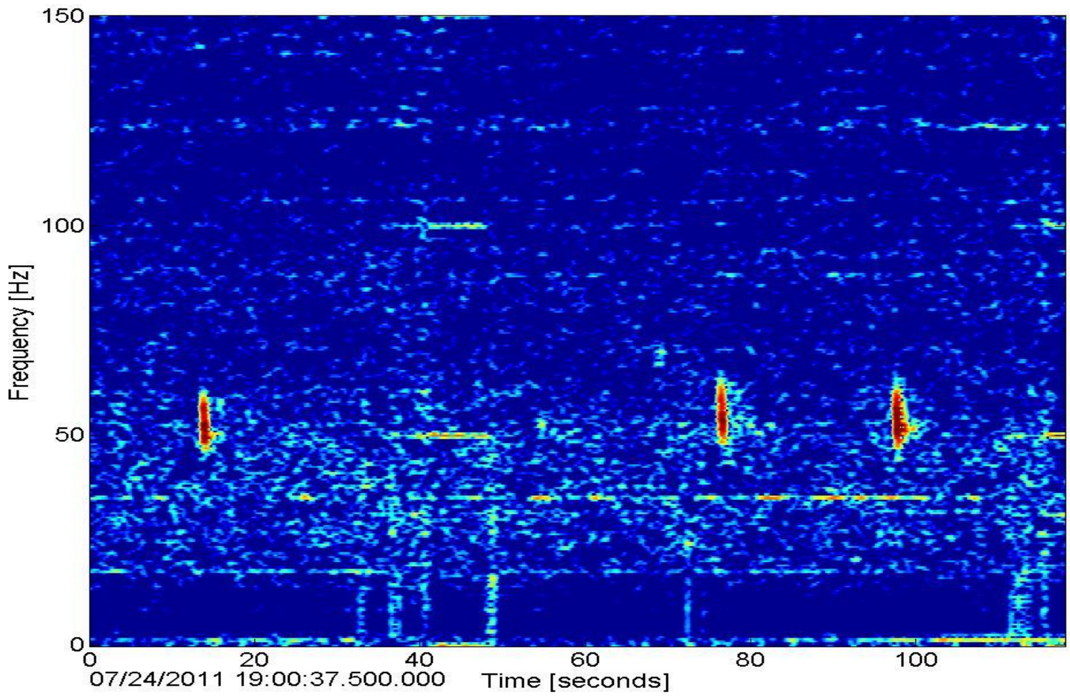


Figure 12. Spectrogram of fin whale 40 Hz calls (4,000-point FFT, 95% overlap, Hanning window) recorded at site CB.

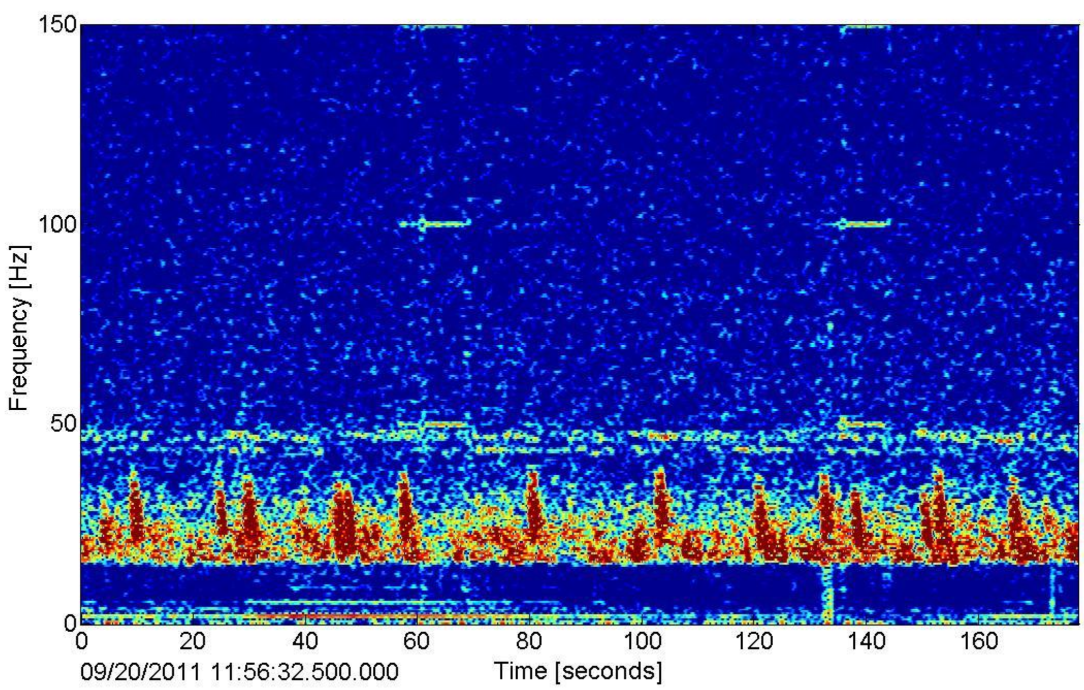


Figure 13. Spectrogram of fin whale 20 Hz nearby calls with additional energy in the "20 Hz band" resulting from more distant calls (4,000-point FFT, 99% overlap, Hanning window) recorded at site CB.

Gray Whale

Gray whales produce a variety of calls, which are often lower source levels than most other baleen whale calls and thus propagate over shorter distances. The only call type for which there was detection effort during our study was the M3 call, which is a low-frequency, short moan with most energy around 50 Hz (Figure 14), and the most common call produced by migrating animals (Crane & Lashkari 1996). No gray whale M3 calls were detected at any of the sites.

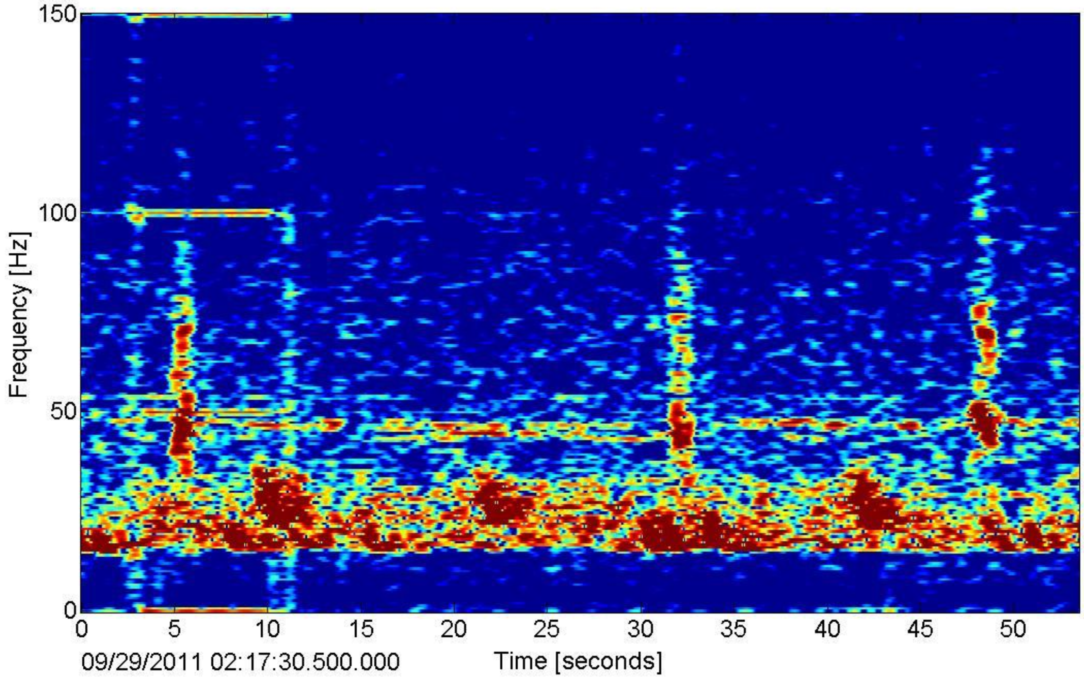


Figure 14. Spectrogram of gray whale M3 calls (3,000-point FFT, 99% overlap, Hanning window) recorded at site CB. Also note persistent “noise” in the fin whale 20 Hz band.

North Pacific Right Whale

North Pacific right whales are a highly endangered cetacean species that was plentiful in the Gulf of Alaska prior to intense whaling efforts (Scarff 1986, Brownell et al. 2001). These whales make a variety of sounds, of which the most common is the "up-call." The "up-call" typically sweeps from about 35 to 150 Hz, and has a duration of approximately one second (McDonald & Moore 2002) (Figure 15). No North Pacific right whale up-calls were detected at any of the sites.

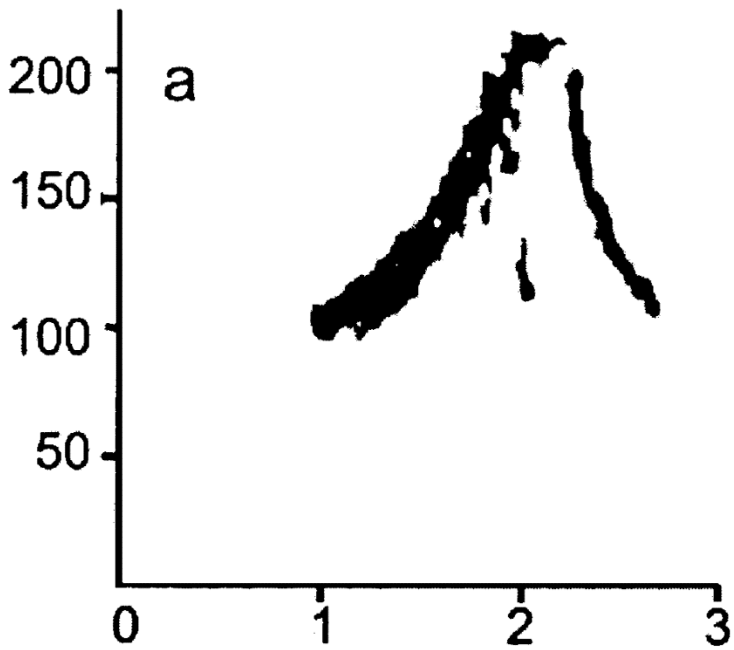


Figure 15. Example of North Pacific right whale "up-call" from McDonald & Moore 2002.

Mid-Frequency Marine Mammals

Marine mammal species with sounds in the mid-frequency range expected in the Gulf of Alaska are humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), killer whales (*Orcinus orca*), and a number of pinnipeds. For mid-frequency data analysis, the 200 kHz HARP data were decimated by a factor of 20 for an effective bandwidth of 5 kHz. The LTSAs for mid-frequency analysis were created using a time average of 5 seconds, and a frequency bin size of 10 Hz. The presence or absence of each call type was determined in one-minute bins for each mid-frequency dataset.

Effort was expended to find mid-frequency sounds including: humpback whale, minke whale, killer whale, pinniped, mid-frequency active sonar (MFA), explosions, and broadband ship noise. The LTSA parameters used to manually search for each sound are given in Table 2. Humpback whale sounds were detected automatically.

Table 2. Mid-frequency LTSA search parameters including plot length and frequency range

Species or Anthropogenic Source	**LTSA Search Parameters**	
	Plot Length (Hr)	**Frequency Range (Hz)**
Minke Whale	0.50	1000 – 2000
Pinniped	0.75	200 – 700
Killer Whale	0.75	200 – 5000
MFA Sonar	0.75	1000 – 5000
Broadband Ship Noise	3.00	0 – 5000
Explosions	0.75	0 – 2000

Humpback Whale Detector

Humpback whale song is categorized by the repetition of units, phrases, and themes as described by Payne & McVay (1971). Non-song vocalizations such as social and feeding sounds consist of individual units (Dunlop et al. 2007, Stimpert et al. 2011). All humpback whale sounds can last from 0.15 to 2.5 seconds. Most humpback whale vocalizations are produced between 100-3000 Hz (Figure 16). For this report we detected humpback calls using a computer algorithm based on the gerealized power law detector (Helble et al. 2012). The validity of the detected signals was subsequently verified by a trained analyst.

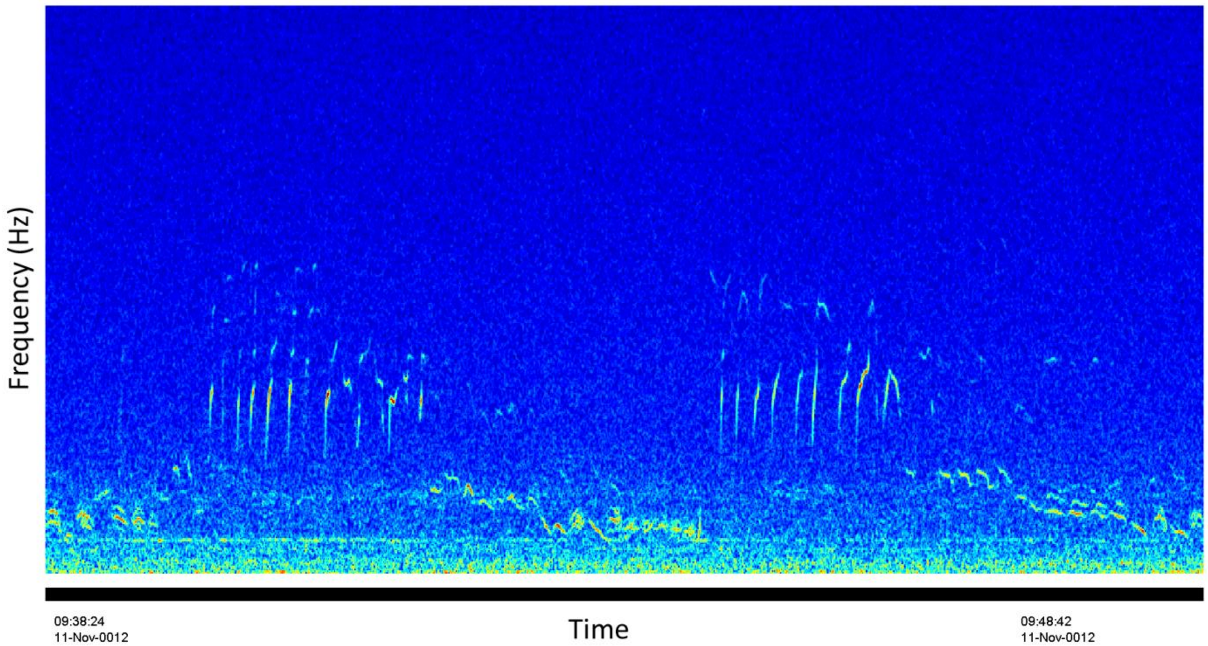


Figure 16. Example of humpback whale song from site PT in analyst verification stage of detector.

Minke Whale

Minke whale “boings” consist of 2 parts, beginning with a burst followed by a long buzz, with the dominant energy band just below 1400 Hz (Figure 17). Boings are divided geographically into an eastern and a central Pacific variant, with a dividing line at about 135°W. Eastern boings have an average duration of 3.6 seconds and a pulse repetition rate of 92 s^{-1} (Rankin & Barlow 2005). Boing sounds recently reported from the Chukchi Sea have measurements that match the central Pacific sounds (Delarue & Martin 2013). No minke whale boings were detected at any of the sites.

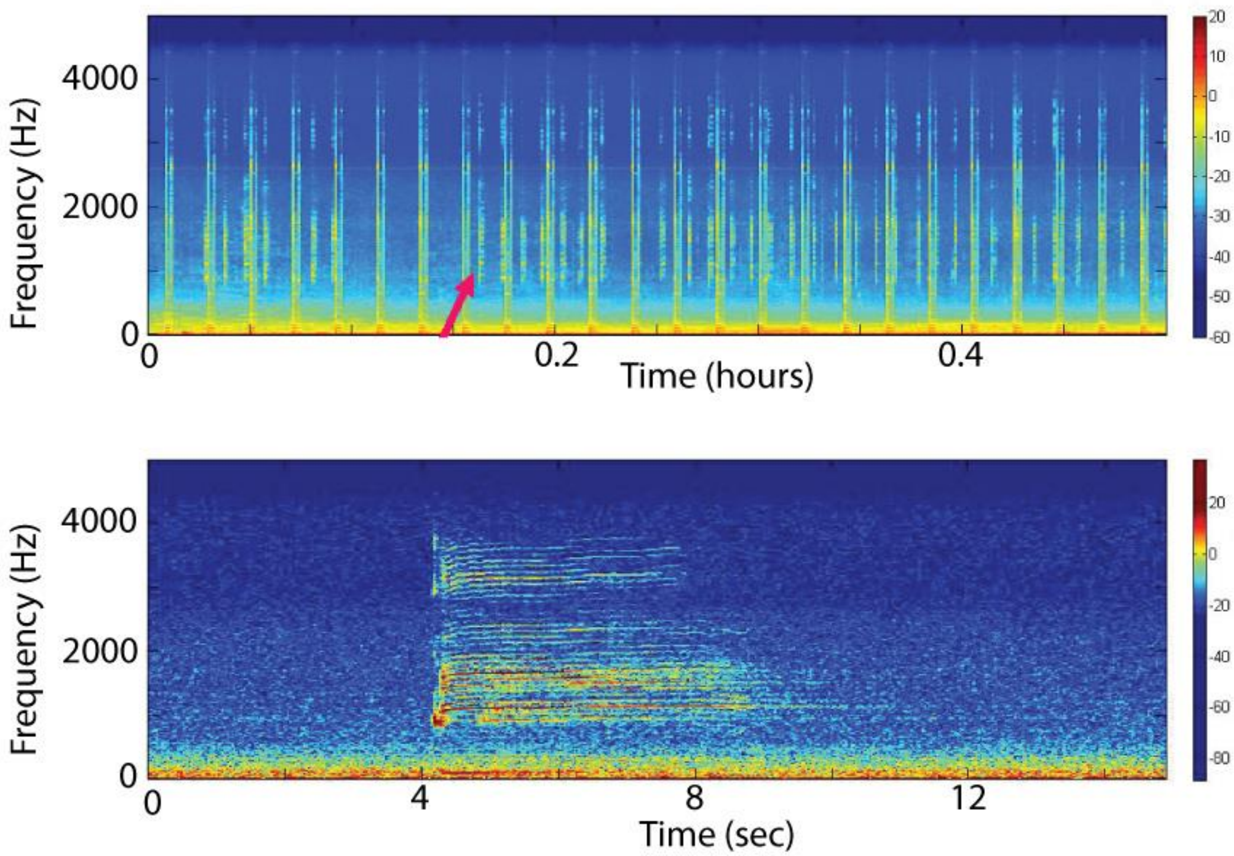


Figure 17. Minke whale boing in the LTSA (top) and spectrogram (bottom) from southern California.

Pinnipeds

Pinnipeds known to occur in the Gulf of Alaska are Steller sea lion (*Eumetopias jubatus*), Northern fur seal (*Callorhinus ursinus*), harbor seal (*Phoco vitulina*), Northern elephant seal (*Mirounga angustirostris*), and possibly California sea lions (*Zalophus californianus*). These species produce a variety of sounds with most of their dominant energy below 1000 Hz (e.g. Figure 18). Pinniped vocalization bouts can continue for up to several hours. No pinniped calls were detected at any of the sites.

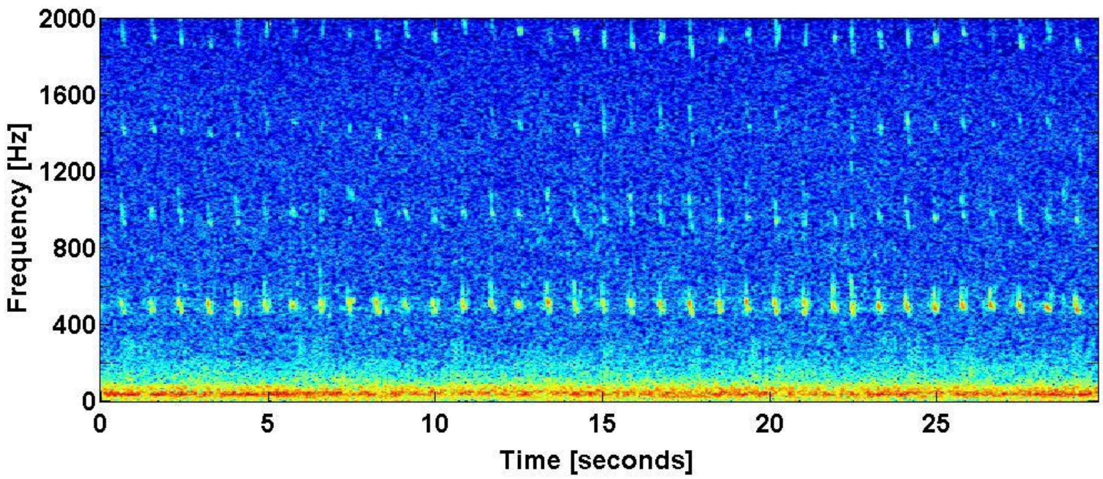


Figure 18. California sea lion barks recorded June 2011 in California.

High-Frequency Marine Mammals

Marine mammal species with sounds in the high-frequency range expected in the Gulf of Alaska are Risso's dolphins (*Grampus griseus*), Pacific white-sided dolphins (*Lagenorhynchus obliquidens*), killer whales, sperm whales (*Physeter macrocephalus*), Baird's beaked whales (*Berardius bairdii*), Cuvier's beaked whales (*Ziphius cavirostris*), Stejneger's beaked whales (*Mesoplodon stejnegeri*), Dall's porpoise (*Phocoenoides dalli*) and harbor porpoise (*Phocoena phocoena*). For the high-frequency data analysis, spectra were calculated for the full effective bandwidth of 100 kHz. The LTSAs were created using a time average of 5 seconds and a frequency bin size of 100 Hz. The presence of call types was determined in one-minute bins.

High-Frequency Call Types

Odontocete sounds can be categorized as either: echolocation clicks, burst pulses, or whistles. Echolocation clicks are broadband impulses with the peak energy between 5 and 150 kHz, dependent on species. Burst pulses are rapidly repeated clicks that have a creak or buzz-like sound quality; they are generally lower in frequency than the echolocation clicks. Dolphin whistles are tonal calls predominantly between 1 and 20 kHz that vary in frequency content, their degree of frequency modulation, as well as duration. These signals are easily detectable in an LTSA as well as the spectrogram (Figure 19).

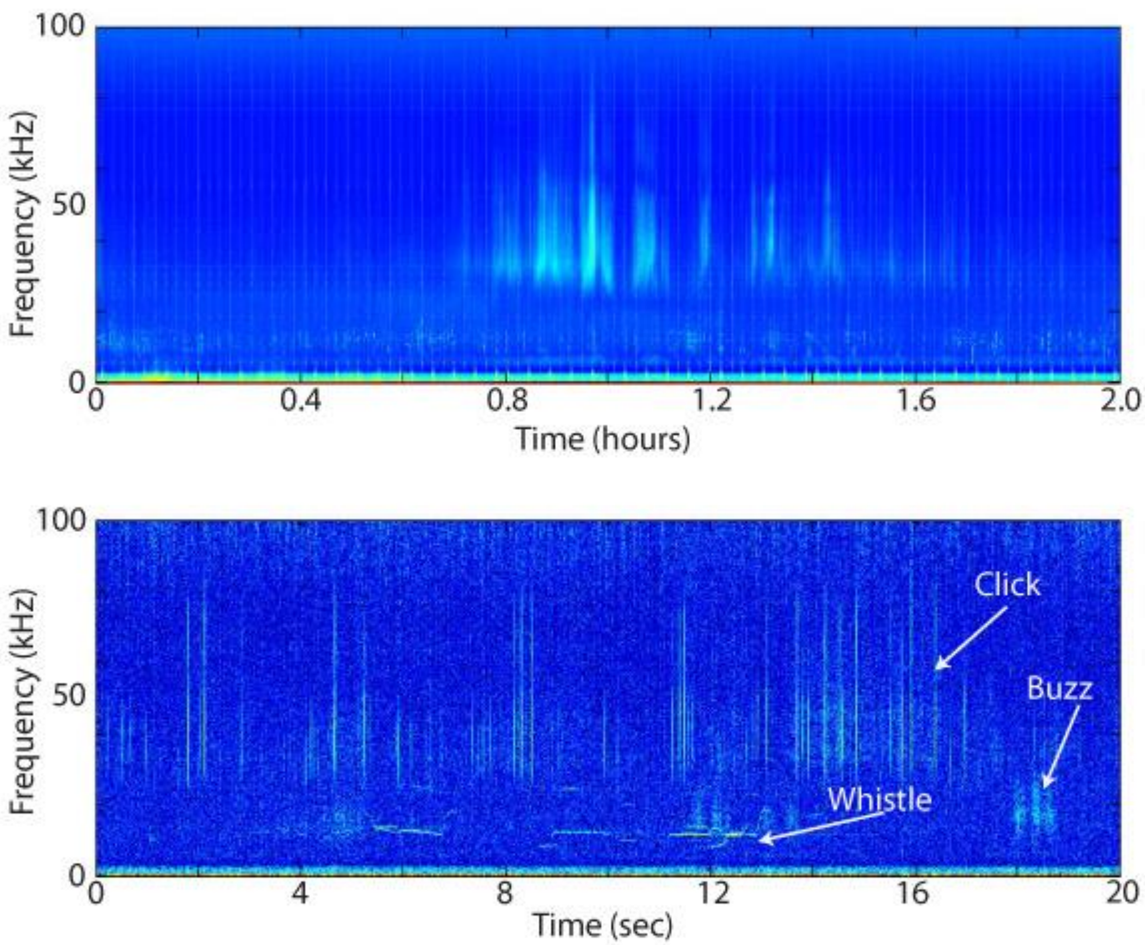


Figure 19. LTSA (top) and spectrogram (bottom) demonstrating the odontocete signal types.

Unidentified Odontocete
Several dolphin species are not yet distinguishable based on the character of their clicks, burst pulses, or whistles (Soldevilla et al. 2008, Roch et al. 2011). Such detections were classified as unidentified odontocetes in this report.

Risso's Dolphin
Risso's dolphin echolocation clicks can be identified to species by their distinctive banding patterns observable in the LTSA (Figure 20). Risso's dolphin echolocation clicks have energy peaks at 22, 26, 30, and 39 kHz (Soldevilla et al. 2008). The peaks in the Gulf of Alaska have a slightly differing peak structure of 22, 25, 29, and 32 kHz indicating possible population level differences.

