Passive Acoustic Monitoring for Marine Mammals in the Northwest Training Range Complex 2011-2012

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Executive Summary

Passive acoustic monitoring using High-frequency Acoustic Recording Packages (HARPs) was conducted at two sites in the Navy's Northwest Training Range Complex; one on the continental shelf near Cape Elizabeth (CE) and the other at the shelf slope near Quinault Canyon (QC). The inshore shelf site was monitored from December 2011 until January 2012, and the offshore shelf slope site was monitored from December 2011 until July 2012. In this report, information on the presence of marine mammals and anthropogenic sounds collected at these sites is presented.

HARPs recorded sounds between 10 Hz and 100 kHz continuously. Data analysis methods consisted of automatic detections of select calls and manual scans of long-term spectral averages and spectrograms. The data were divided into three frequency bands and each band was analyzed for marine mammal vocalizations and anthropogenic sounds. Representative sounds recorded during monitoring, as well their occurrence at these sites, are presented.

Four baleen whale species were recorded: blue whales, fin whales, gray whales, and humpback whales. All four species were recorded at both sites, though fin whales were more common at QC, and gray whales were more common at CE. Seasonal pattern of all three species was similar, with calls most commonly detected during the winter and early spring. Few fin whale calls were detected between May and July and blue whale calls were rarely detected between April and July. Signals from at least seven known odontocete species were recorded at these two sites. Risso's dolphin echolocation clicks occurred only at site QC primarily from May until and July, and less during January and February, but always during the night. Pacific white-sided dolphins were detected in high numbers at site CE in December and January, and only sporadically at site QC between January and July, also displaying nighttime preference. Killer whale signals were detected at both sites throughout the deployment periods, but they were much more common at site CE. Sperm whale echolocation clicks were detected consistently throughout the deployment period at the slope site QC as well as at site CE. Stejneger's beaked whales were the most consistently recorded beaked whale, with all their detections occurring only at the slope site QC between December and June. Baird's beaked whale clicks were detected at both sites, though were much more common at site QC, and most abundant in late January and June. While overall they were not detected as frequently as Stejneger's beaked whales, in the winter at CE and the summer at QC, their echolocations were more common than any other beaked whale signals recorded during this monitoring period off Washington. Cuvier's beaked whales were detected sporadically and only at the slope site QC. Narrow-bandwidth high frequency clicks from porpoises were commonly detected at the shelf site CE.

Ship noise was a common anthropogenic sound at both sites. At site CE, ship noise decreased slightly between late December and early January, but it was largely constant at QC. Mid-frequency active (MFA) sonar events were rare during the deployment period and were recorded only on 4 days, exclusively at site QC. Using automatic detection and measurement method, 56 pings were detected at site QC, with received levels ranging from 108 to 127 dB pp re: 1 µPa. Echosounder pings were also rare and only recorded on 2 days at site QC. In general, explosions were not common at either site, though a sustained seismic survey was recorded over the period of a few weeks in June and July 2012.

Project background

The Navy's Northwest Training Range Complex (NWTRC) contains an offshore area that extends west 250 nautical miles (nm) beyond the coasts of Washington, Oregon, and Northern California. This area is a productive ecosystem inhabited by many species of marine mammals. The area includes deep water habitats, utilized by beaked and sperm whales, as well as continental shelf waters frequented by coastal cetaceans, pinnipeds, and porpoises. Endangered species known to occupy this area include blue, fin, sperm, humpback, and killer whales.

An acoustic and visual monitoring effort for marine mammals was initiated within the boundaries of the NWTRC with a focus on the Quinault Underwater Tracking Range (QUTR), off the coast of Washington, beginning in July 2004. Two High-frequency Acoustic Recording Packages (HARPs) have been deployed near the QUTR, one in deeper water on the shelf slope within Quinault Canyon (QC) and a second on the continental shelf off Cape Elizabeth (CE) intermittently since 2004. In 2011 and 2012, support for continuation of acoustic monitoring in the NWTRC was provided by the Pacific Fleet, under a contract to the Scripps Institution of Oceanography from the Naval Postgraduate School. The goal of this monitoring 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 operations. This report documents the analysis of data collected using two High-frequency Acoustic Recording Packages (HARPs) that were deployed within NWTRC in December 2011 and recovered in July 2012. Recordings were obtained from December 2011 through January 2012 at site CE, and through July 2012 at site QC (Figure 1).

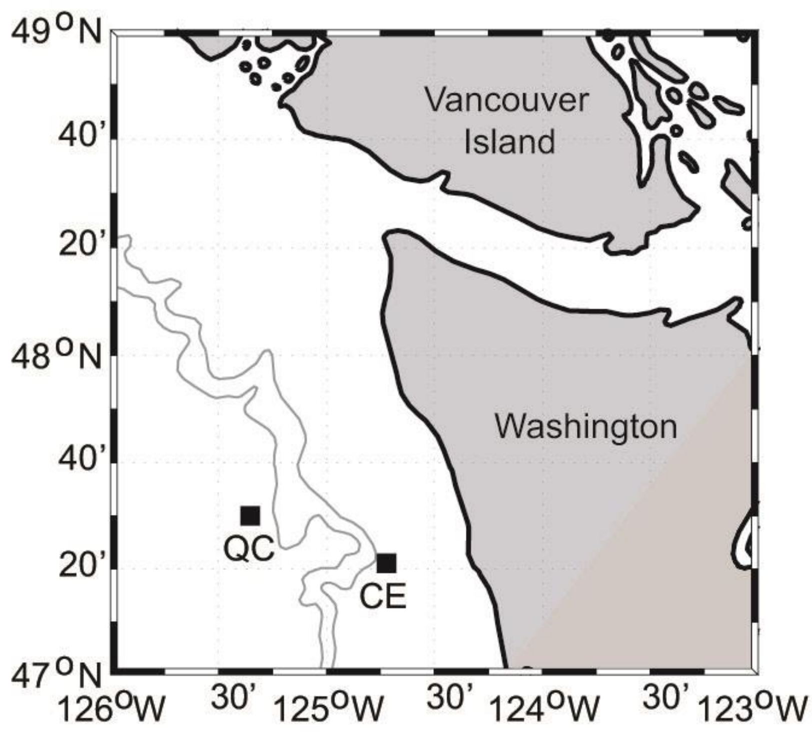


Figure 1. Locations of High-frequency Acoustic Recording Packages, QC and CE (black squares), deployed in the NWTRC during December 2011 through July 2012. Gray thin lines represent 500 m and 1000 m bathymetric contours.

Methods

High Frequency Acoustic Recording Packages

HARPs record underwater sounds from 10 Hz to 100 kHz and are capable of up to 300 days of continuous recording (Wiggins and Hildebrand 2007). For the NWTRC deployments, the HARPs were located on the seafloor with their hydrophone suspended 10 m above the seafloor. Each HARP was calibrated in the laboratory to allow a quantitative analysis of the received sound field. Representative data loggers and hydrophones were calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations.

Data Collected to Date

Acoustic data have been collected at two sites within NWTRC using HARPs since July 2004 (Table 1). The two sites are designated Quinault Canyon, QC (47° 30.00N, 125° 21.20W) and Cape Elizabeth, CE (47° 21.12N, 124° 43.26W). Analysis of recordings collected before 2012 were described by Oleson et al. (2009), Širović et al. (2011), and Širović et al. (2012). Here we present the results of the analyses conducted on the data collected at site CE between December 2011 and January 2012