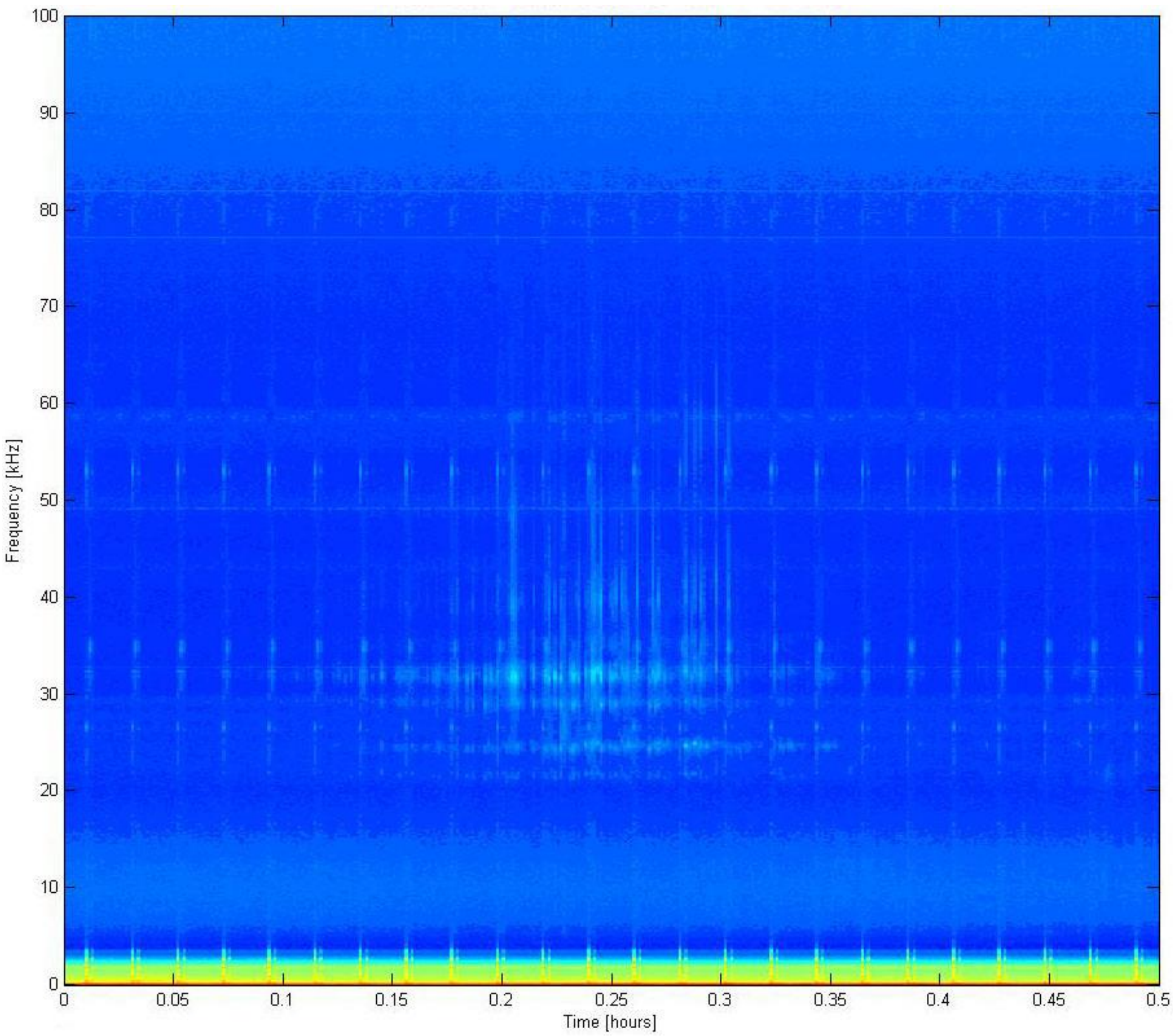


Figure 20. Risso's dolphin acoustic encounter (LTSA) recorded in the Northwest Training Range Complex. Note a distinctive banding pattern typical for this region.

Pacific White-Sided Dolphin

Pacific white-sided dolphin echolocation clicks can also be identified to species by their distinctive banding patterns (Figure 21). Pacific white-sided dolphin echolocation clicks (Type A) have energy peaks at 22, 26, and 37 kHz (Soldevilla et al. 2011).

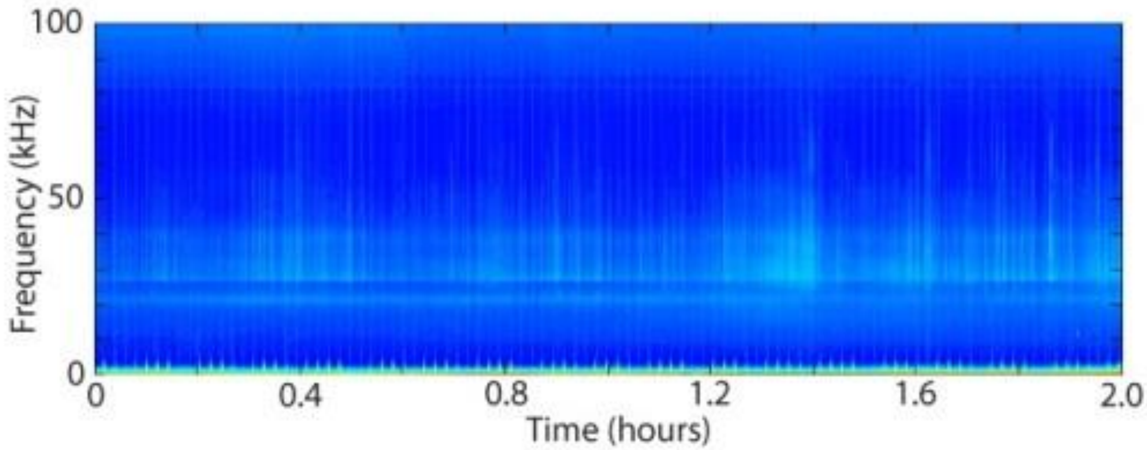


Figure 21. Pacific white-sided dolphin type A echolocation clicks in the LTSA.

Killer Whale

Killer whales are known to produce four call types: pulsed calls, high-frequency modulated (HFM) signals, echolocation clicks, and low frequency whistles (Ford 1989, Samarra et al. 2010). Killer whale pulsed calls are well documented and the best described of their call types. Pulsed calls' primary energy is between 1 and 6 kHz, with high frequency components occasionally >30 kHz and duration primarily between 0.5 and 1.5 seconds (Ford, 1989). HFM signals have only recently been attributed to killer whales in both the Northeast Atlantic (Samarra et al. 2010) and Northeast Pacific (Simonis et al. 2012, Filatova et al. 2012). These signals have fundamental frequencies between 17 and 75 kHz, the highest of any known delphinid tonal calls. We primarily use pulsed calls (Figure 22) and HFM signals (Figure 23) for killer whale species identification. Echolocation clicks and low-frequency whistles are used to a lesser extent for the classification of killer whale signals as these call types are not as easily distinguishable from other odontocete clicks and whistles (e.g. Baird's beaked whales, pilot whales).

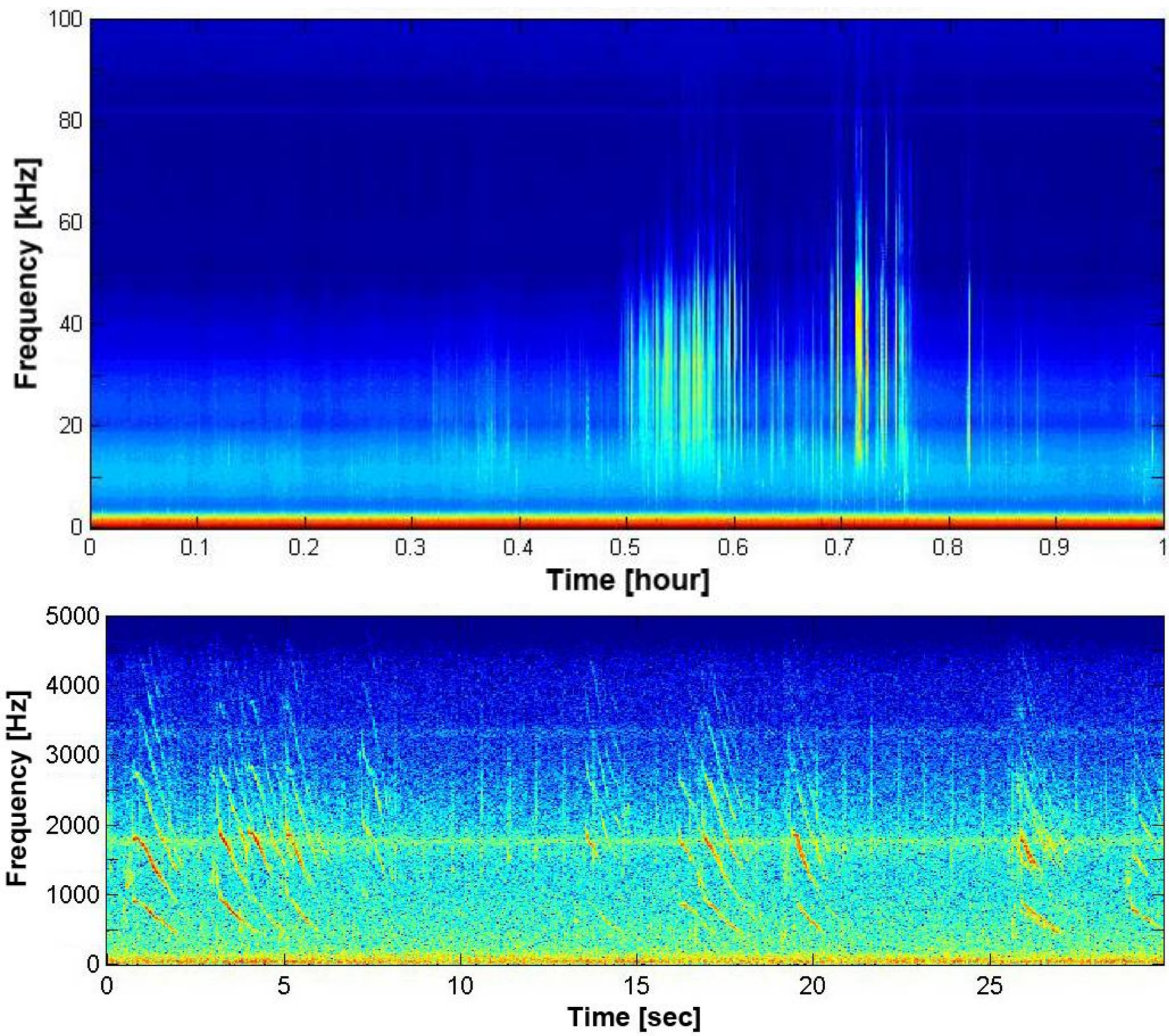


Figure 22. Killer whale echolocation clicks in the LTSA (top), whistles and pulsed calls in the spectrogram (bottom).

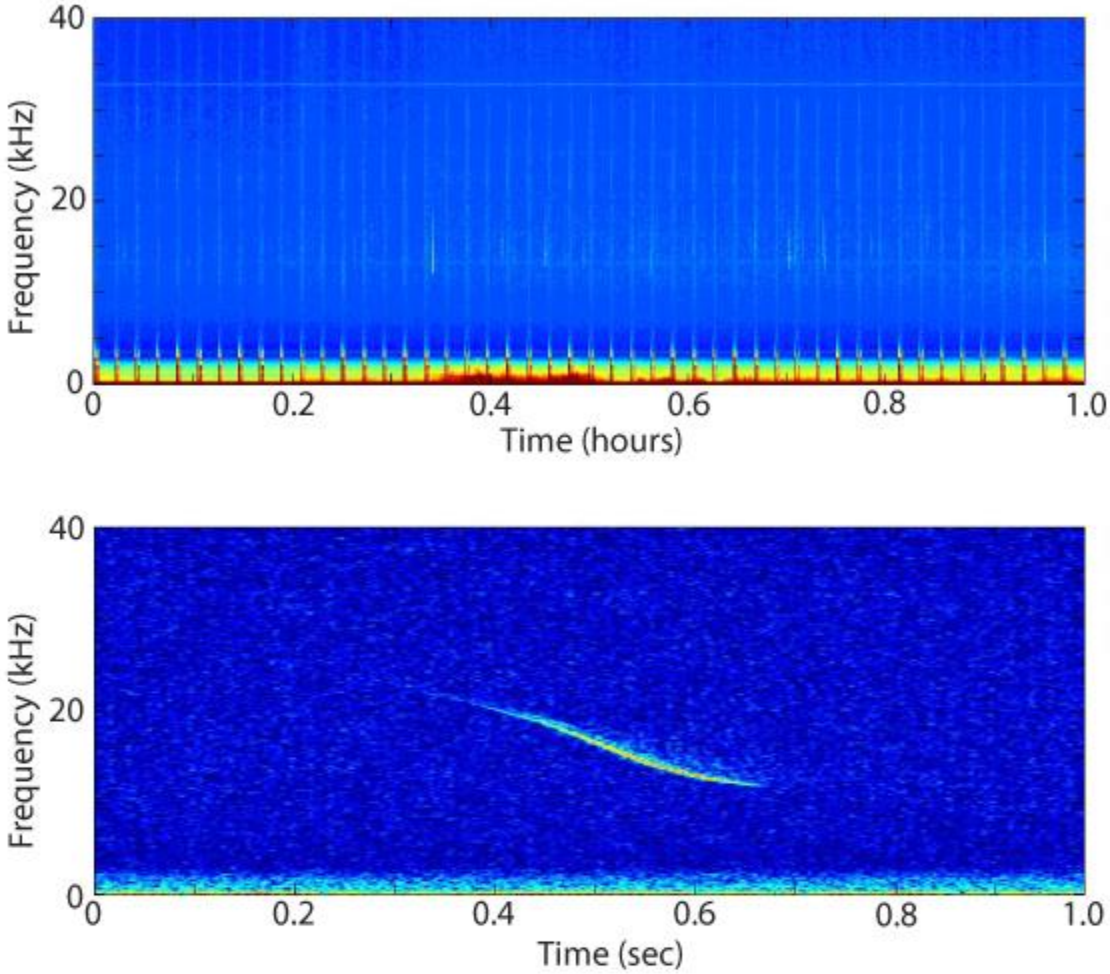


Figure 23. Killer whale high-frequency modulated (HFM) signal in the LTSA (top) and spectrogram (bottom).

Sperm Whale

Sperm whale clicks contain energy from 2-20 kHz, with peak energy between 10-15 kHz (Møhl et al. 2003). Regular clicks, observed during foraging dives, have a uniform inter-click interval of about one second (Goold & Jones 1995, Madsen et al. 2002, Møhl et al. 2003). Short bursts of closely spaced clicks, called buzzes, are observed during foraging dives and are believed to indicate a predation attempt (Watwood et al. 2006). Sperm whales emit regular clicks and buzzes during dives typically lasting about 45 minutes, followed by a quiet period of about 9 minutes while the whales are at the surface (Watwood et al. 2006). Multiple foraging dives and rest periods are often observed over a long period of time in the LTSA (Figure 24).

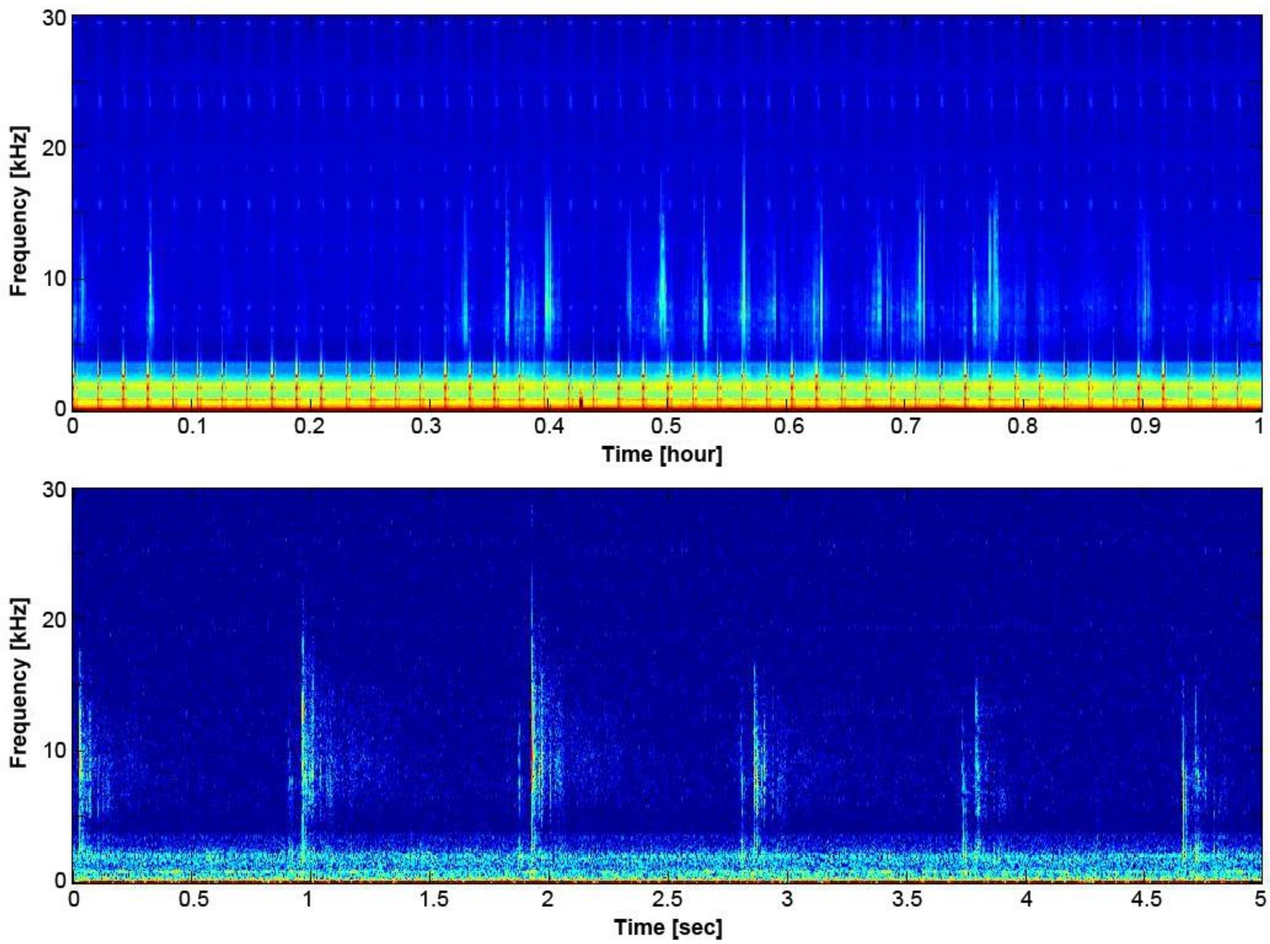


Figure 24. Echolocation clicks of sperm whales in the LTSA (top) and spectrogram (bottom).

Baird's Beaked Whale

Baird's beaked whale is the most commonly observed beaked whale species within their range (>30° N, North Pacific Ocean and adjacent seas), probably since they are relatively large and travel in groups of up to several dozen individuals (Allen & Angliss 2011). Baird's echolocation signals are distinguishable from other species' acoustic signals. They demonstrate the typical beaked whale polycyclic, frequency modulated (FM) upsweep but additionally use a delphinid-like echolocation click. These FM pulses and clicks are identifiable due to their comparably low-frequency content. Spectral peaks are notable around 15, 30, and 50-60 kHz (Baumann-Pickering et al. 2013c, Baumann-Pickering et al. 2013a) (Figure 25). Unlike other beaked whales in the area, Baird's beaked whales incorporate whistles and burst pulses into their acoustic repertoire (Dawson et al. 1998).

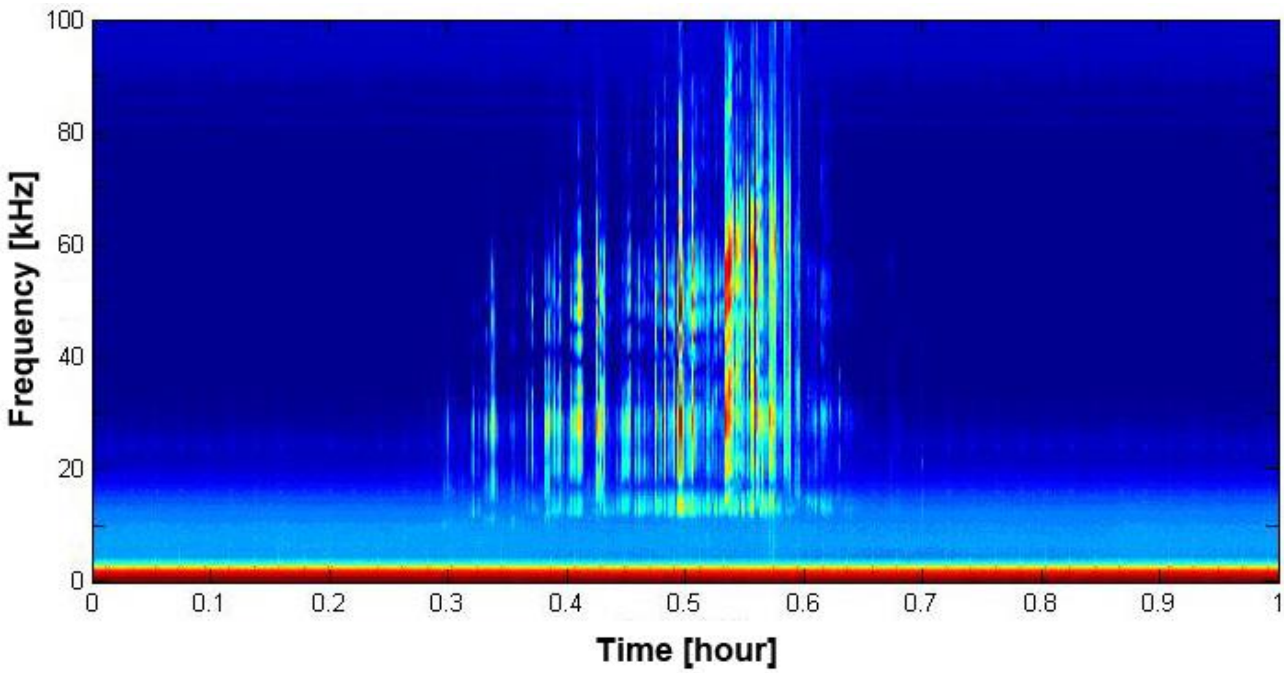


Figure 25. Echolocation sequence of Baird's beaked whale in LTSA with typical banding pattern of spectral peaks at about 15, 30, and 50-60 kHz.

Cuvier's Beaked Whale

Cuvier's beaked whale is uncommon in the Gulf of Alaska. Cuvier's echolocation clicks are well differentiated from other species' acoustic signals. These clicks are polycyclic, with a characteristic FM upsweep, peak frequency around 40 kHz (Figure 26) and uniform inter-pulse interval of about 400 ms (Johnson et al. 2004, Zimmer et al. 2005, Baumann-Pickering et al. 2013a).

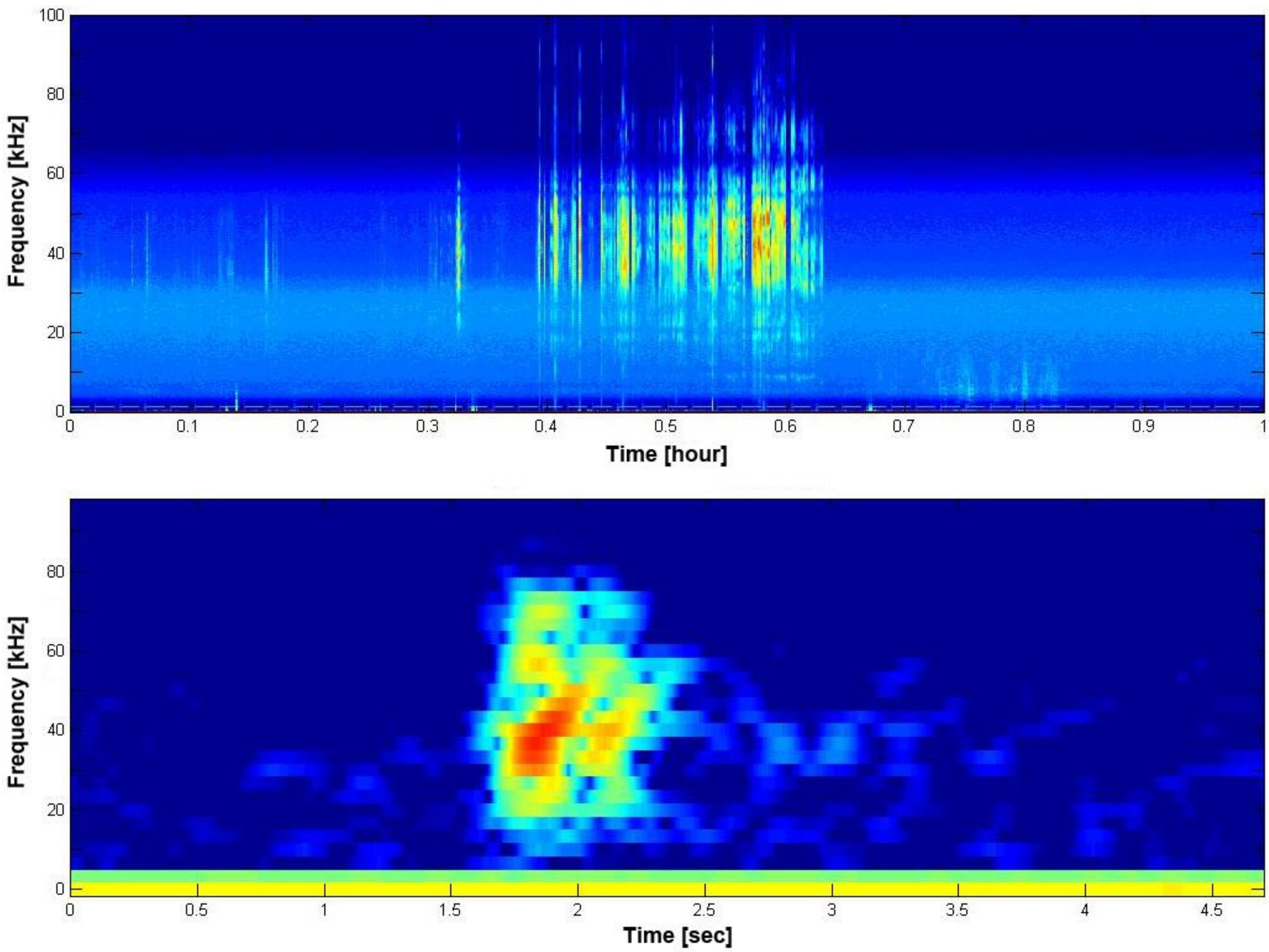


Figure 26. Echolocation sequence of Cuvier's beaked whale from Southern California in LTSA (top) and example FM pulse in spectrogram (bottom).

Stejneger's Beaked Whale

Stejneger's beaked whales are acoustically the most commonly encountered beaked whale in the Aleutian Islands chain; however, they have been rarely encountered at sea otherwise (Mead 1989, Walker & Hanson 1999, Loughlin et al. 1982) and their distribution has been inferred from stranded animals (Allen & Angliss 2011). They produce a FM pulse (Baumann-Pickering et al. 2013a, Baumann-Pickering et al. 2013b) as their echolocation signal in a regularly spaced interval (Figure 27). Their dominant energy is distributed between 45 and 75 kHz, with a peak frequency around 50 kHz. Their median inter-pulse interval is 80 ms (Baumann-Pickering et al. 2013a, Baumann-Pickering et al. 2013b).

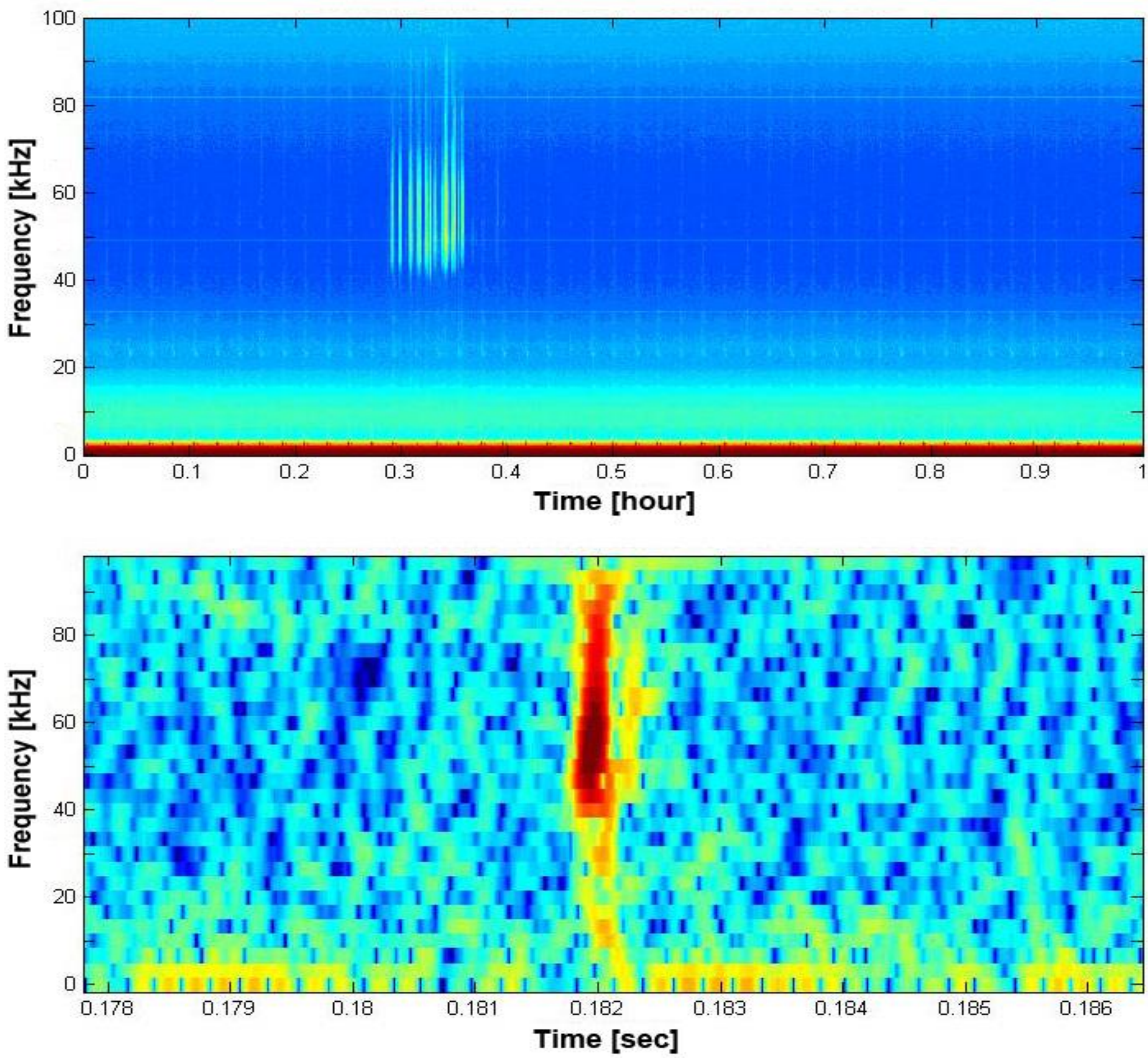


Figure 27. Echolocation sequence of Stejneger's beaked whale in LTSA (top) and single FM pulse in spectrogram (bottom).

Unidentified Porpoise

Dall's porpoise and harbor porpoise are known to occur in the Gulf of Alaska region. Harbor porpoises tend to inhabit more coastal areas with preferred water depths not exceeding 100 m, while Dall's porpoises are more widely distributed, using shallow as well as deep, oceanic waters (Allen & Angliss 2011). Both harbor porpoise as well as Dall's porpoise produce a similar, narrowband, high-frequency echolocation click (Bassett et al. 2009, Villadsgaard et al. 2007), with dominant energy between 120 and 150 kHz. Acoustically, we have not yet determined a classification scheme to differentiate between these two species. However, given their distribution and higher abundance estimates for Dall's porpoise in areas of the HARP deployments (Allen & Angliss 2011), we would expect most, if not all porpoise detections at all three sites to be Dall's porpoise.

The HARP only records acoustic energy up to 100 kHz, so the peak energy of the porpoise clicks is above the upper frequency band recorded by the HARPs. However, the HARP anti-alias filter will allow some spectral leakage from energy above 100 kHz, resulting in 120-140 kHz energy appearing at 60-80 kHz (Figure 28). Detection of porpoise clicks is therefore possible when the animals are close to the HARP (< ~1 km) and their received levels are high.

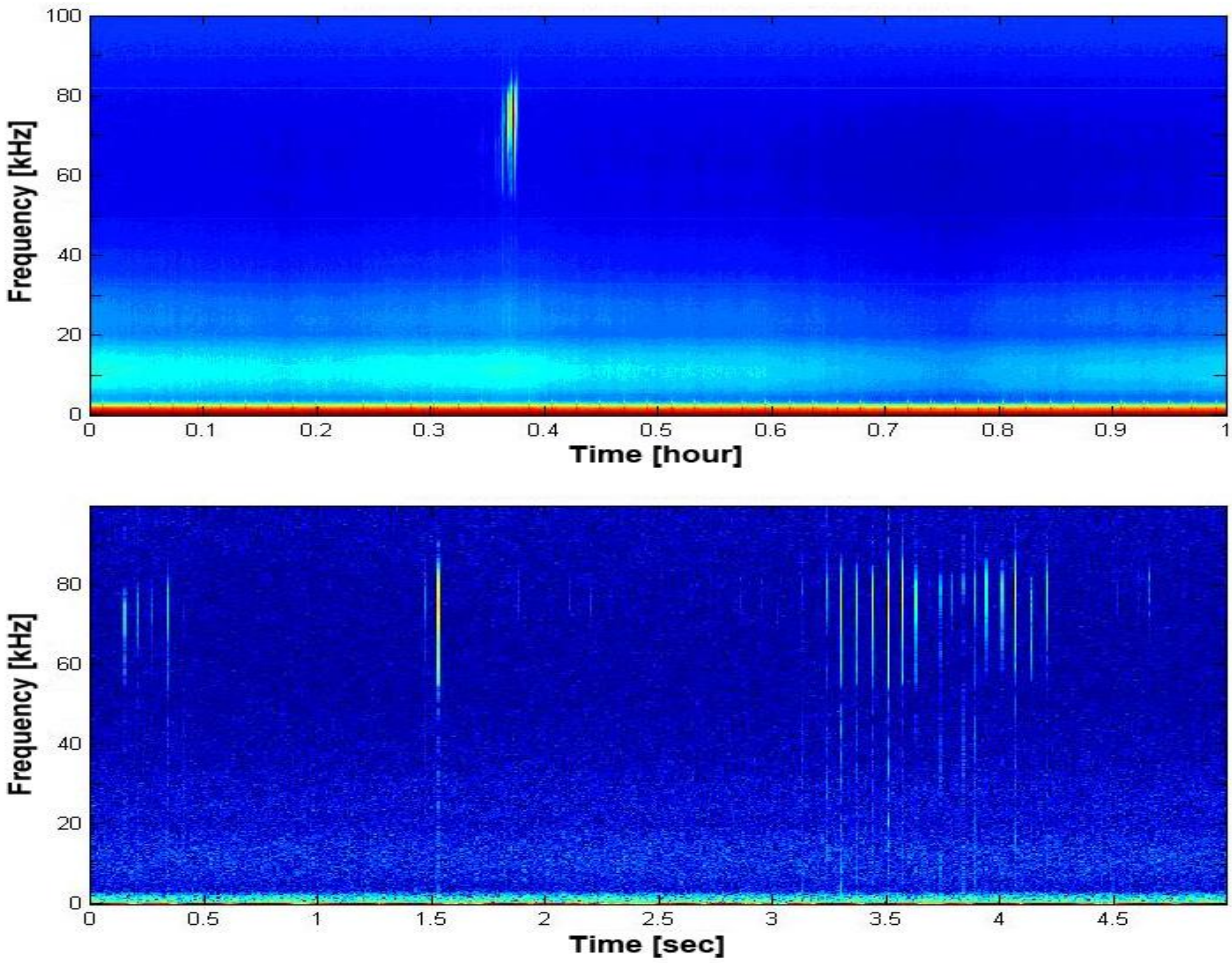


Figure 28. Example LTSA (top) and spectrogram (bottom), presumably produced by spectral aliasing of Dall's porpoise clicks (120 – 150 kHz frequency content).

Anthropogenic Noise

Broadband Ship Noise

Broadband ship noise occurs when a ship passes relatively close to the hydrophone. Ship noise can occur for many hours at a time, but broadband ship noise typically lasts from 10 minutes up to 3 hours. Ship noise has a characteristic interference pattern in the LTSA (McKenna et al. 2012). Combination of direct paths and surface reflected paths produce constructive and destructive interference (bright and dark bands) in the spectrogram that varies by frequency and distance between the ship and the receiver (red arrows in Figure 29). Noise can extend to above 10 kHz, though it typically falls off above a few kHz.

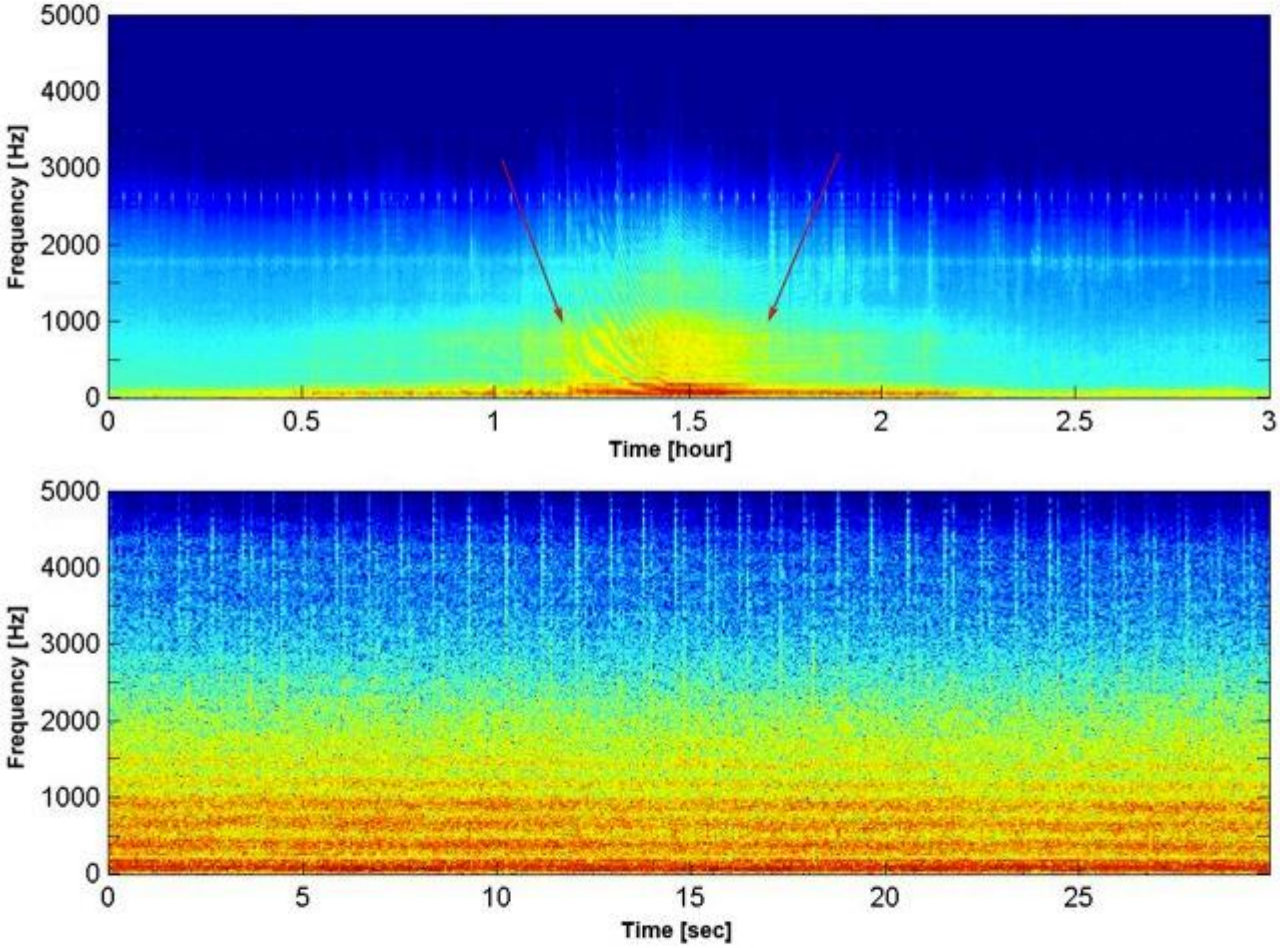


Figure 29. Broadband ship noise (arrows) in the LTSA (top) and spectrogram (bottom).

Mid-frequency Active Sonar

There are multiple types of active sonar. These span frequencies from about 1 kHz to over 50 kHz and include short duration pings, frequency modulated (FM) sweeps, and short and long duration constant frequency (CF) tones. One common type of sonar used during naval training is mid-frequency active (MFA) sonar for anti-submarine warfare (ASW) exercises. Sounds from MFA sonar vary in frequency and duration and can be used in a combination of FM sweeps and CF tones; however, many of these are between 2 and 5 kHz and are more generically known as '3.5 kHz' sonar. There were no MFA detections at any of the sites.

Echosounders

Echosounding sonars transmit short pulses or frequency sweeps, typically in the mid-frequency (8-12 kHz) or high frequency (30-100 kHz) band (Figure 30). These sonars may be used for sea bottom mapping, fish detection, or other ocean sensing. Many large and small vessels are equipped with echosounding sonar for water depth determination; typically these echosounders are operated much of the time a ship is at sea, as an aid for navigation. Echosounders were detected by analysts using the LTSA plots at both mid- and high-frequency.

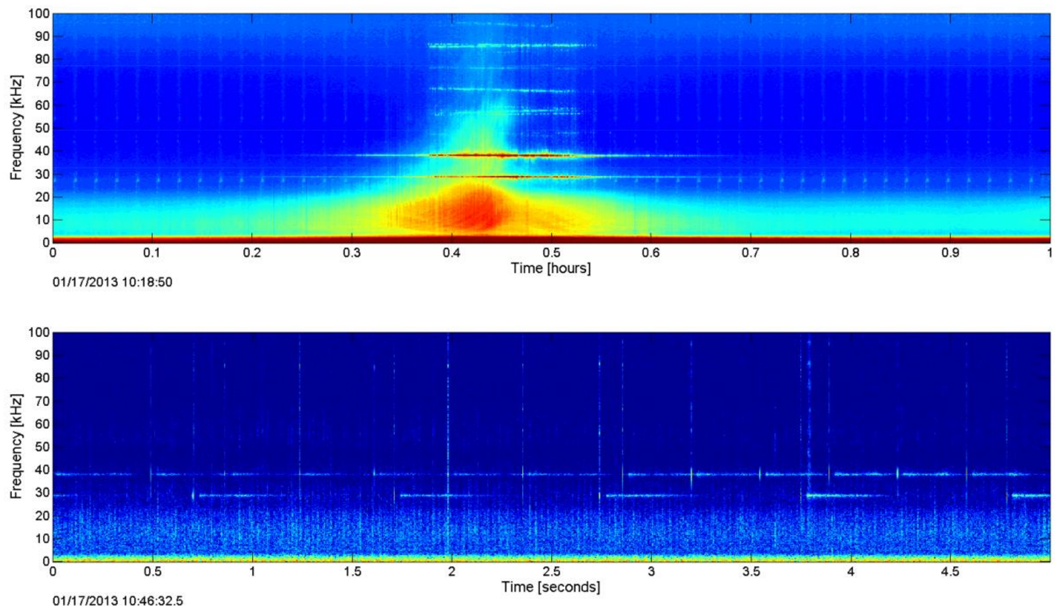


Figure 30. Example of an echosounder from site PT in the LTSA (top) and spectrogram (bottom).

Explosions

Effort was directed toward finding explosive sounds in the data 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 31, Figure 32). These sounds have peak energy as low as 10 Hz and often extend up to 2000 Hz or higher, lasting for a few seconds including the reverberation.

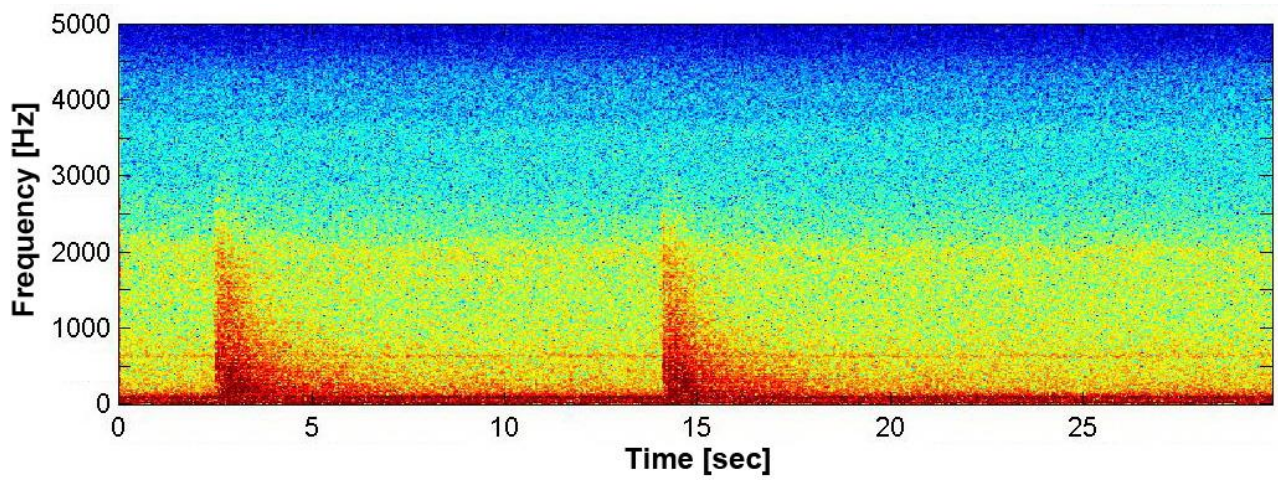


Figure 31. Two explosions are shown with rapid onset and extended reverberation.

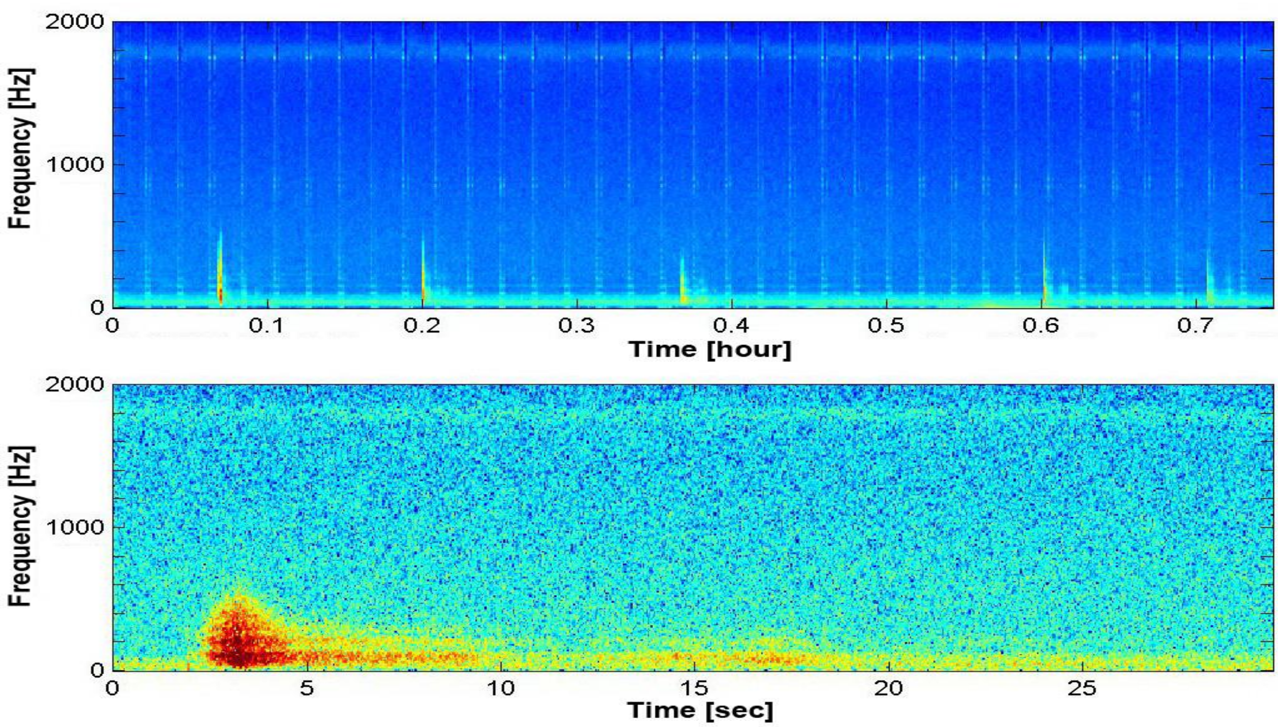


Figure 32. Five explosion events are shown at lower received levels (LTSA, top) and one example explosion (spectrogram, bottom). This explosion type shows a slower onset in comparison to the examples in Figure 31, suggesting a more distant source.

Results

We describe ambient noise, the seasonal occurrence and relative abundance of marine mammal species, and anthropogenic sounds. For clarity of presentation, all marine mammal and anthropogenic sound source occurrences will be displayed as weekly averages.

Ambient Noise

Underwater ambient noise at sites CA, CB, and PT has spectral shapes with higher levels at low frequencies (Figure 33). For site CA, the high noise levels experienced below 20 Hz are related to the strong tidal currents and strumming of the hydrophone mooring. At site PT, there is evidence of long-range ship noise at frequencies below 100 Hz (Hildebrand 2009). At all three sites, noise levels were generally lower in the summer relative to the fall and winter, probably due to decreased noise from wind and waves. Prominent seasonal peaks in noise were observed at frequency band 15-30 Hz and also at 47-45 Hz, related to the presence of blue and fin whale calls at sites CB and PT.

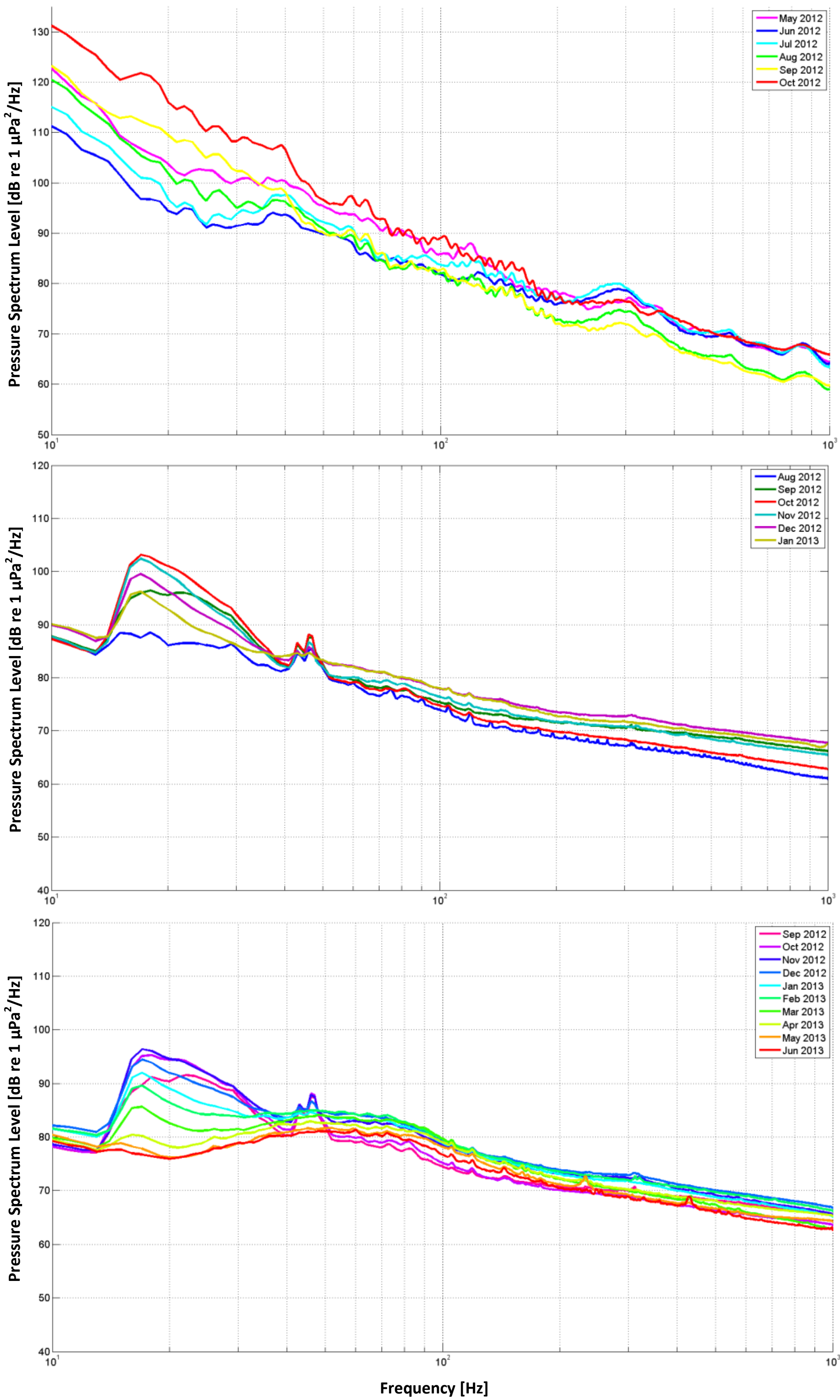


Figure 33. Monthly ambient noise in site CA (top), CB (middle), and PT (bottom).

Mysticetes

Three baleen species were recorded between May 2012 and June 2013 at sites CA, CB, and PT: blue whales, fin whales, and humpback whales. No calls were detected for gray whales (M3 calls) or North Pacific right whales (up-calls). In general, fewer baleen whale vocalizations were detected at site CA than at CB or PT. While that is likely a reflection of the distribution of the species, it may also be confounded by a decreased effective effort due to strumming. More details of each species' presence at these sites are given below.

Blue Whale

Blue whale calls were detected in the Gulf of Alaska from May 2012 through June 2013, with a brief gap from late February until late March (Figure 34). Whales from both the central Pacific, as well as the population found off the U.S. west coast, are found in this area.

- Peaks in overall calling occurred between August and November 2012 (Figure 34), with some variability across sites. This is consistent with recordings collected further south in the Gulf of Alaska (Watkins et al. 2000).
- Northeast Pacific B calls were the most abundant blue whale call detected with the highest number of hours with calls in August and again October - November 2012 at site CB, and peak detections at site PT from September to December 2012 (Figure 35).
- Central Pacific tonal calls were substantially less common than the Northeast Pacific B and D calls. These calls were detected at site CB in July and August 2012 and at site PT in September and early October 2012 (Figure 36). No Central Pacific tonal calls were detected at site CA.
- Blue whale D calls peaked earlier in the year than B calls; their peak occurred May and June 2012 at site CB and then again in April and May 2013 at site PT (Figure 37).
- There was no diel pattern in blue whale B and Central Pacific tonal calls (Figure 38, Figure 39). D calls, however, generally occurred more during daylight hours with additional peaks at sunset (Figure 40).

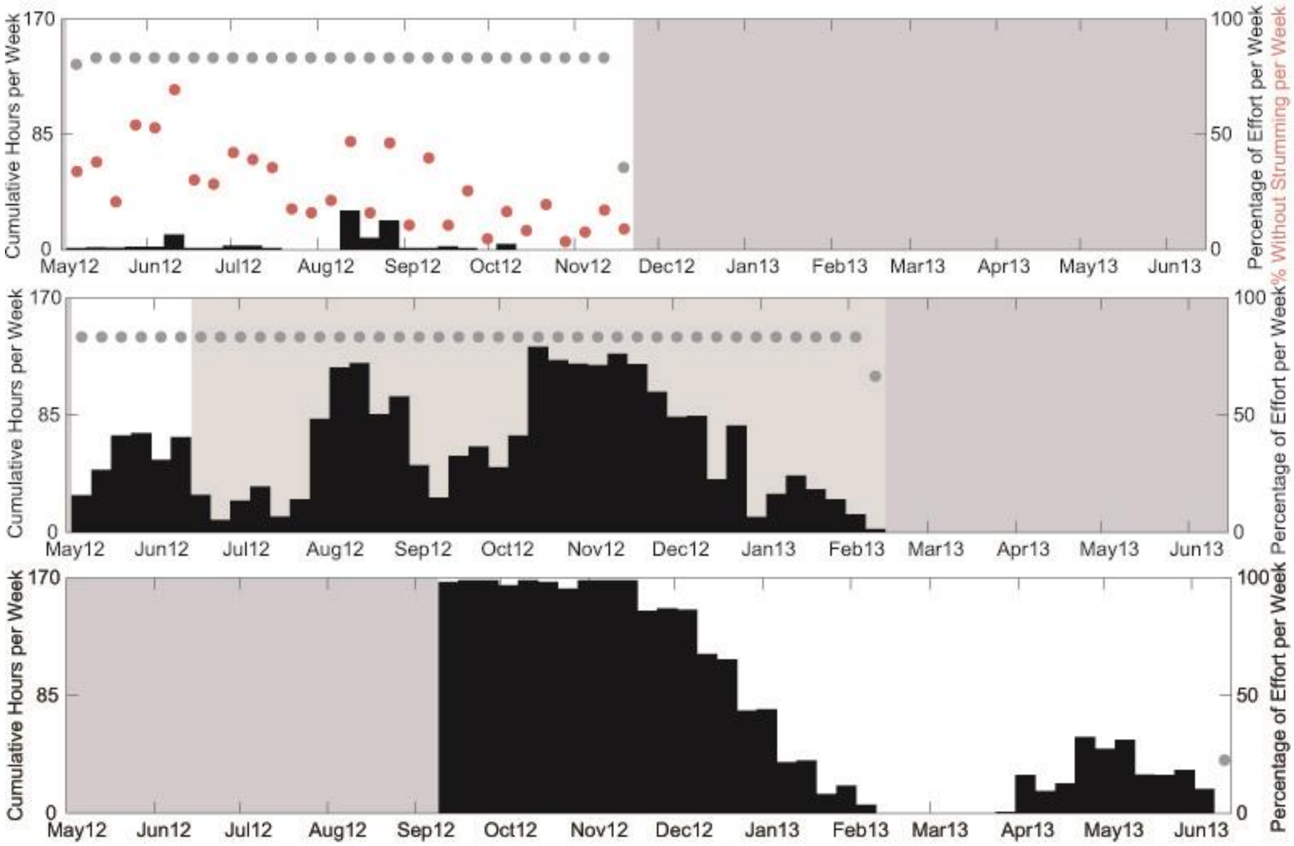


Figure 34. Weekly presence of all blue whale calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Grey dots represent percent of effort per week in weeks with less than 100% recording effort. Red dots represent percent of hours per week without strumming or broadband spikes. Dark gray shading shows periods with no recording effort, while lighter gray is period with lower quality data. Where gray or red dots or shading are absent, full recording effort occurred for the entire week.

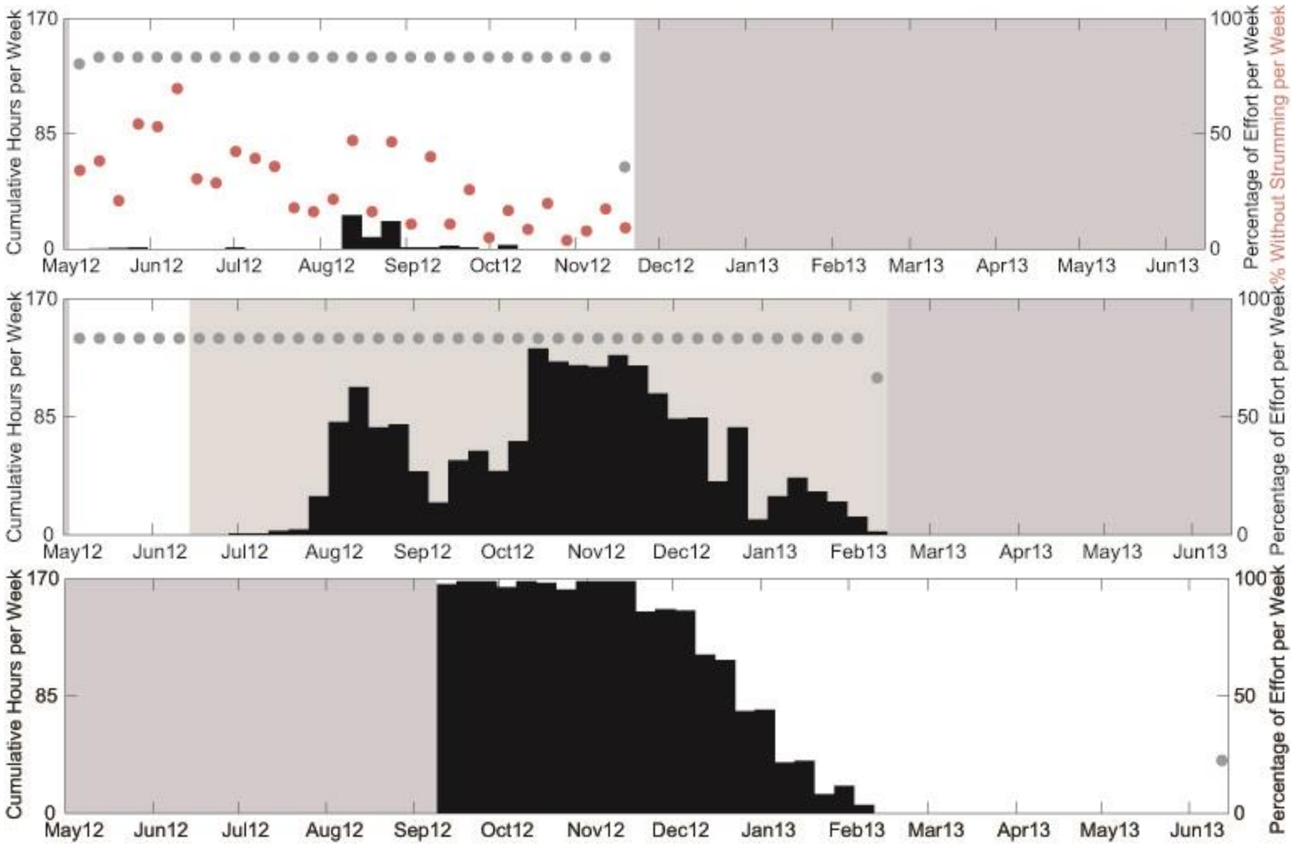


Figure 35. Weekly presence of Northeast Pacific blue whale B calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 34.

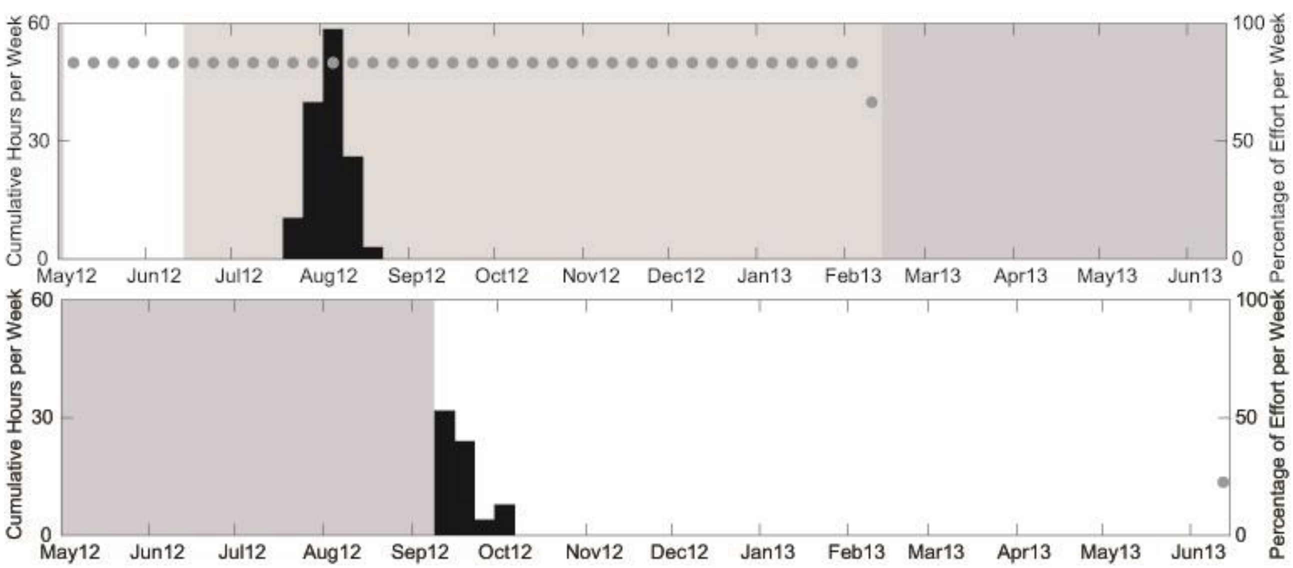


Figure 36. Weekly presence of Central Pacific blue whale calls (black bars) at sites CB (top) and PT (bottom) between May 2012 and June 2013. No calls were detected at site CA. Effort as described in Figure 34.

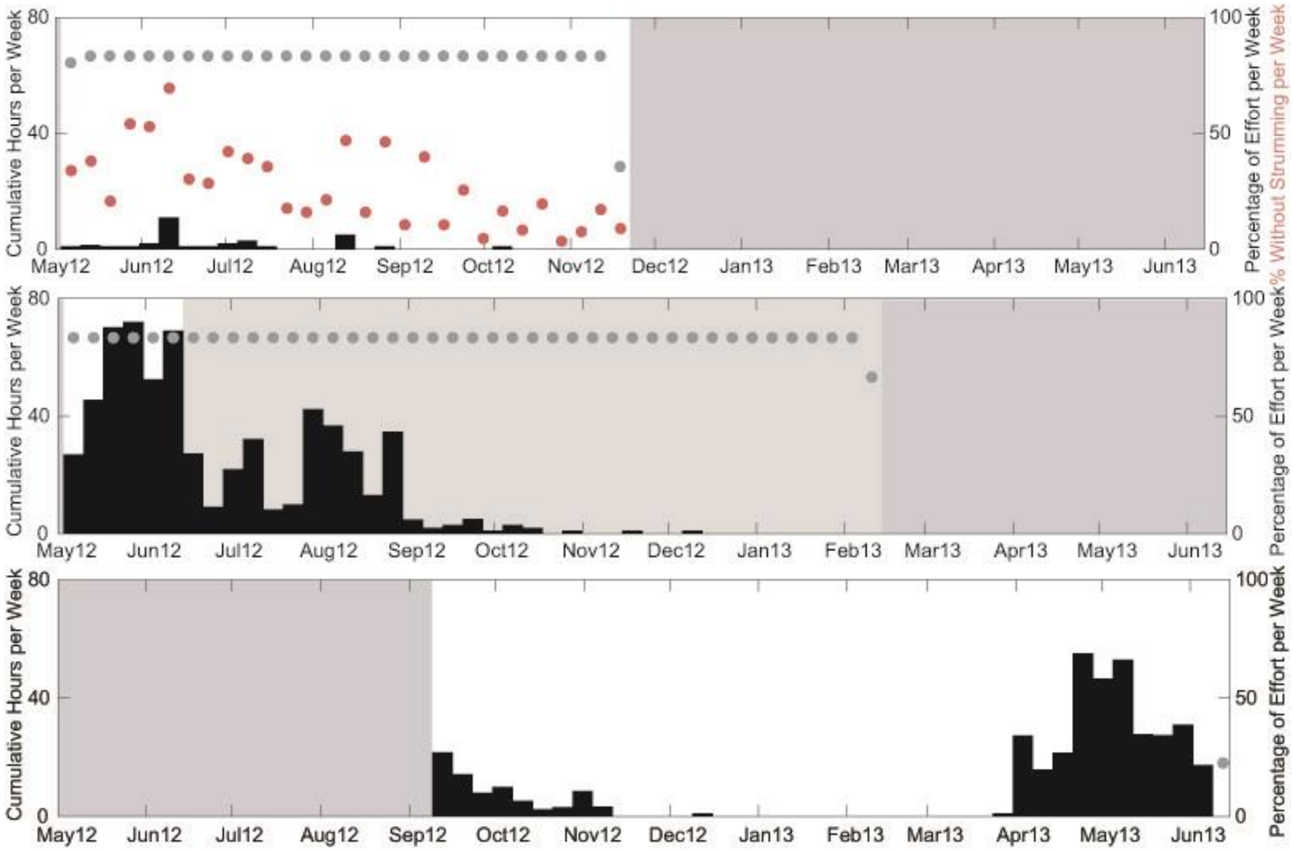


Figure 37. Weekly presence of blue whale D calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 34.

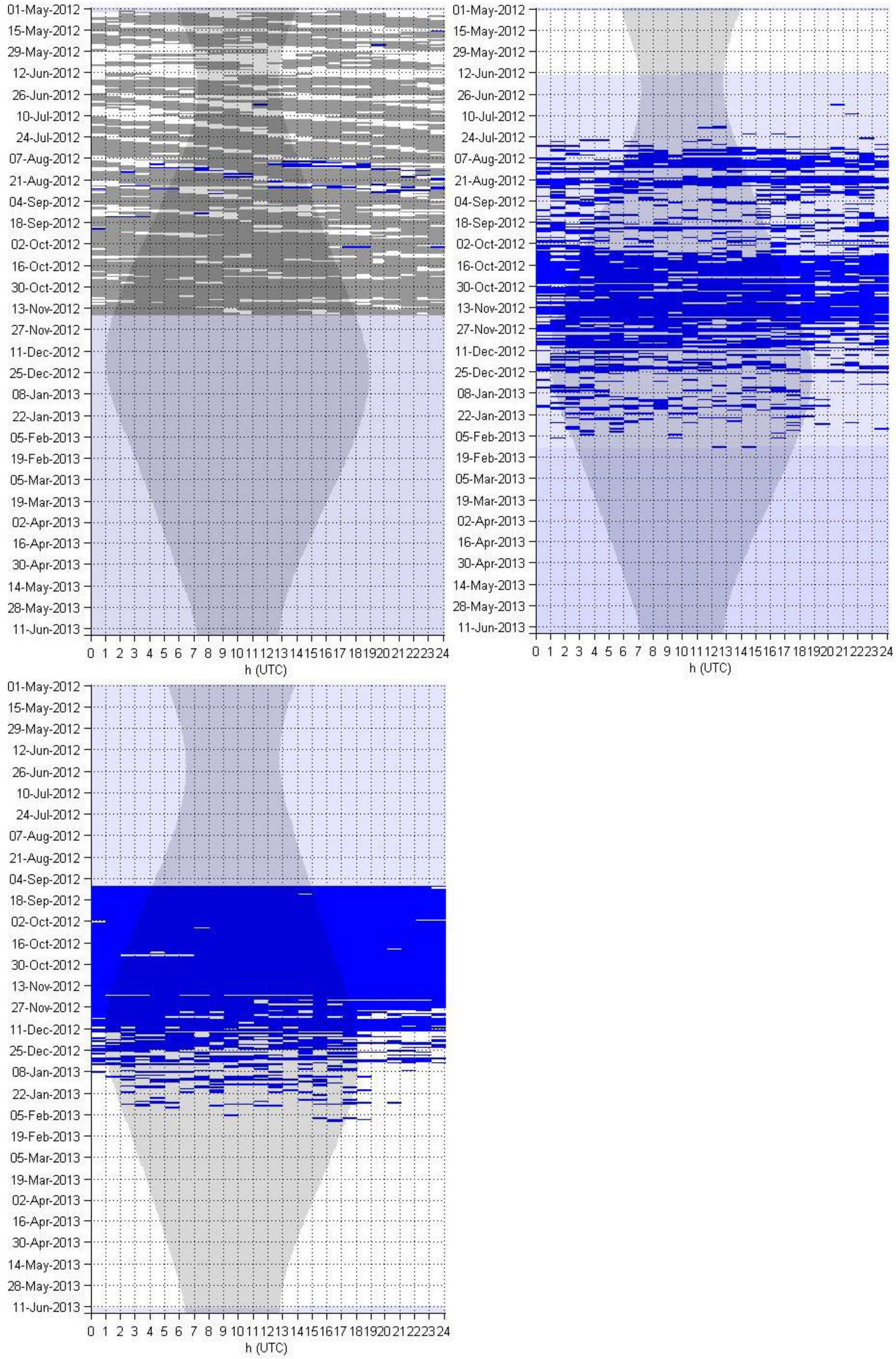


Figure 38. Blue whale B calls in hourly bins at sites CA (top left), CB (top right), and PT (bottom). Gray shading denotes nighttime and light purple shading denotes lower quality data and dark purple denotes lack of acoustic data. At site CA, dark gray shows periods of strumming causing masking.

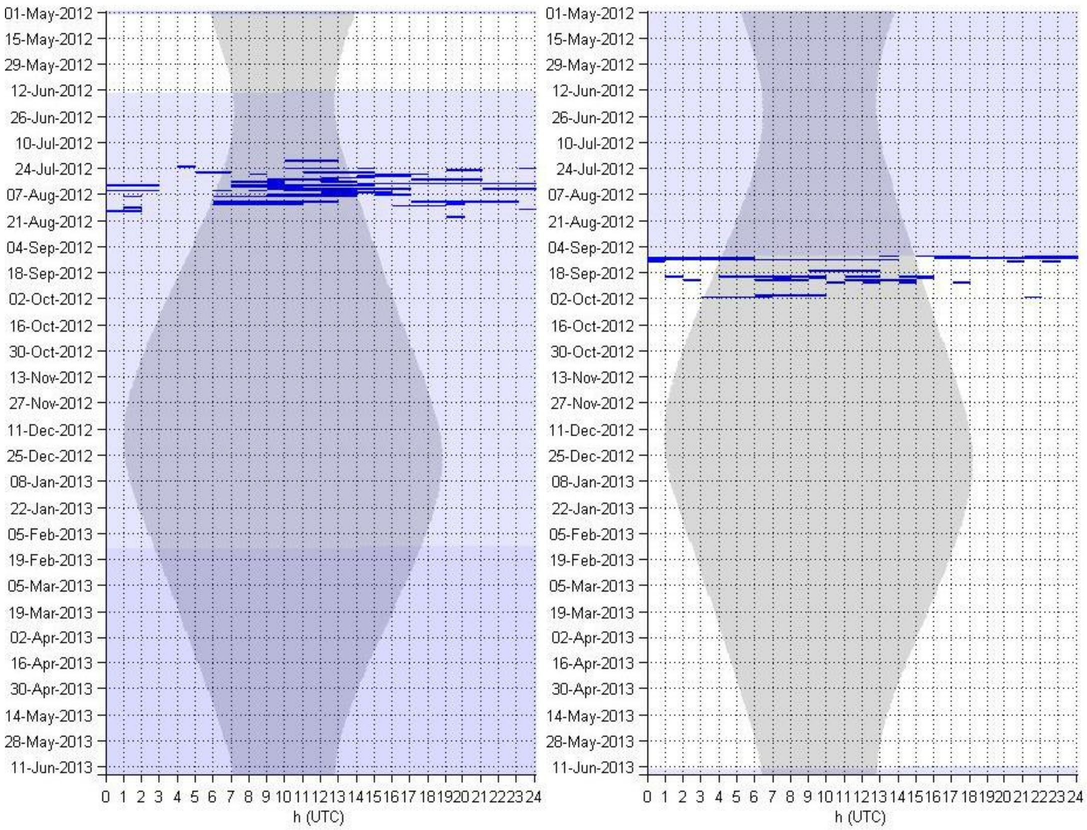


Figure 39. Central Pacific blue whale calls in hourly bins at sites CB (left) and PT (right). Shading is as described in Figure 38.

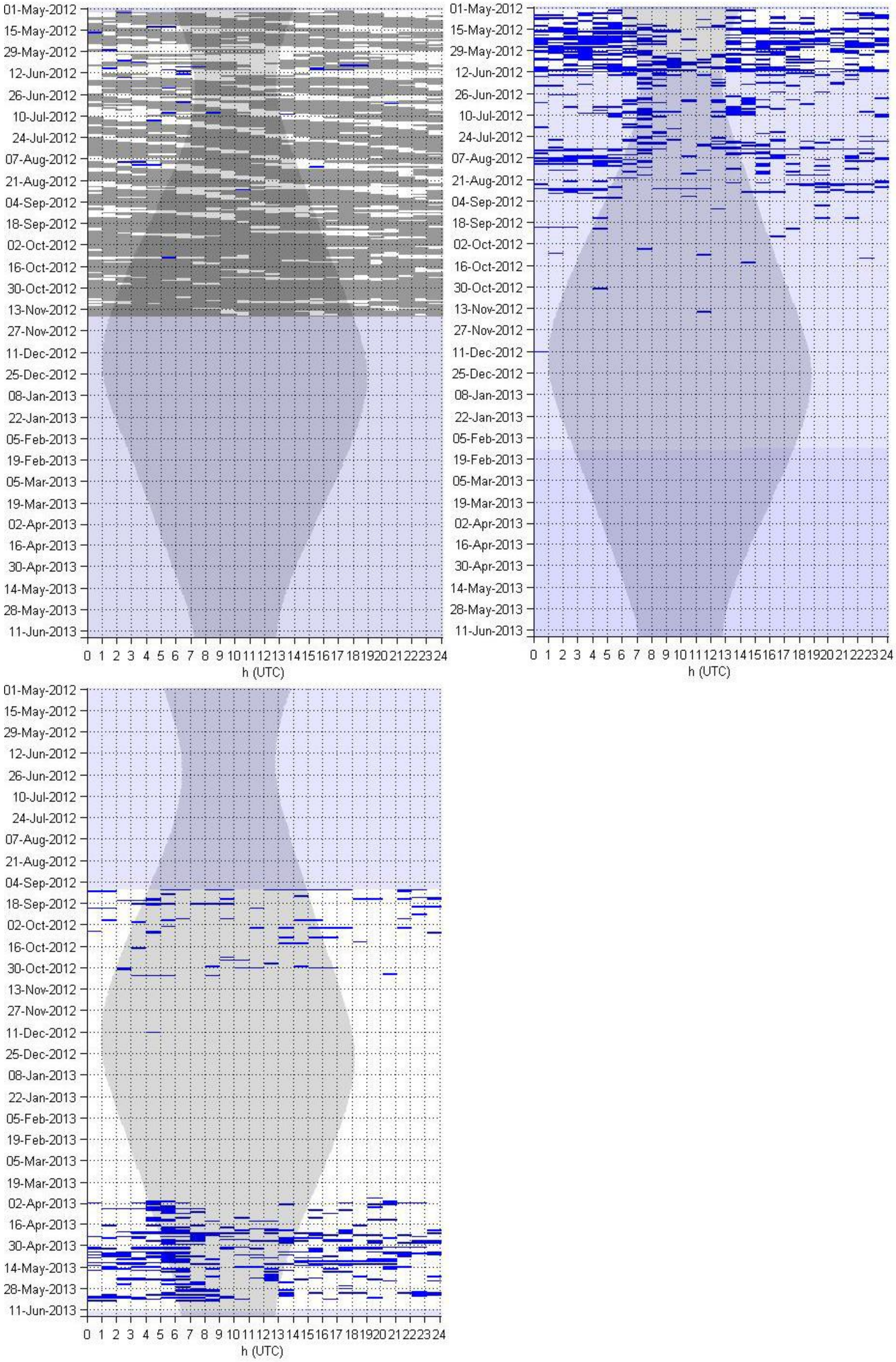


Figure 40. Blue whale D calls in hourly bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38. At site CA, dark gray shows periods of strumming causing masking.

Fin Whale

Fin whale calls were detected throughout the recording period at all sites (Figure 41). This indicates that not all fin whales undergo seasonal migration to lower latitudes, but some fraction of the population remains in the North Pacific year-round.

- The 20 Hz calls, associated with singing and call-countercall among animals, were the dominant fin whale call type (Figure 42). Detections were high September 2012 through March 2013 at sites CB and PT.
- An additional fin whale sound, the 40 Hz call, was also frequently recorded at both sites, although these calls were not as common as the 20 Hz fin whale pulses (Figure 43). Detections of 40 Hz calls peaked in May 2012 and 2013, with a secondary peak at site CB in November 2012.
- Fin whale 20 Hz (Figure 44) and 40 Hz (Figure 45) calls are detected both during daylight and nighttime hours.

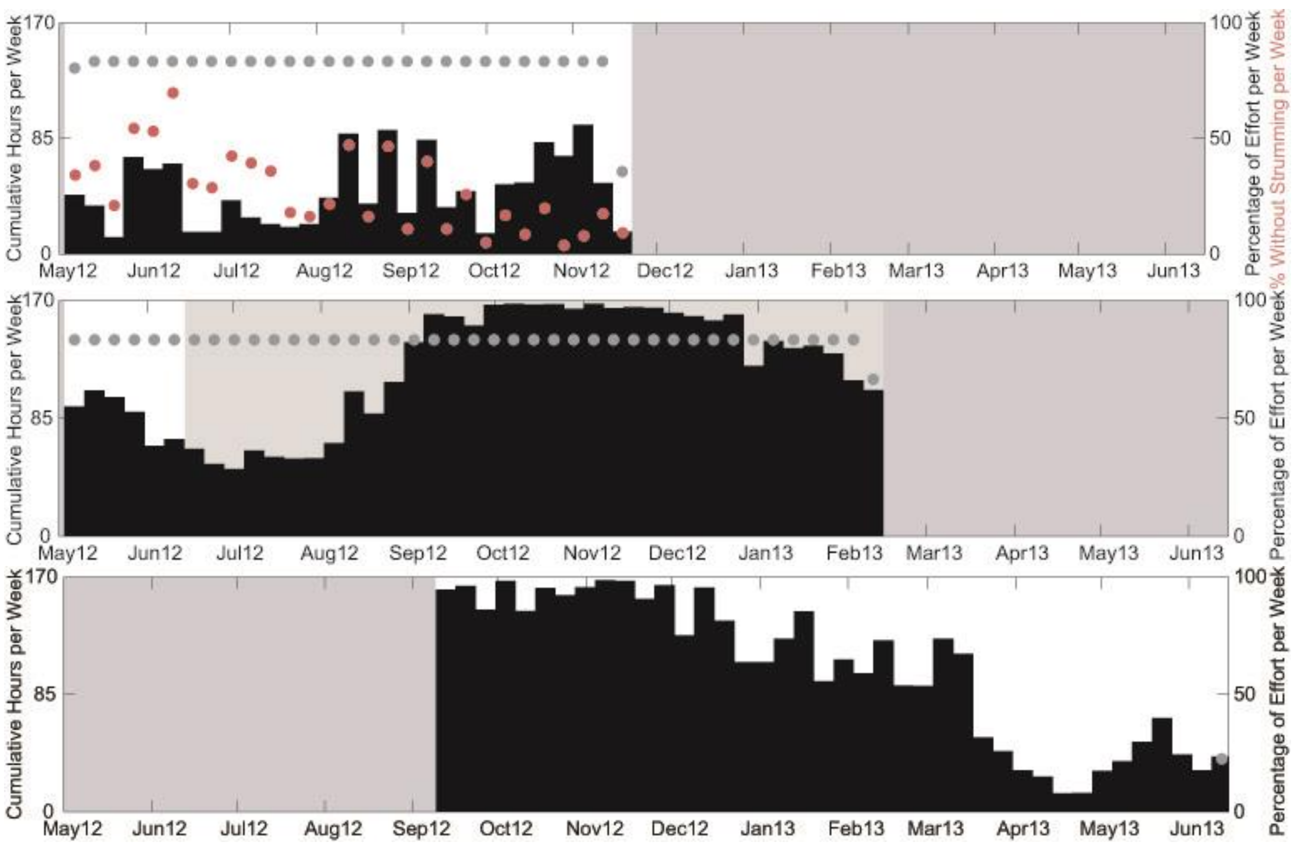


Figure 41. Weekly presence of all fin whale calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 34.

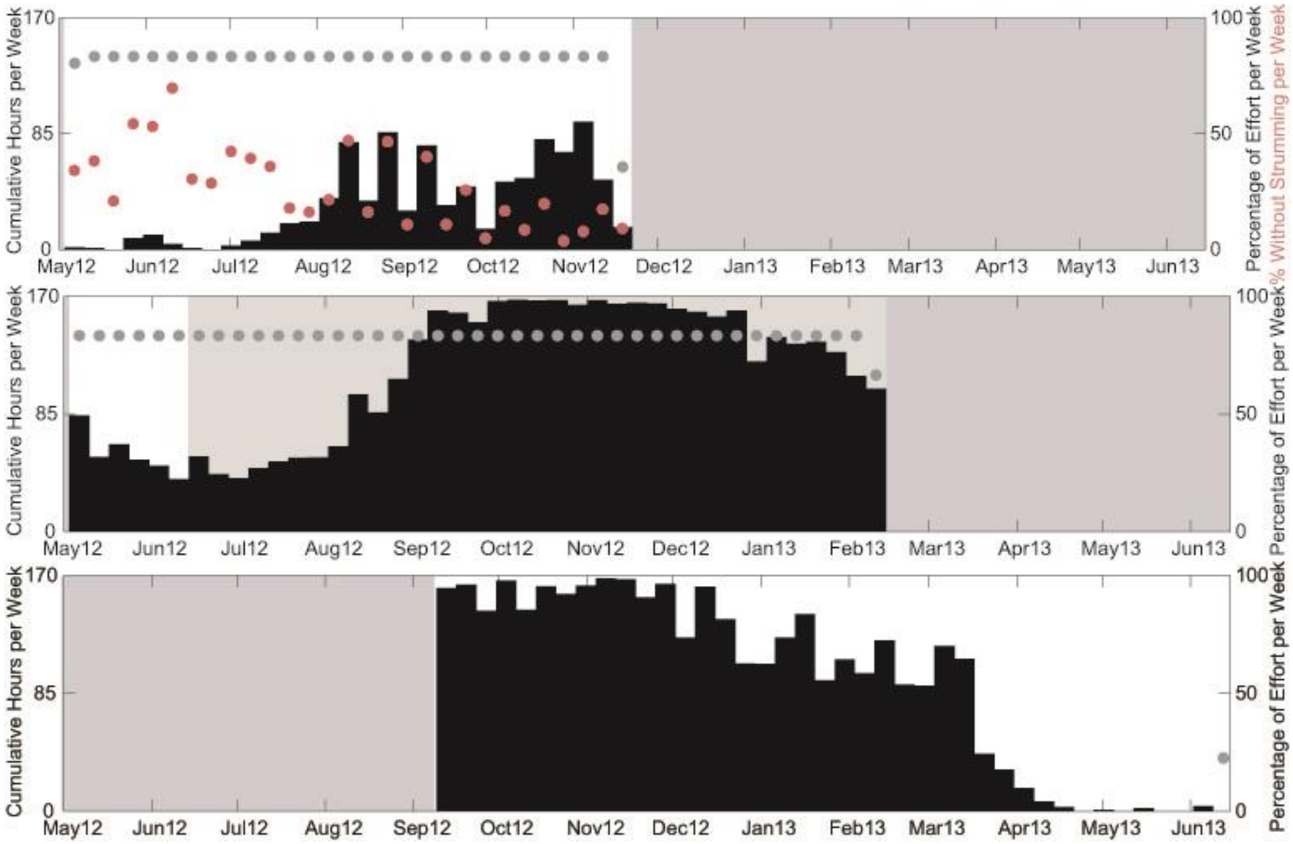


Figure 42. Weekly presence of fin whale 20 Hz calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 34.

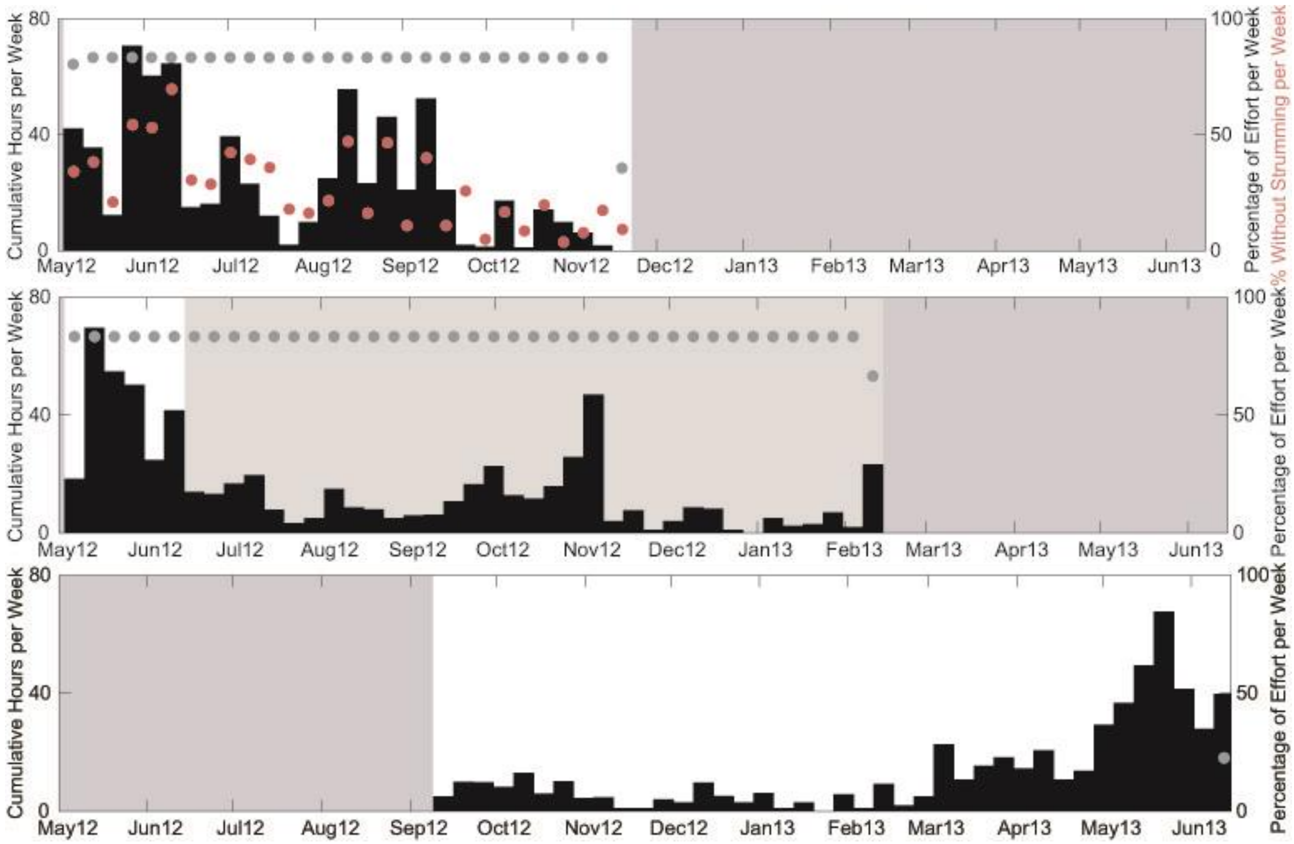


Figure 43. Weekly presence of fin whale 40 Hz pulse (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 34.

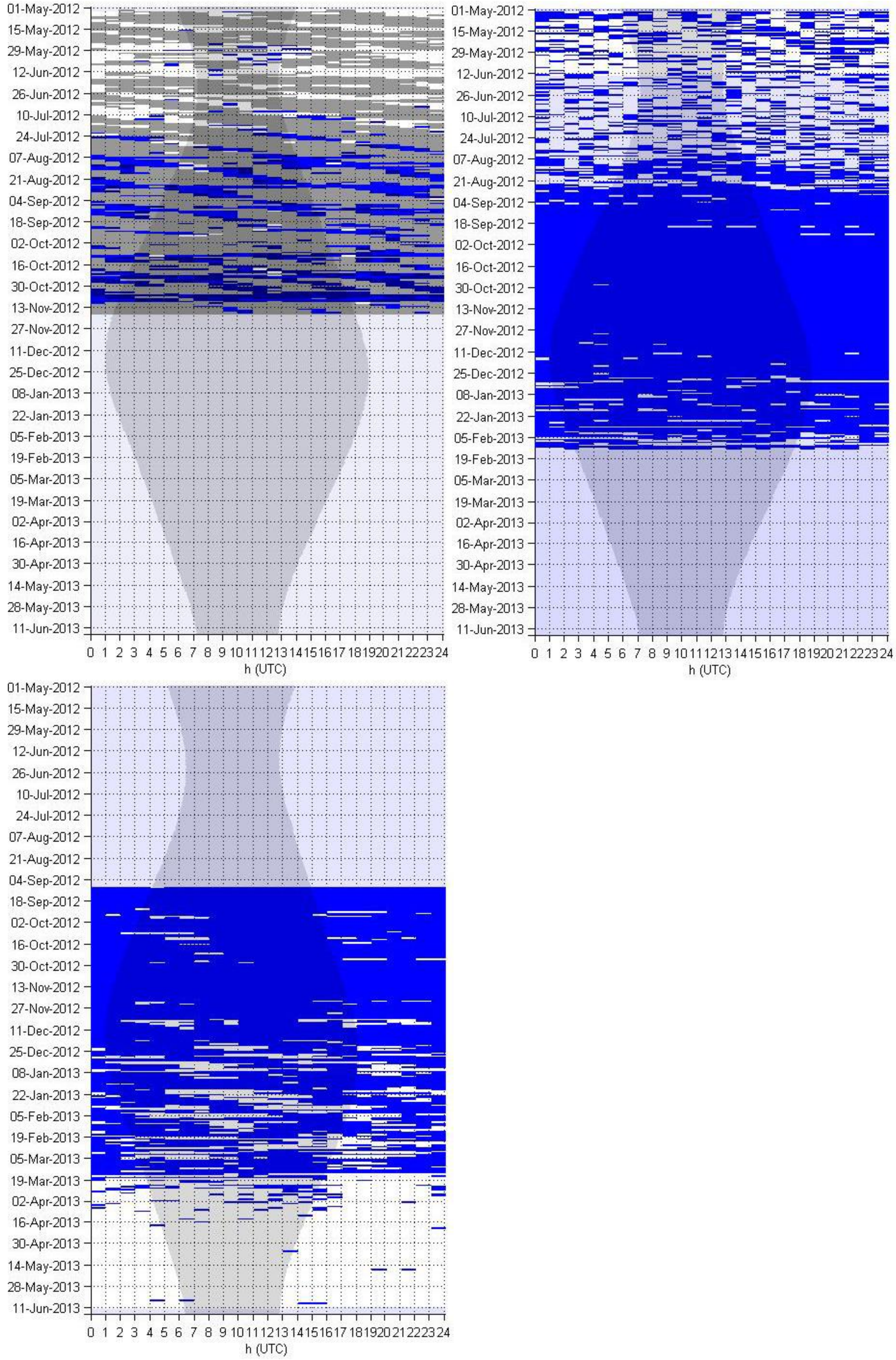


Figure 44. Fin whale 20 Hz calls in hourly bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38. At site CA, dark gray shows periods of strumming causing masking.

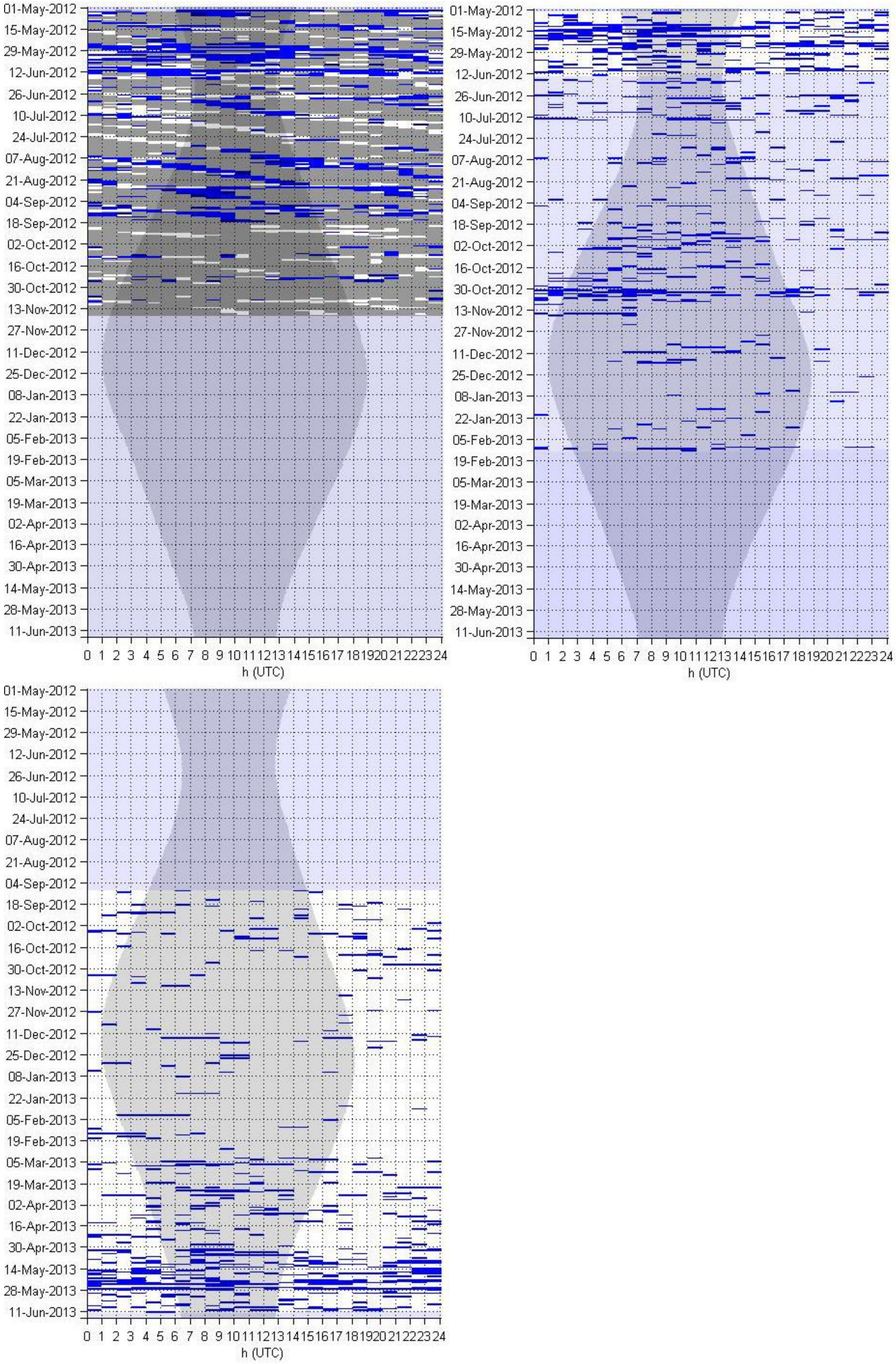


Figure 45. Fin whale 40 Hz calls in hourly bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38. At site CA, dark gray shows periods of strumming causing masking.

Humpback Whale

Humpback whales were detected at all three sites (Figure 46). Humpback whales are thought to inhabit the Gulf of Alaska primarily during summer and fall, and animals seen in this area have been connected by photo-identification studies to winter breeding grounds in Hawaii and off the coast of Mexico (Calambokidis 2010).

- There were peaks in calling hours from late-fall and early-winter. The substantial presence of humpback whales at all sites during the fall and at sites CB and PT during winter does not fit models of whale migration to subtropical or tropical waters during the winter breeding season. These data instead suggest that some whales remain in subpolar waters during the winter.
- Song and non-song call types were grouped together for this analysis, but peaks in calling during the winter months are likely due to song, reflecting a possible shift in primary behavior from foraging to pairing and mating.
- Humpback whale calls were produced somewhat more at night than during the day at site CA; however there was no discernable diel pattern at the other two sites (Figure 47).

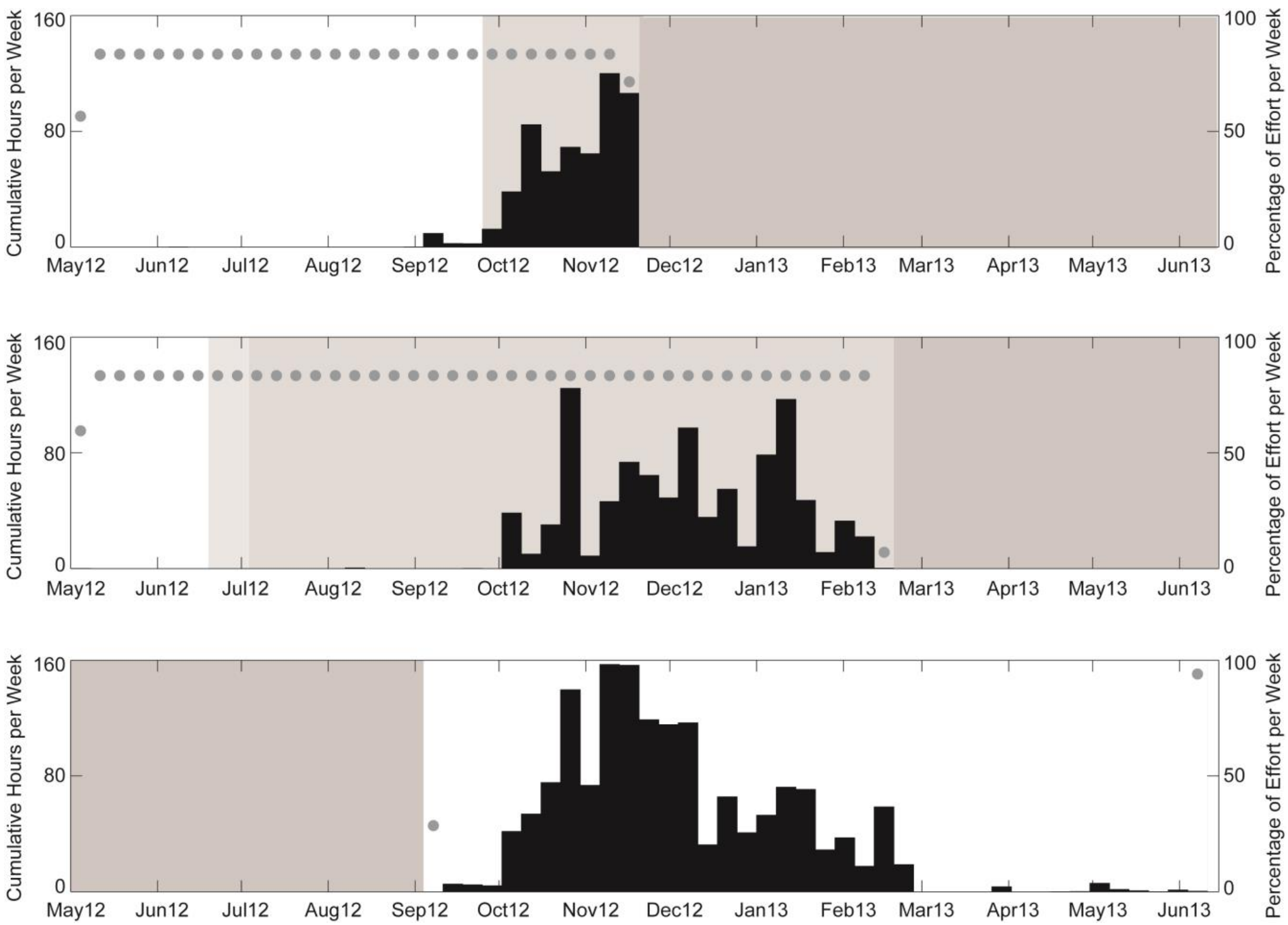


Figure 46. Weekly presence of all humpback whale calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Grey dots represent percent of effort per week in weeks with less than 100% recording effort. Dark gray shading shows periods with no recording effort, while shades of lighter gray are periods with lower quality data.

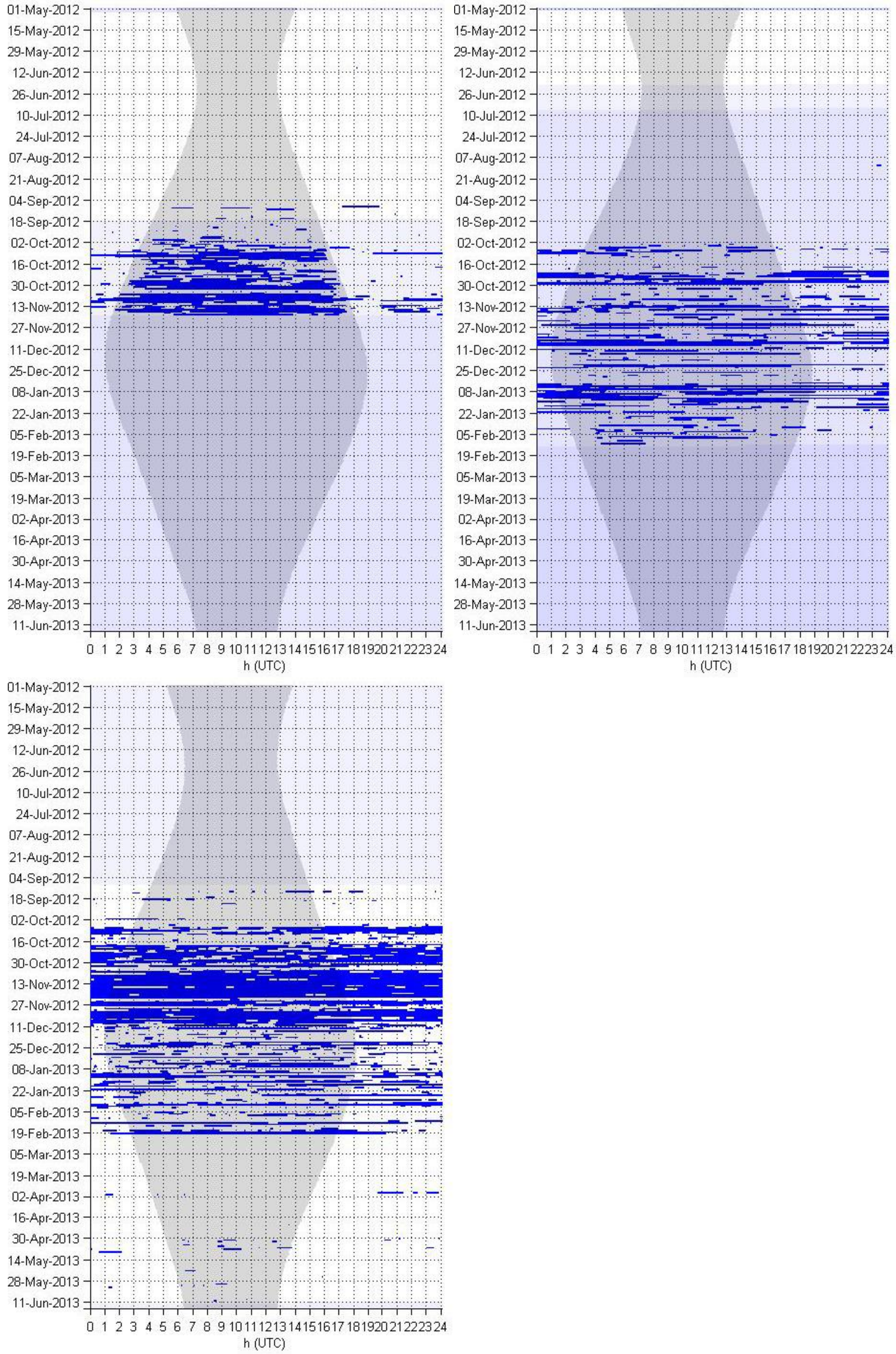


Figure 47. Humpback whale calls in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Odontocetes

At least seven species of odontocetes were detected during these deployments: Risso's dolphin, killer whale, sperm whale, Baird's beaked whale, Cuvier's beaked whale, Stejneger's beaked whale, and unidentified porpoise (likely Dall's porpoise). No Pacific white-sided dolphins were detected at any of the sites during the time period May 2012 through June 2013.

Unidentified Odontocetes

Signals that could not be classified to species were grouped together as unidentified odontocetes.

- These calls occurred throughout the year and peaks in detections varied at the three different sites (Figure 48).
- More detections were made at sites CB and PT than at site CA.
- Most unidentified odontocete signals at site CB were detected during nighttime hours, but the pattern is less clear at the other sites (Figure 49).

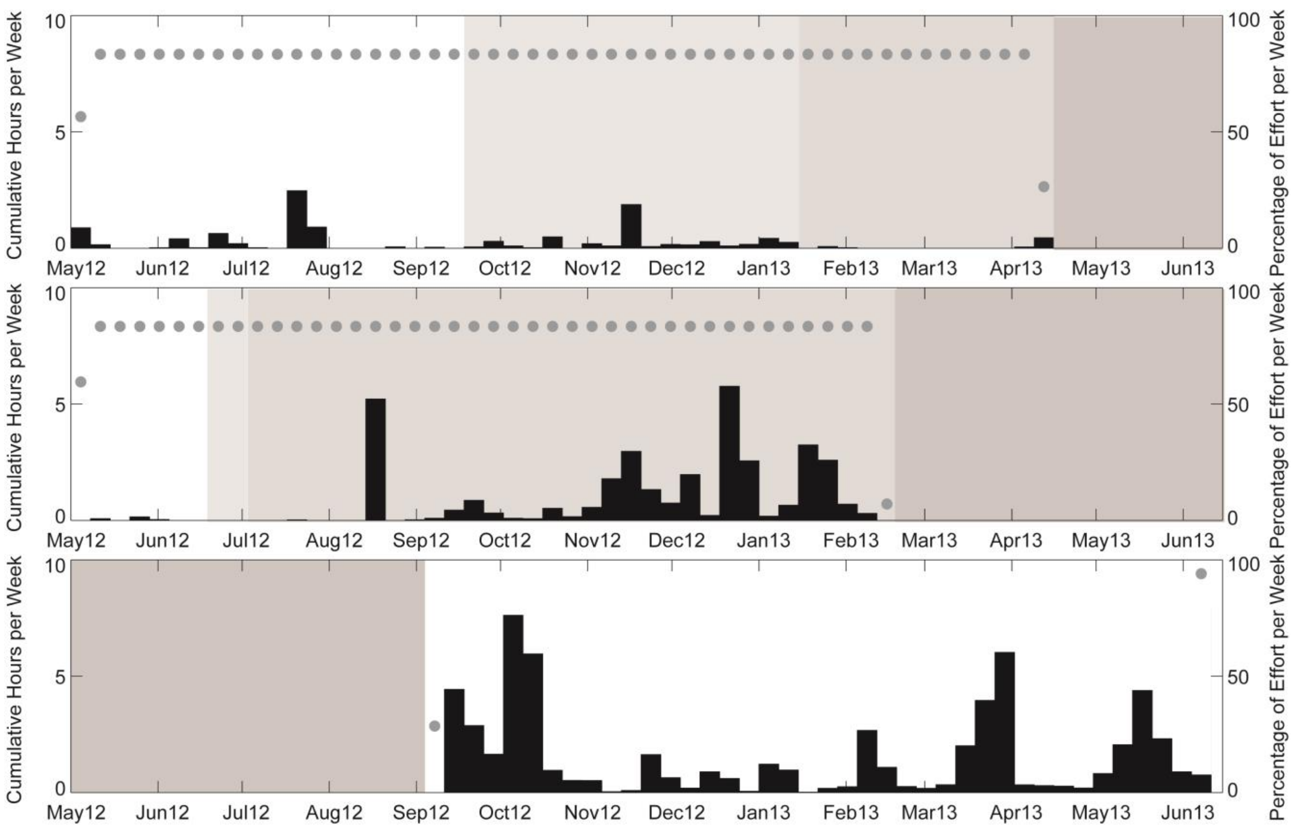


Figure 48. Unidentified odontocete signals (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

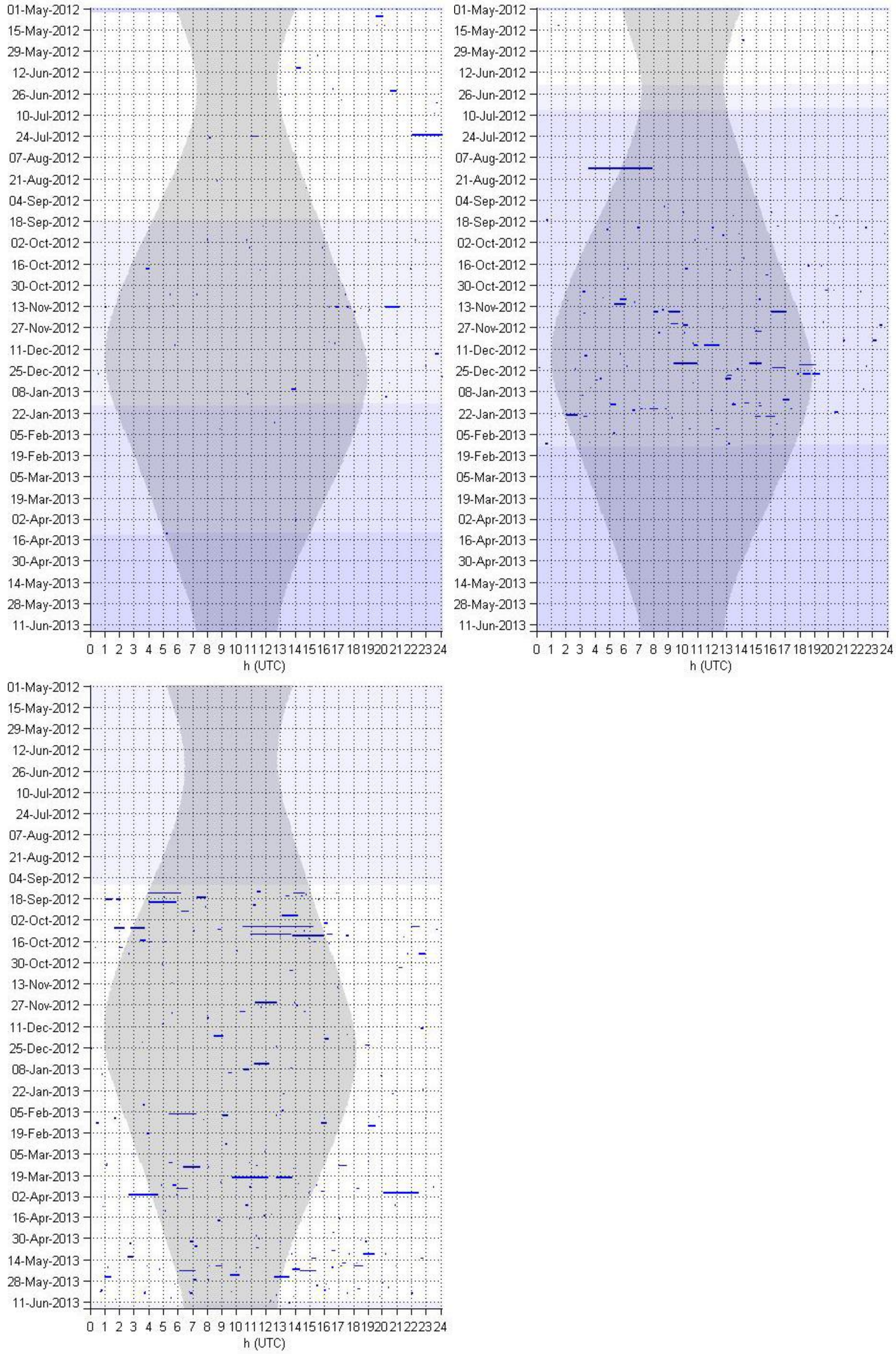


Figure 49. Unidentified odontocete signals in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Risso's Dolphin

Risso's dolphin echolocation clicks were only detected once at site PT.

- The detection consisted of a single bout of clicks on January 16, 2013 (Figure 50).

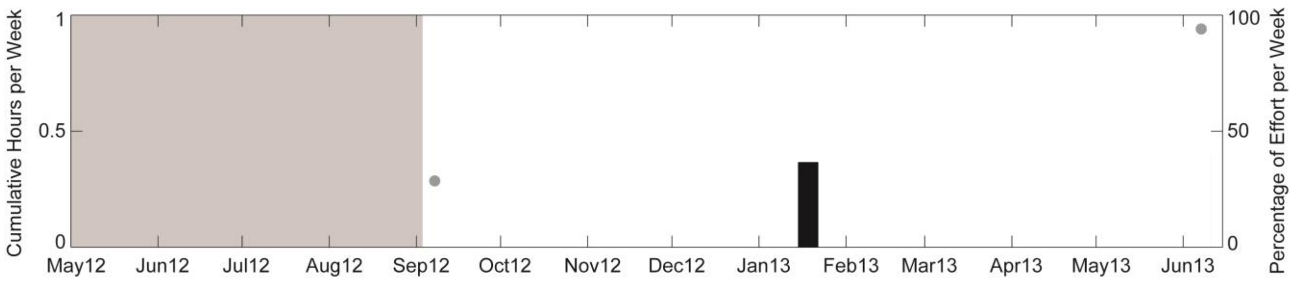


Figure 50. Weekly presence of Risso's dolphin clicks (black bars) at site PT between May 2012 and June 2013. Effort as described in Figure 46.

Killer Whale

Killer whale signals were encountered intermittently at all three sites, although site CB had the highest occurrence of signals.

- Killer whale clicks were generally more common at each site than whistles and pulsed calls. More clicks were detected at site CB than sites CA or PT (Figure 51).
- Whistles and pulsed calls were detected sporadically at each site, though they were also more prevalent at site CB than sites CA or PT (Figure 52).
- There were no discernible diel patterns for either clicks (Figure 53) or whistles and pulsed calls (Figure 54).

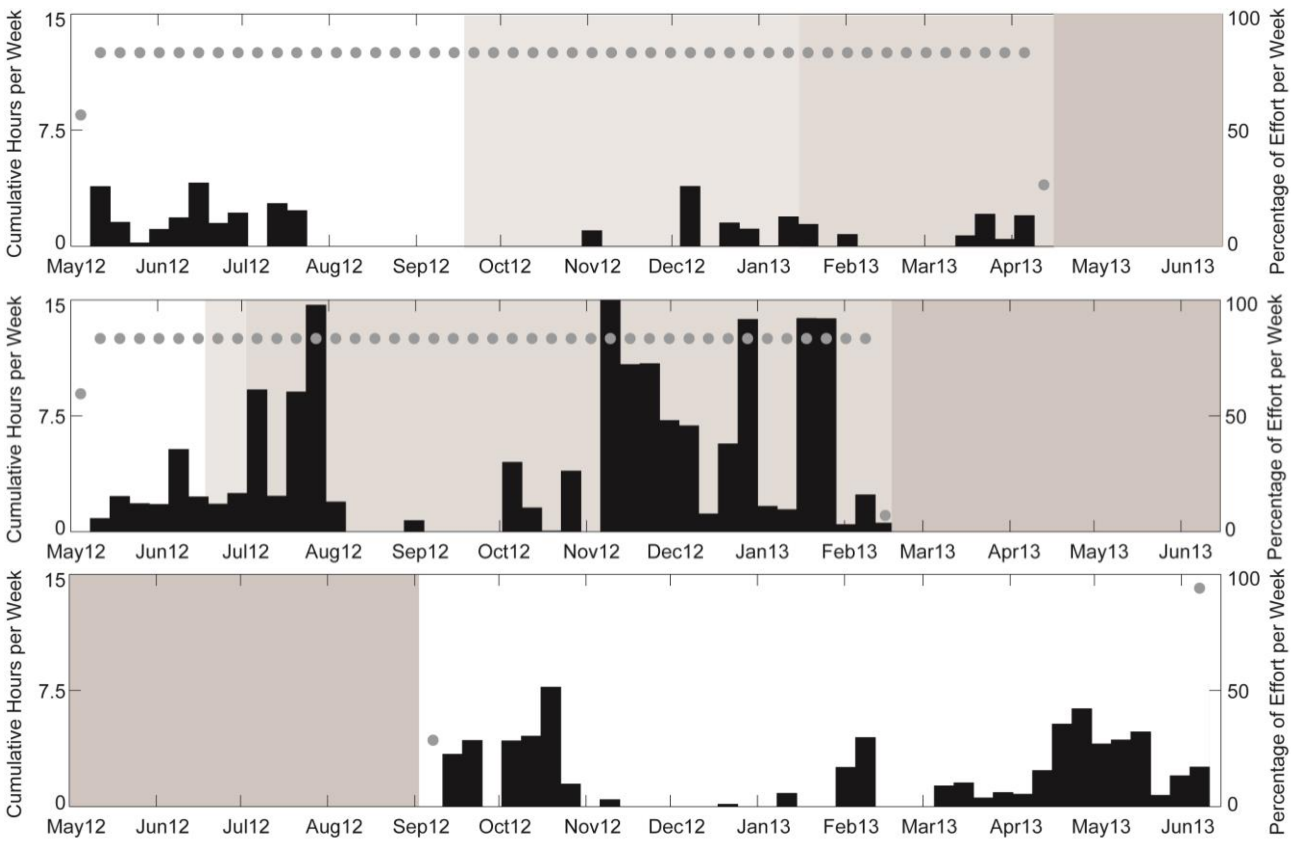


Figure 51. Weekly presence of killer whale clicks (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

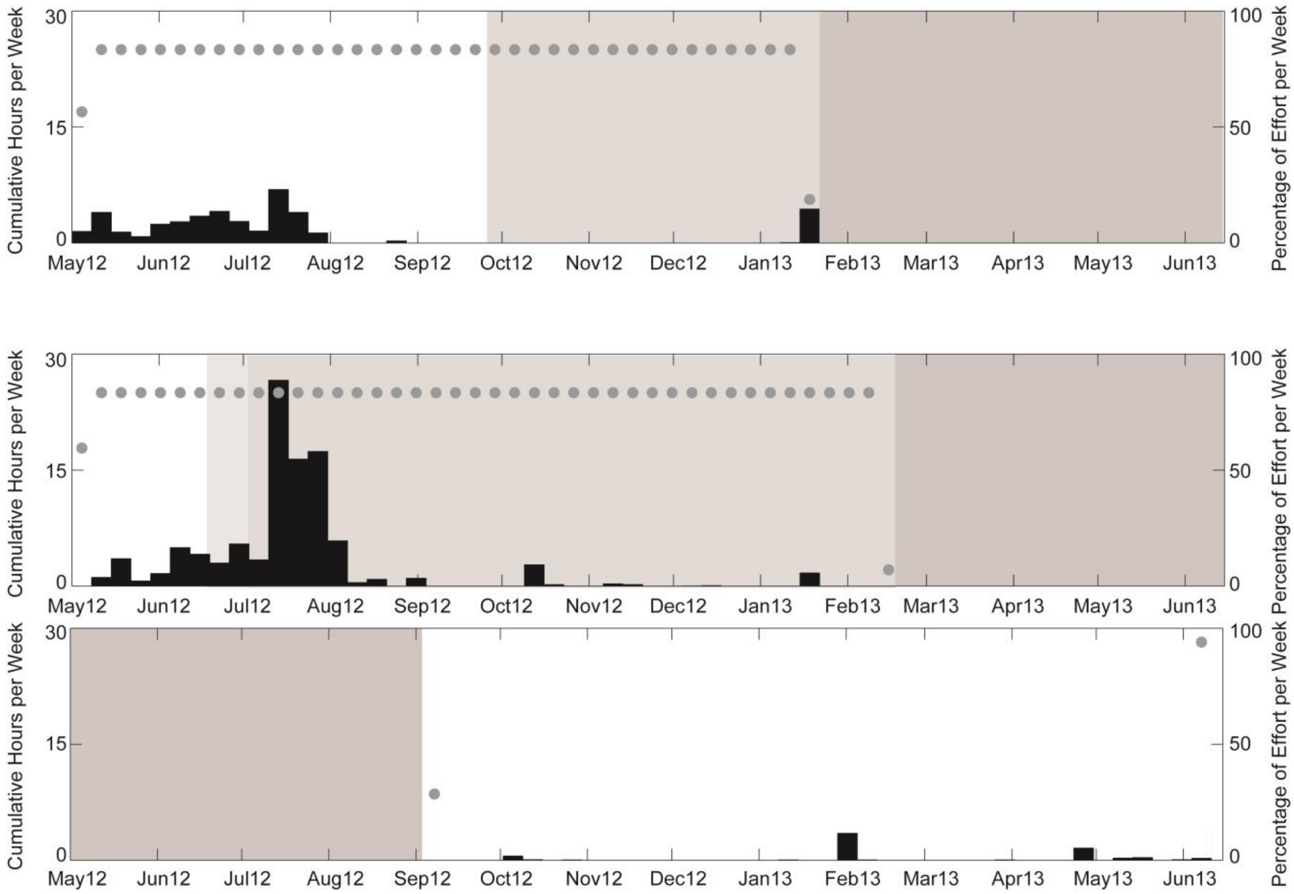


Figure 52. Weekly presence of killer whale whistles and pulsed calls (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

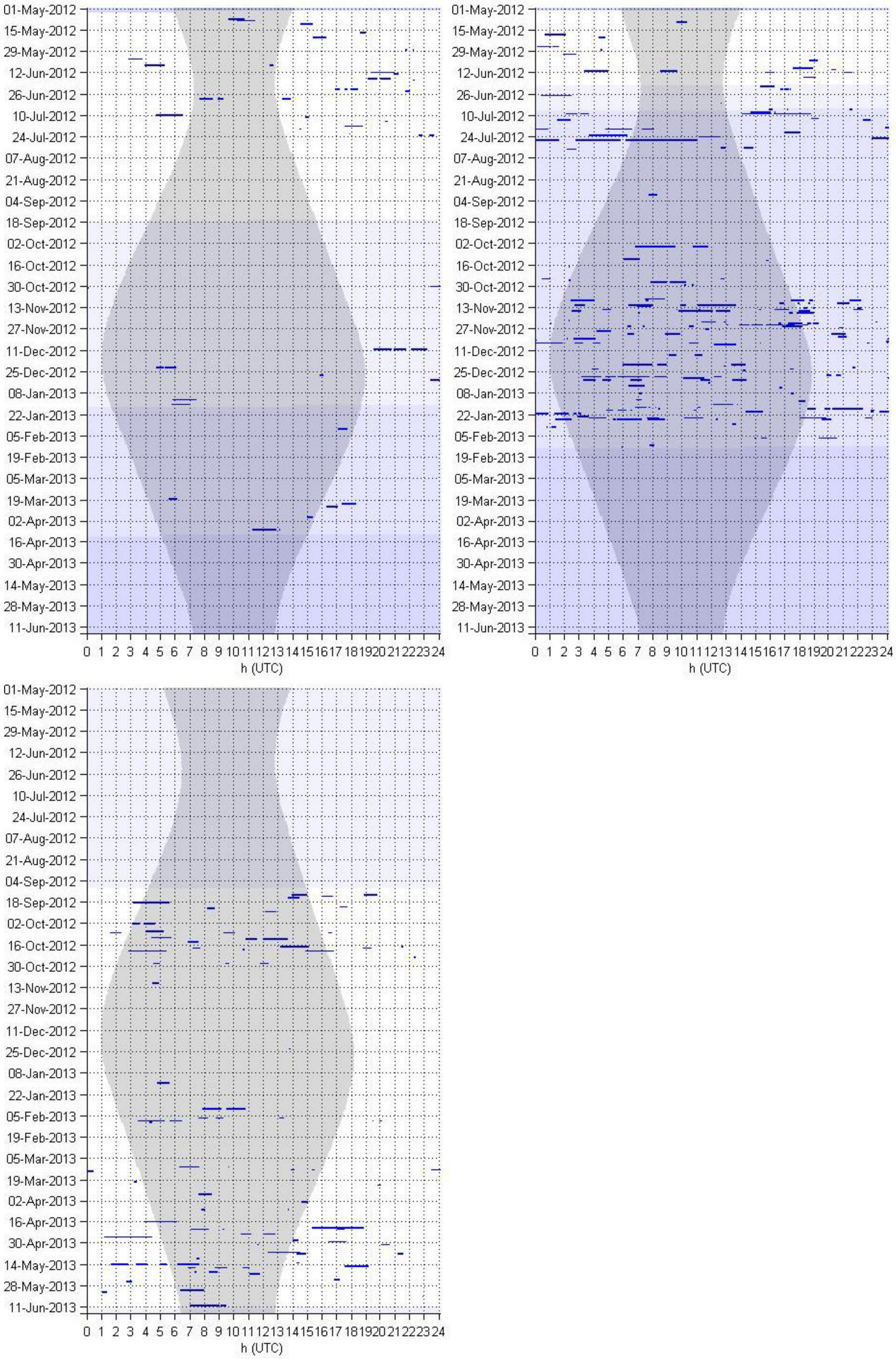


Figure 53. Killer whale clicks in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

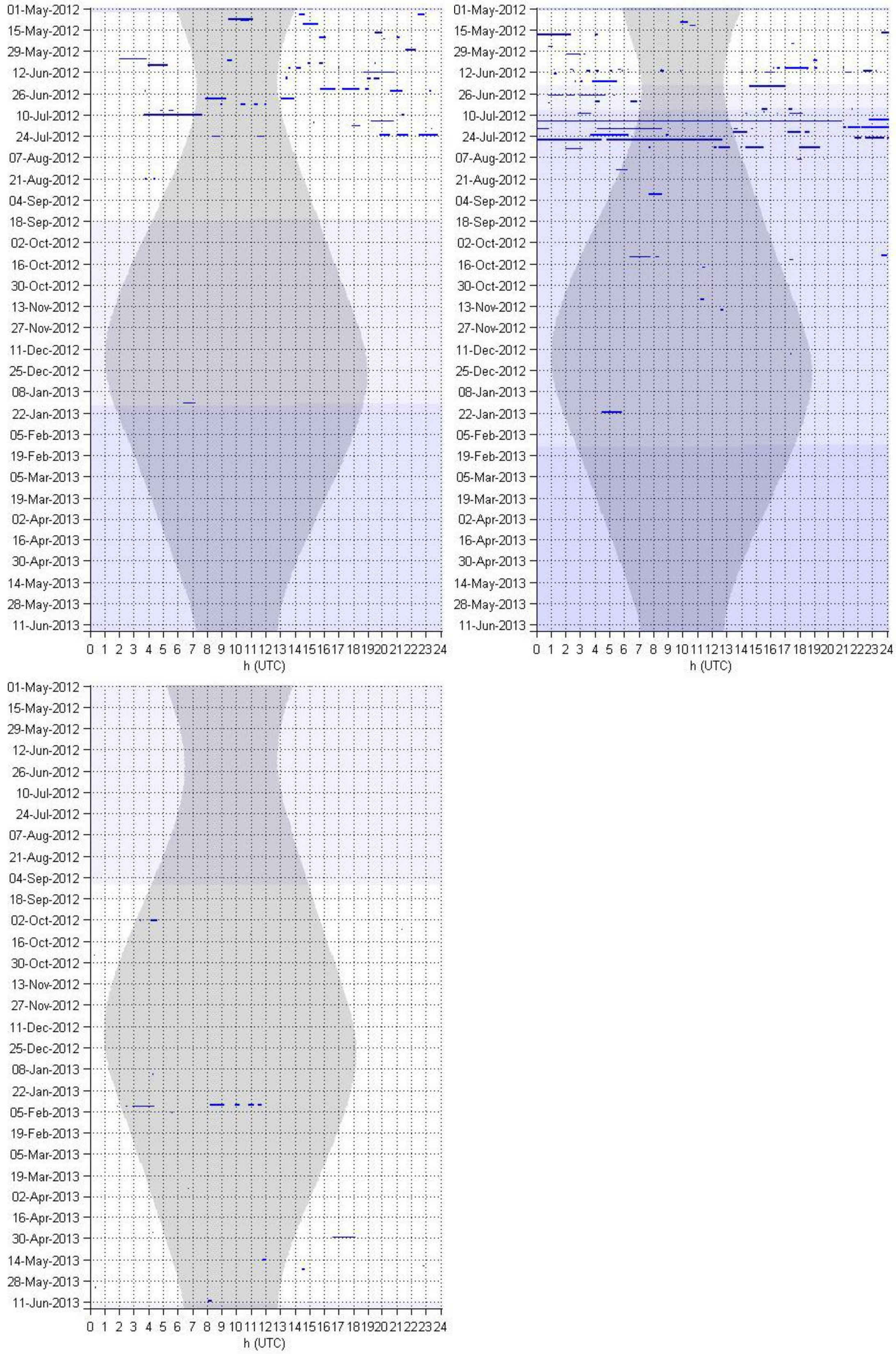


Figure 54. Killer whale whistles in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Sperm Whale

Sperm whale echolocation clicks were detected at all three sites.

- Echolocation clicks were very common at site CB (Figure 55), with peaks in May and November 2012, and relatively few detection in January and February.
- Very few detections occurred at the shallow site CA.
- Sperm whale echolocation clicks occurred throughout day and nighttime hours (Figure 56).

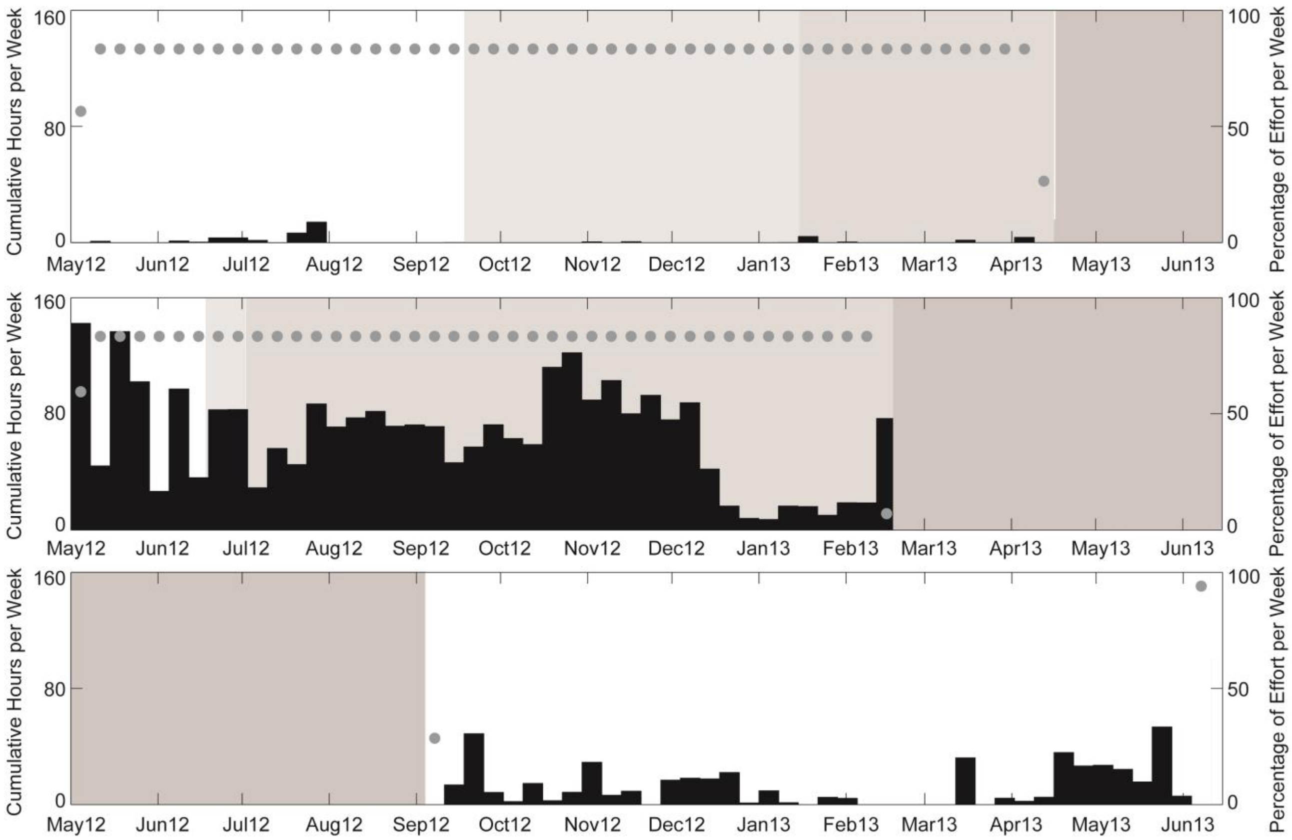


Figure 55. Weekly presence of sperm whale echolocation clicks (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

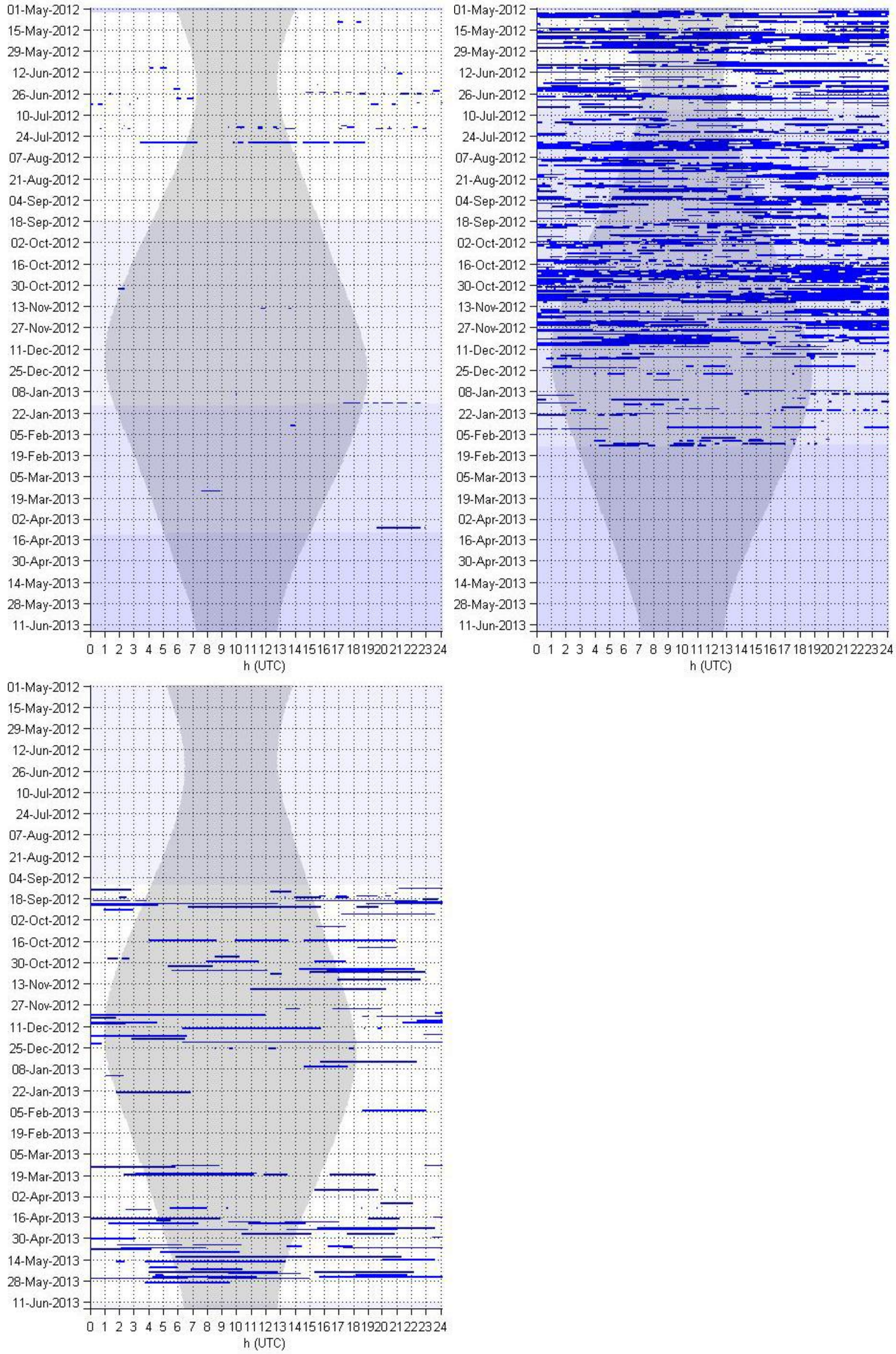


Figure 56. Sperm whale calls in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Baird's Beaked Whale

Baird's beaked whale FM pulses were detected at sites CB and PT (Figure 57).

- Most of the detections at site CB occurred November 2012 through January 2013.
- Detections in site PT were more consistent during most of the deployment period, but with somewhat higher levels in September and October 2012, and no detections in November and December
- No Baird's beaked whale detections occurred at site CA.
- More Baird's beaked whale detections occurred at night than during the day (Figure 58).

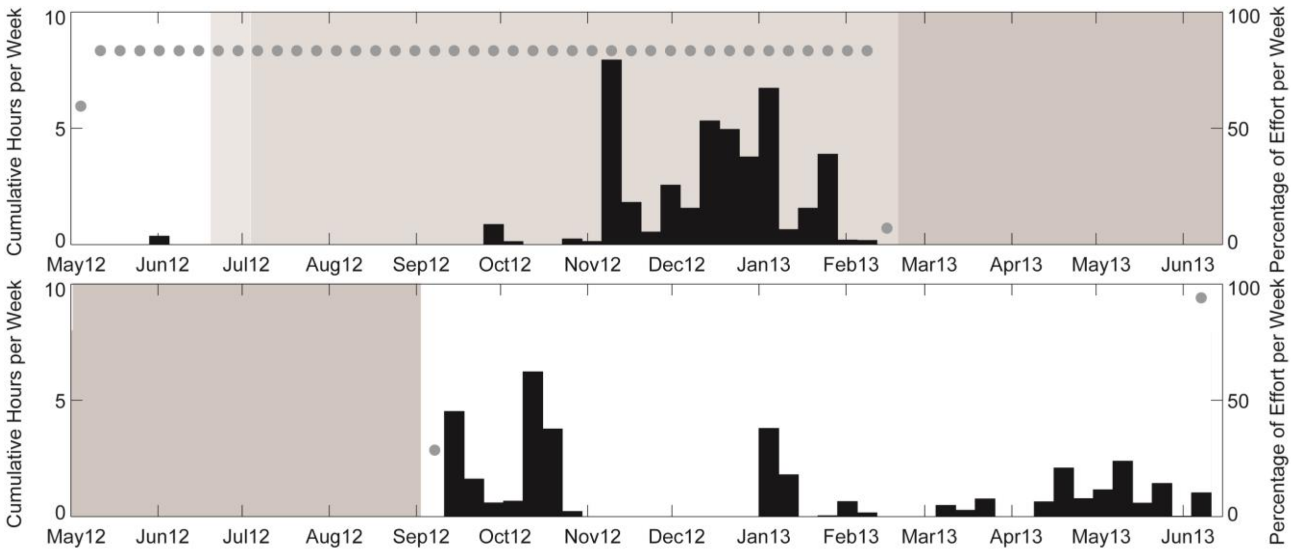


Figure 57. Weekly presence of Baird's beaked whale echolocation clicks and FM pulses (black bars) at sites CB (top) and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

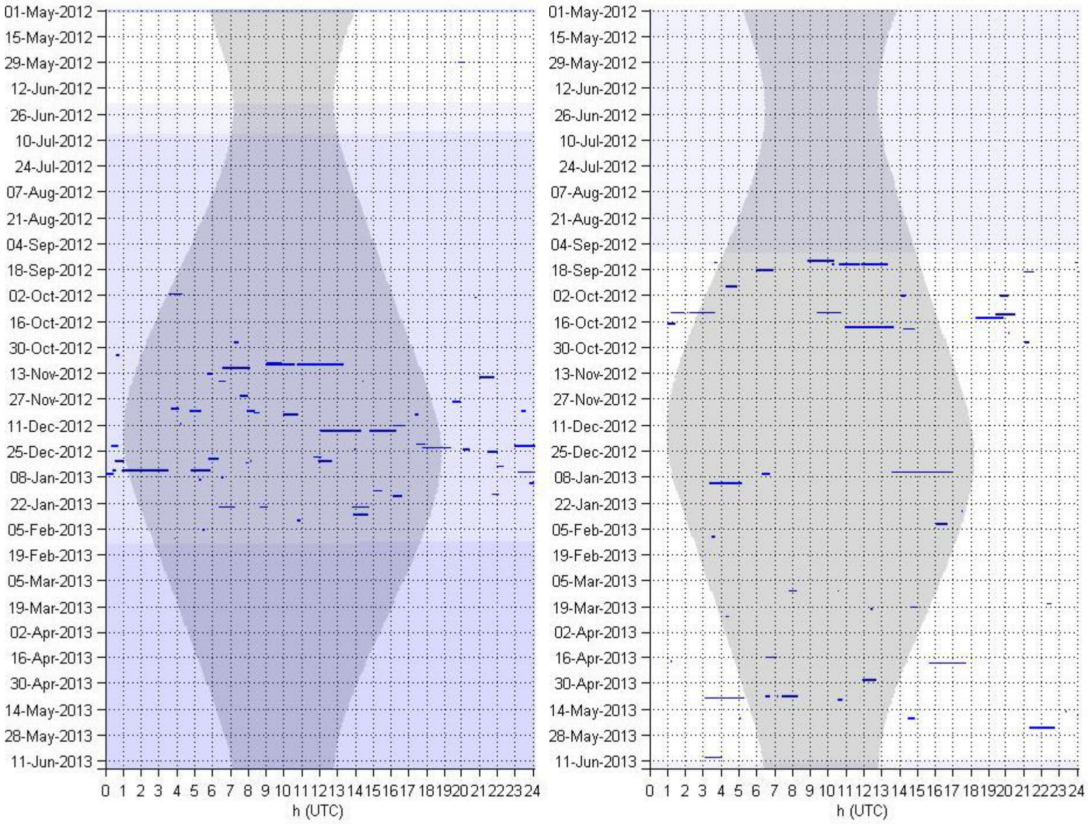


Figure 58. Baird's beaked whale echolocation signals in one-minute bins at sites CB (left) and PT (right). Shading is as described in Figure 38.

Cuvier's Beaked Whale

There were very few Cuvier's beaked whale detections in the deployment period.

- No Cuvier's beaked whale FM pulses were detected at the shallow site CA (Figure 59).
- One calling bout detected at site CB occurred in February 2013 (Figure 59).
- Most detections occurred at site PT and peaked in December 2013 (Figure 59).
- There was no apparent diel pattern in the Cuvier's beaked whale FM pulse occurrence (Figure 60).

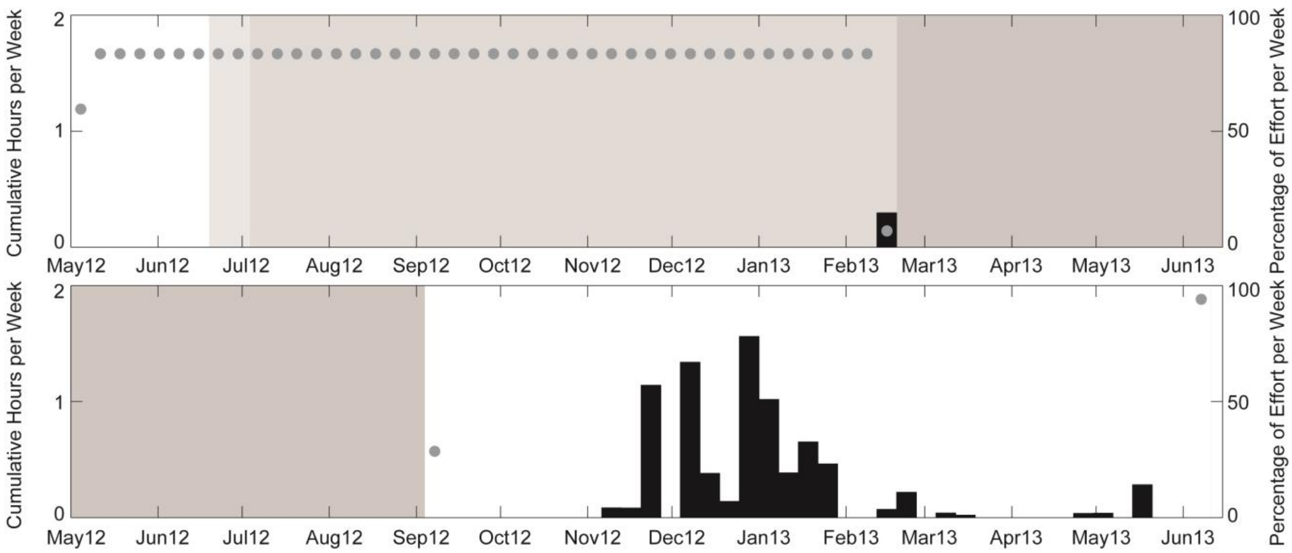


Figure 59. Weekly presence of Cuvier's beaked whale FM pulses (black bars) at sites CB (top) and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

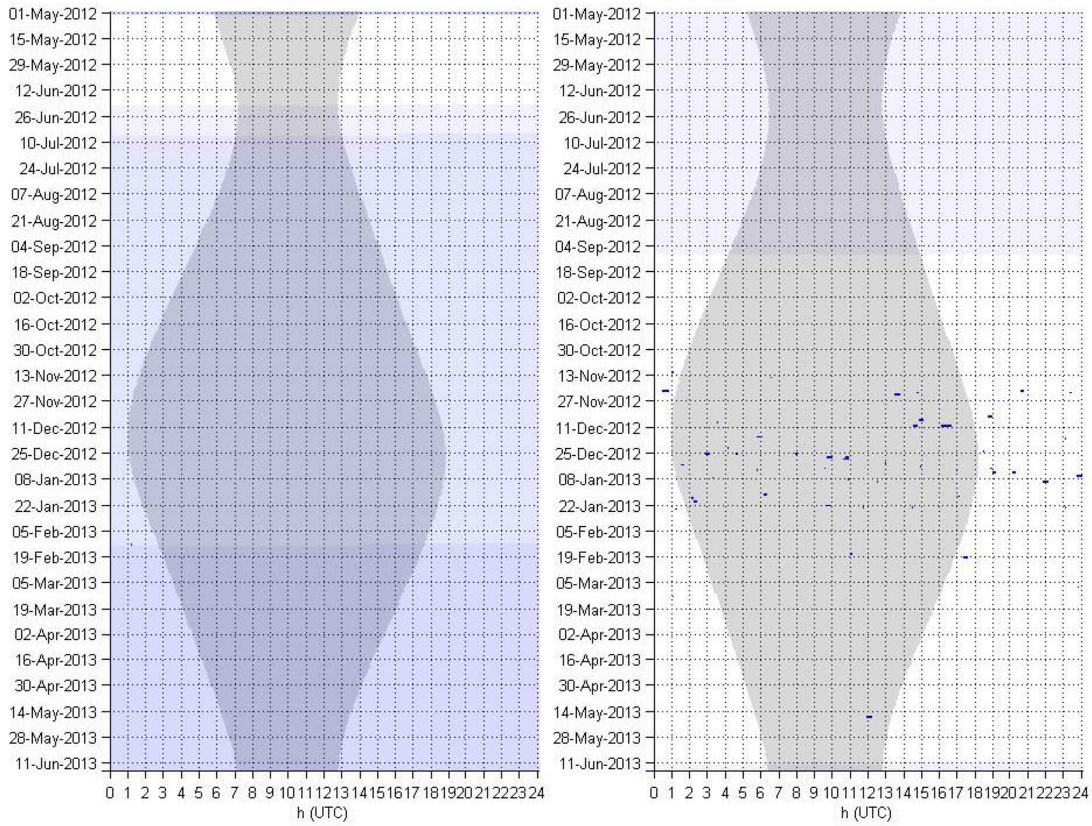


Figure 60. Cuvier's beaked whale FM pulses in one-minute bins at sites CB (left) and PT (right). Shading is as described in Figure 38.

Stejneger's Beaked Whale

Stejneger's beaked whale FM pulses were detected at sites CB and PT.

- No Stejneger's beaked whale FM pulses were detected at the shallow site CA (Figure 61).
- More detections occurred at site CB than PT, with a peak in detections at CB in late-September and early-October 2012 (Figure 61).
- There was no clear diel pattern of occurrence in Stejneger's beaked whale FM pulses (Figure 62).

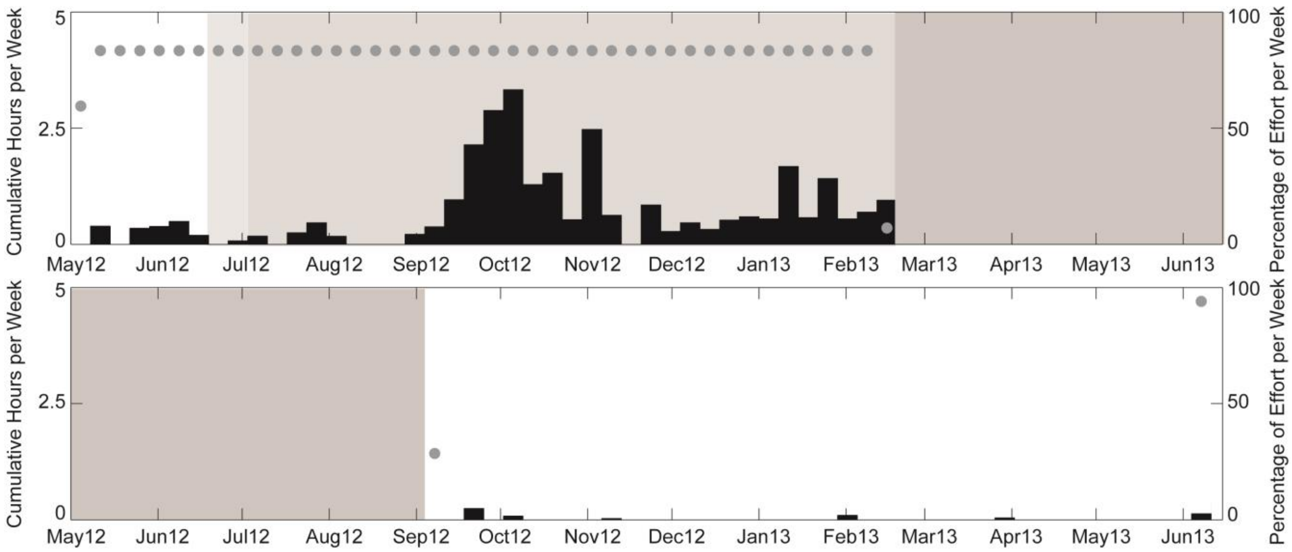


Figure 61. Weekly presence of Stejneger's beaked whale FM pulses (black bars) at sites CB (top) and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

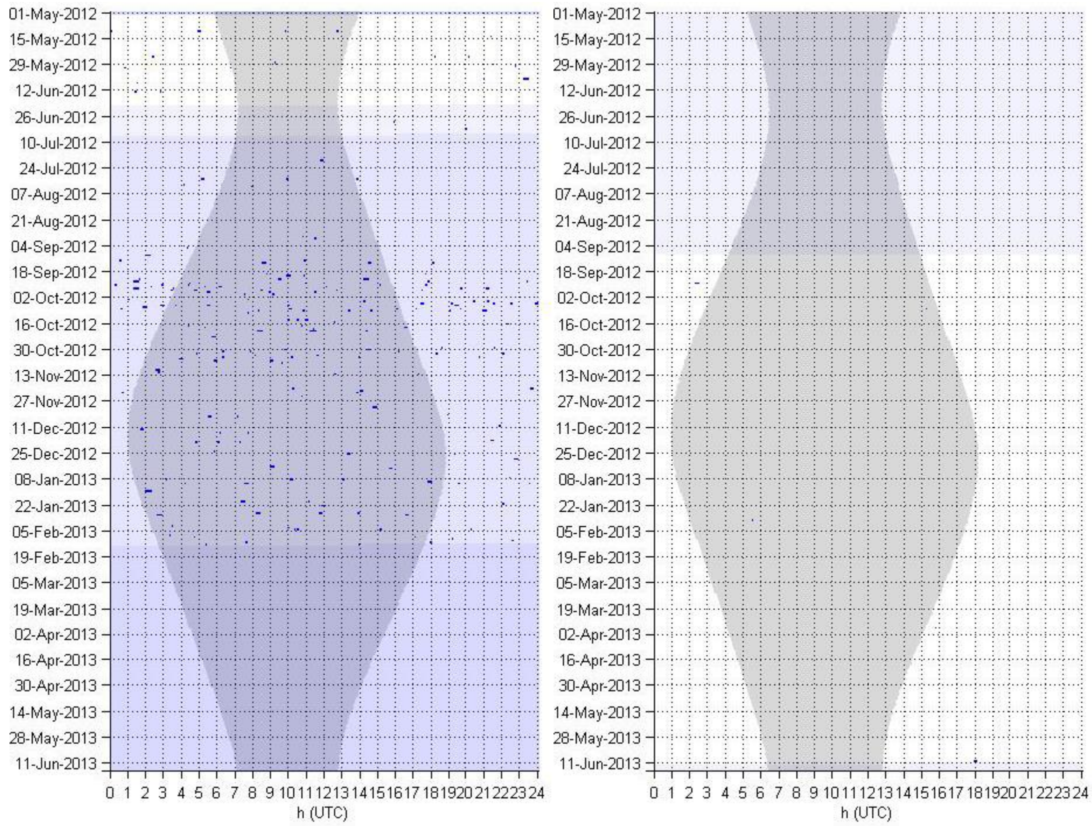


Figure 62. Stejneger's beaked whale FM pulses in one-minute bins at sites CB (left) and PT (right). Shading is as described in Figure 38.

Unidentified Porpoise

Unidentified porpoise echolocation clicks, likely from Dall's porpoise, were detected primarily at the shallow site CA.

- Most unidentified porpoise detections occurred at site CA, with very few detections at site PT, and no detections at CB (Figure 63).
- Detections at site CA were low from June through August, and had higher counts during the remainder of the deployment.
- There was a higher instance of unidentified porpoise echolocation clicks at night (Figure 64), suggesting nighttime foraging.

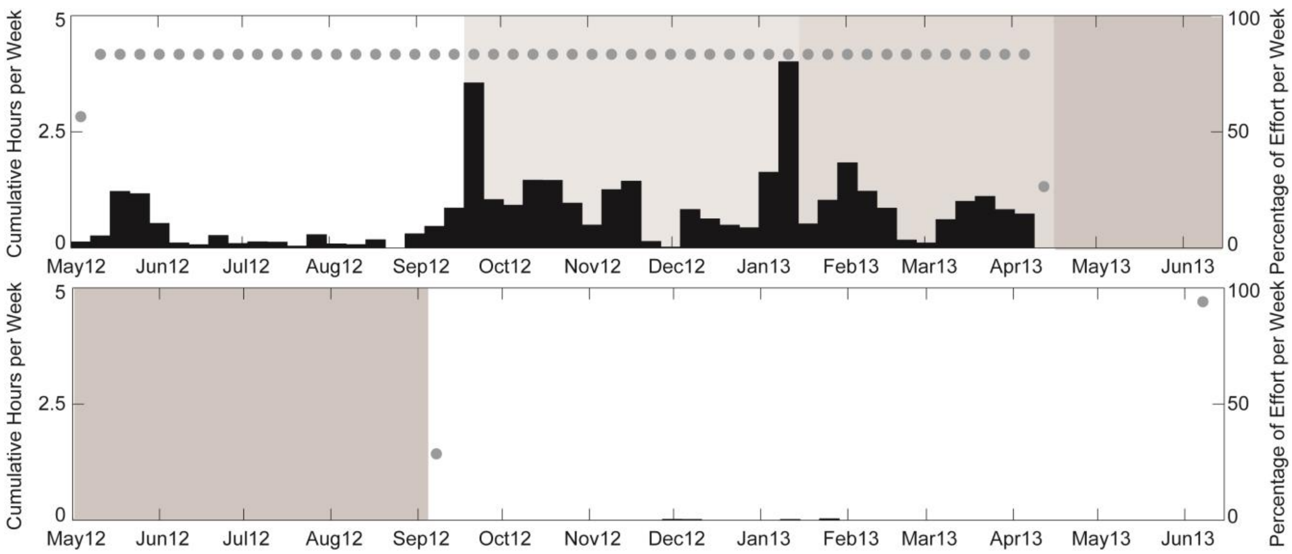


Figure 63. Weekly presence of unidentified porpoise echolocation clicks (black bars) at sites CA (top) and PT (bottom) between May 2012 and June 2013. No porpoise clicks were detected at site CB. Effort as described in Figure 46.

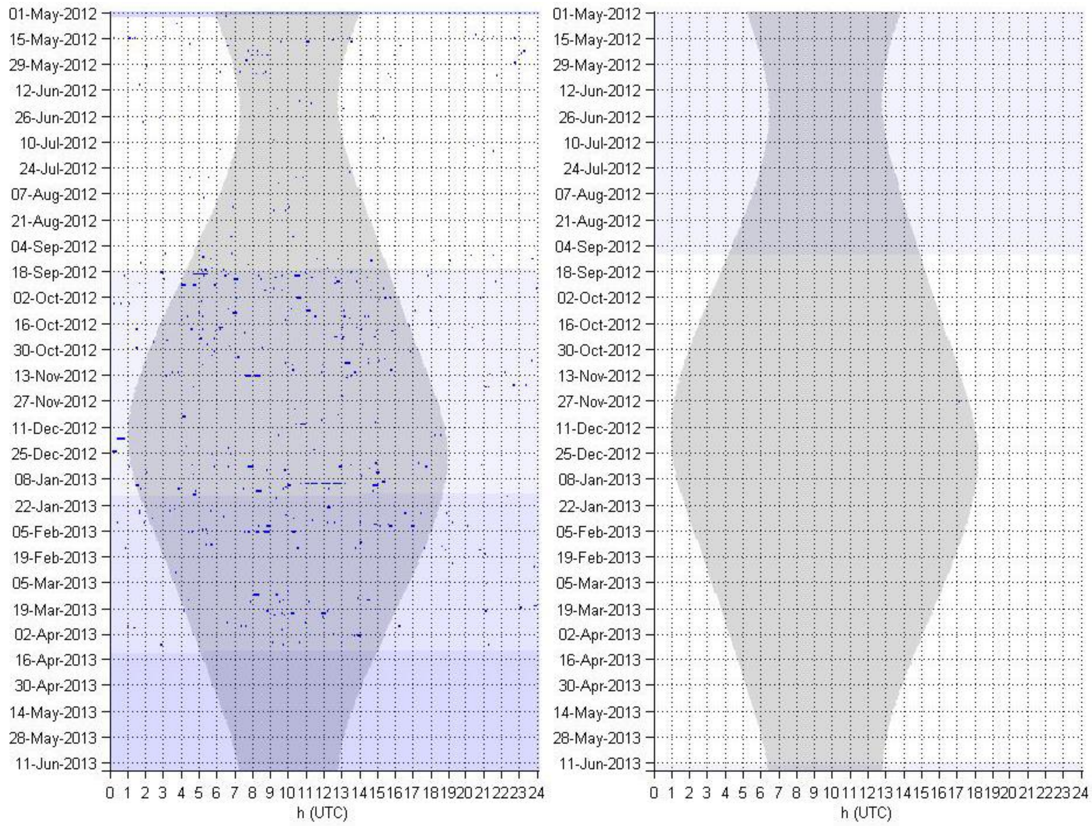


Figure 64. Unidentified porpoise echolocation clicks in one-minute bins at sites CA (left) and PT (right). Shading is as described in Figure 38.

Anthropogenic Sounds

Three types of anthropogenic sounds were detected in the Gulf of Alaska: broadband ship noise, echosounders, and explosions. There were no MFA detections.

Broadband Ship Noise

Broadband ship noise was a common anthropogenic sound, occurring more frequently at sites CB and PT than CA (Figure 65).

- Occurrence of broadband ship noise decreased at site CB after November 2012 (Figure 65). This could indicate that the noise at this site is more likely to be produced by local shipping and boating, which likely decreases in the winter, while shipping noise at site PT is likely the result of trans-oceanic vessels.
- There was no distinct diel pattern to ship acoustic detections (Figure 66).

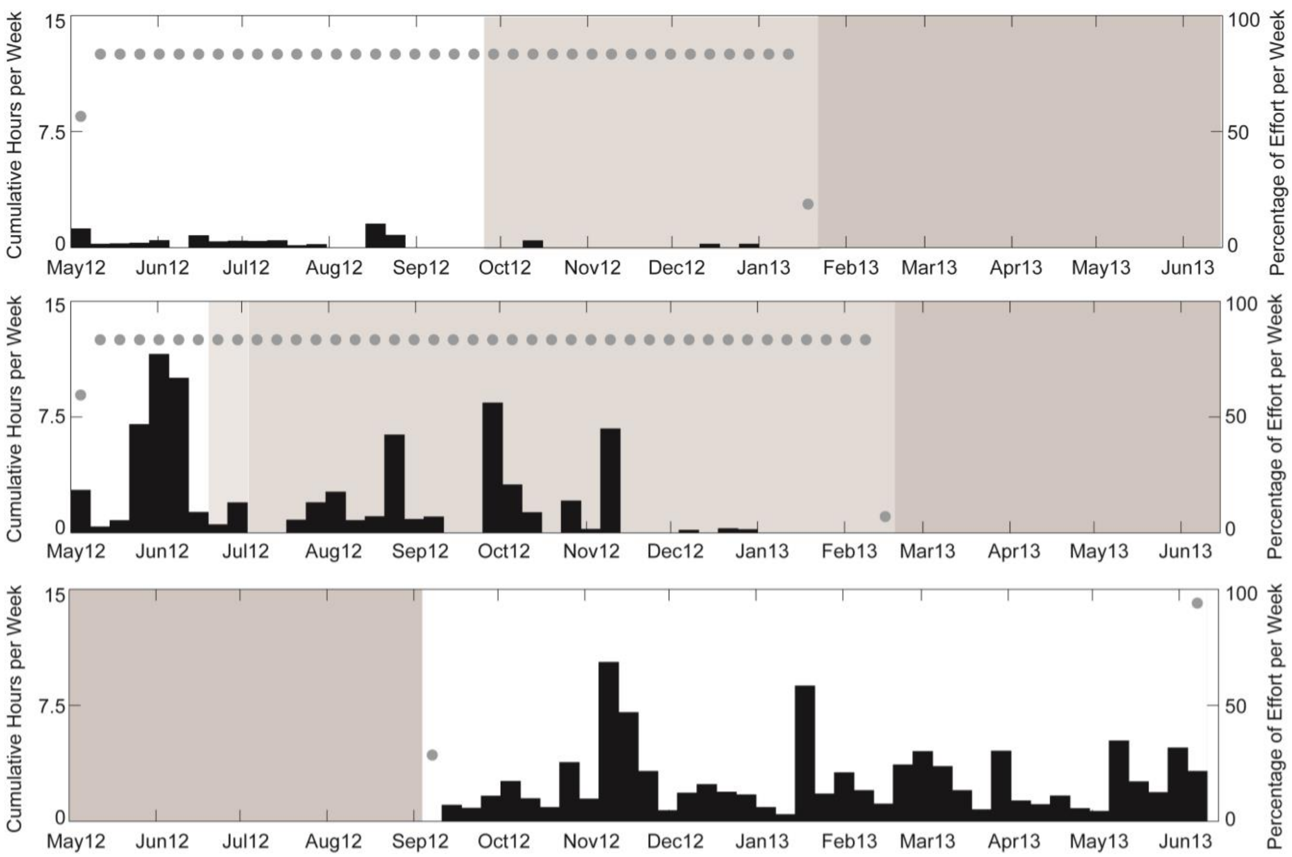


Figure 65. Weekly presence of all broadband ship noise (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

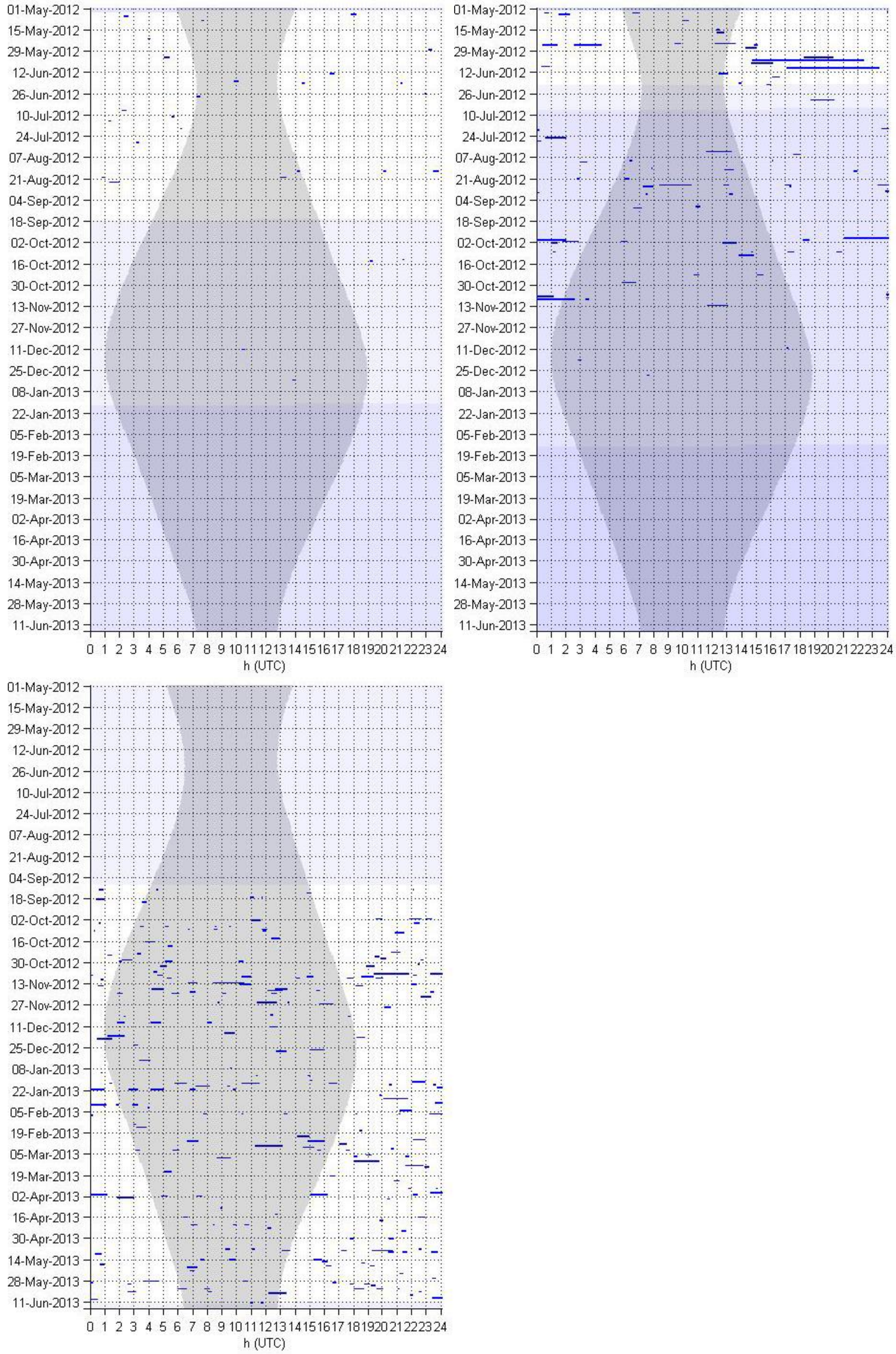


Figure 66. Broadband ship noise presence in one-minute bins at sties CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Echosounders

Echosounder pings from a variety of frequencies were found at all three sites (Figure 67).

- Echosounder pings were more prevalent at sites CA and CB than site PT. This could again indicate closer and more likely local sources of shipping and these sounds at site CA and CB.
- While echosounders were detected throughout most of the deployment at site CA, pings were only detected May through early-October at site CB, consistent with a decrease of shipping noise at that site.
- There was no discernible diel pattern to echosounder pings (Figure 68).

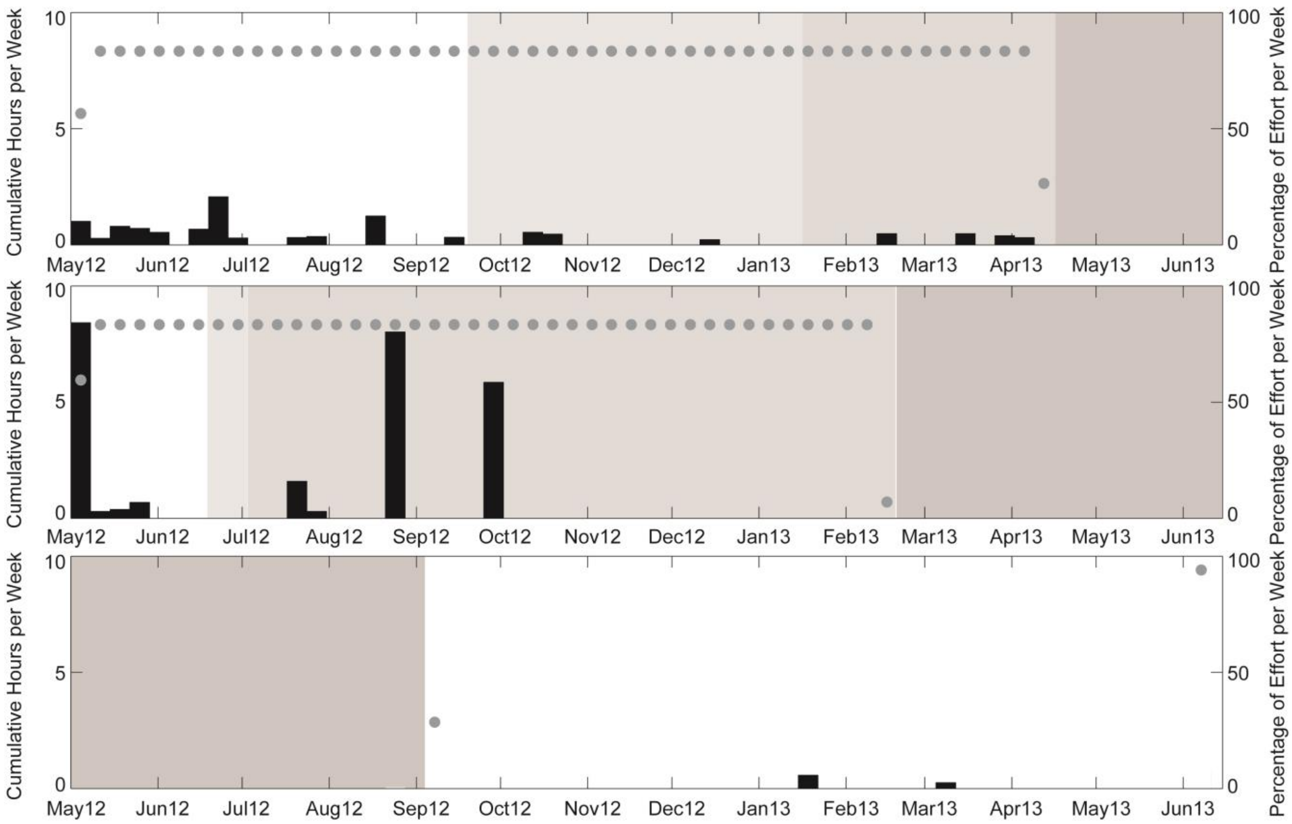


Figure 67. Weekly presence of echosounder pings (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.

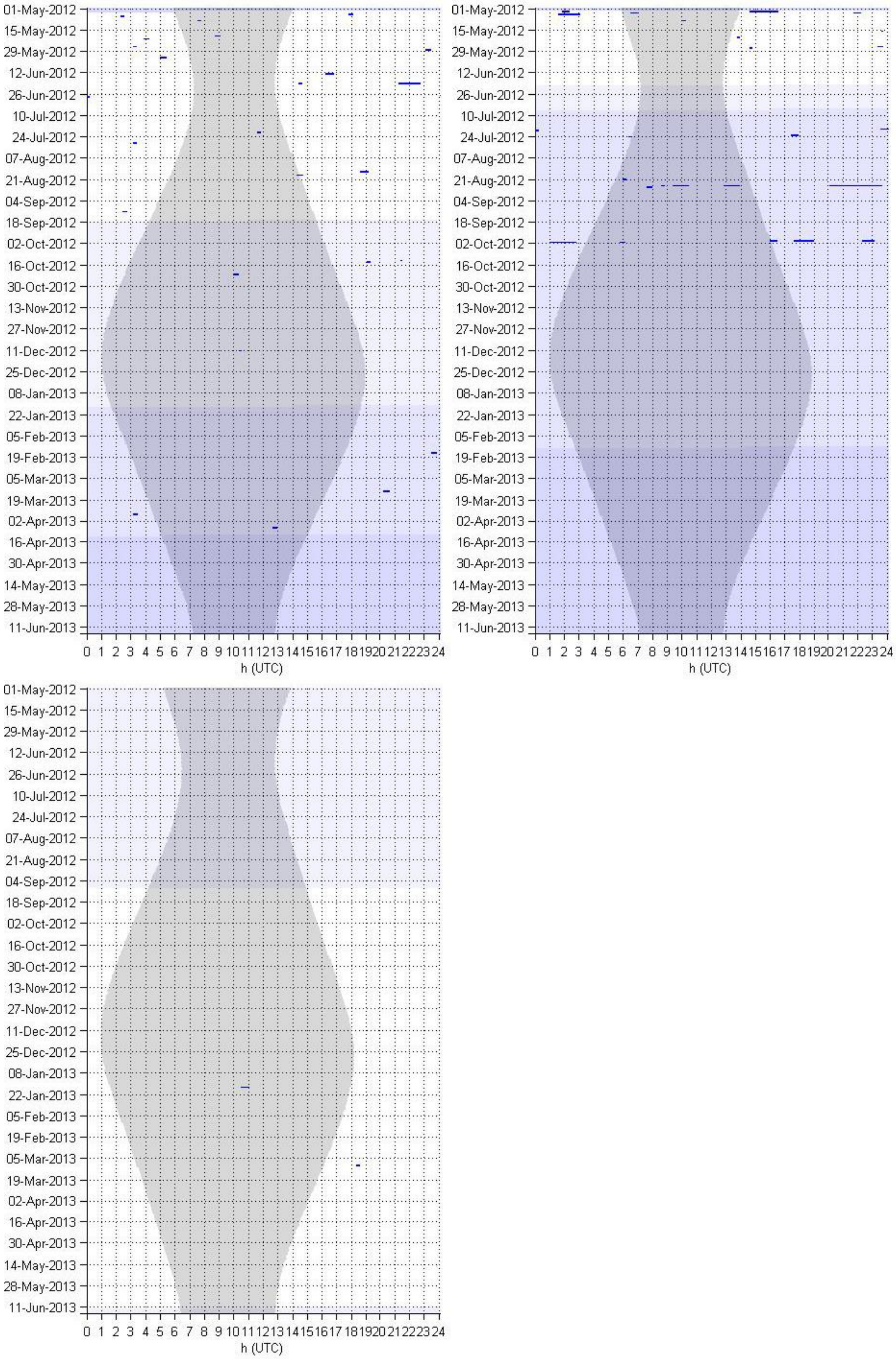


Figure 68. Echosounder ping detections in one-minute bins at sites CB (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

Explosions

Sites CB and PT had higher number of hours per week with explosions than site CA (Figure 69).

- Most explosions at site CB occurred in May 2012.
- Explosions at site PT were most common in September 2012 and May-June 2013.
- There was higher occurrence of explosions occurring during daytime than night, particularly at site PT (Figure 70).

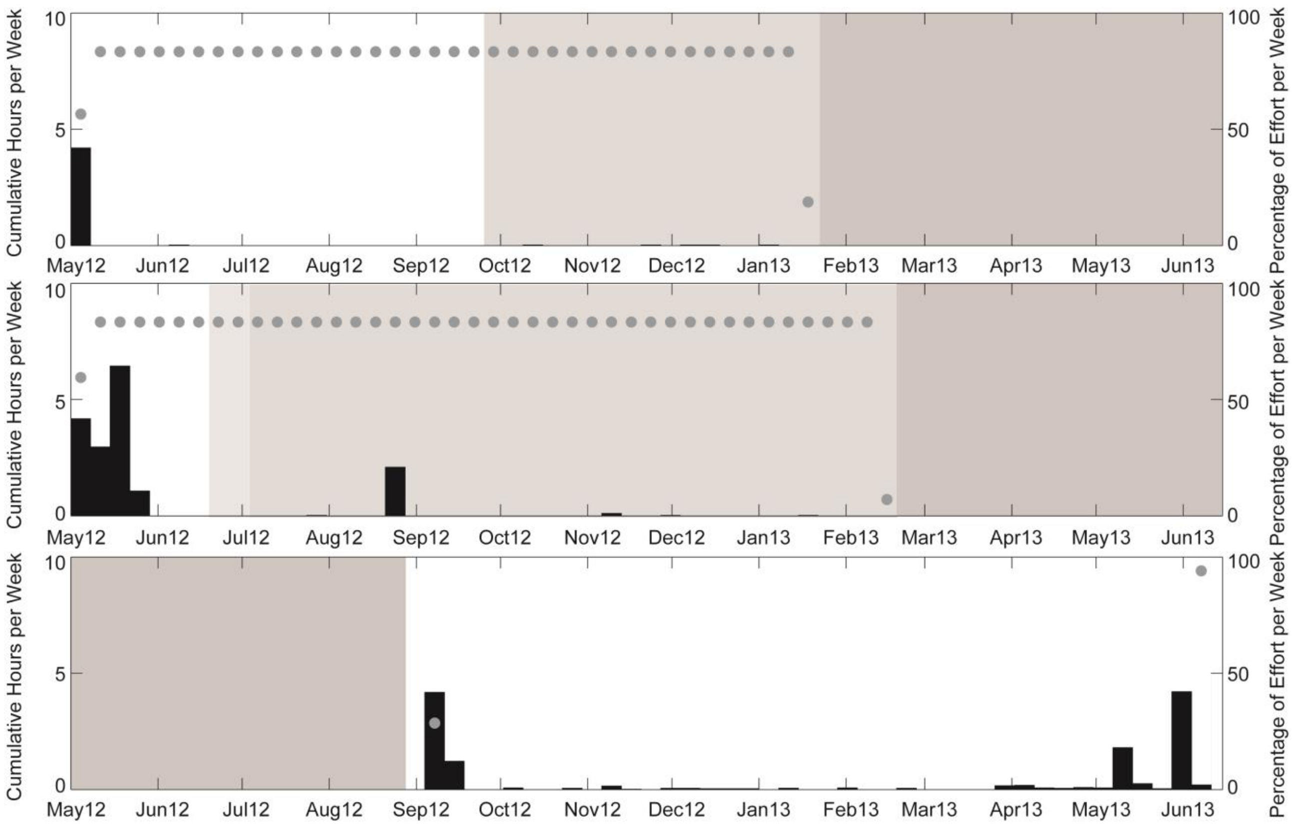
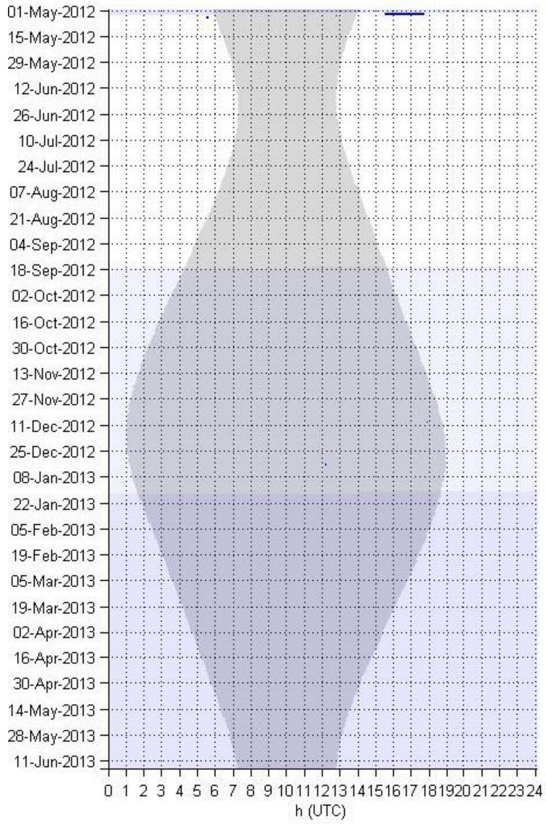
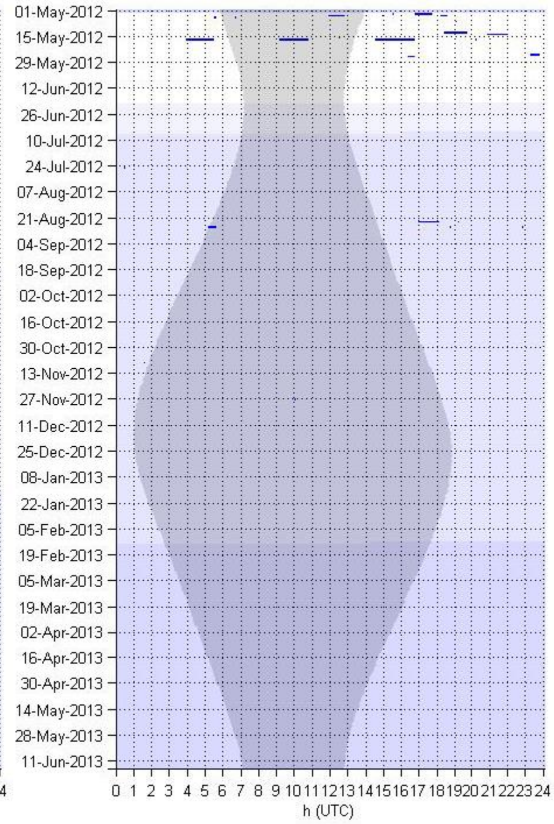


Figure 69. Weekly presence of explosions (black bars) at sites CA (top), CB (middle), and PT (bottom) between May 2012 and June 2013. Effort as described in Figure 46.





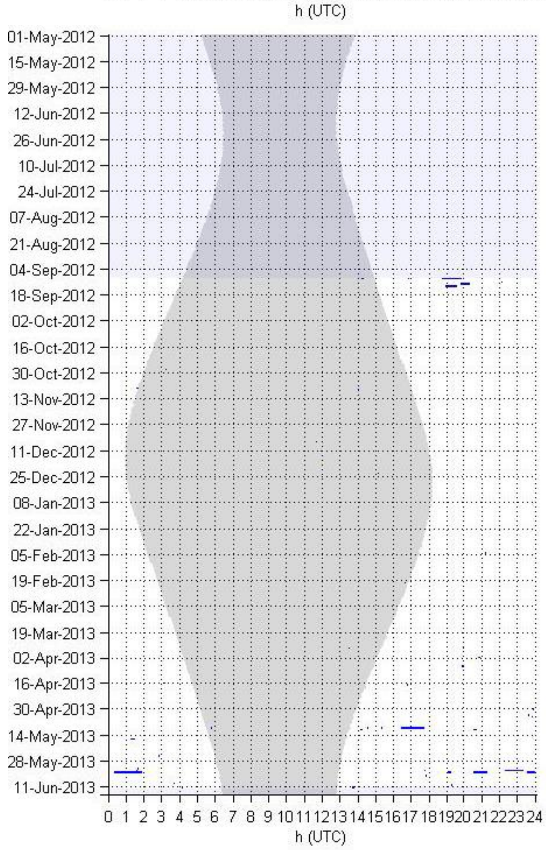


Figure 70. Explosions in one-minute bins at sites CA (top left), CB (top right), and PT (bottom). Shading is as described in Figure 38.

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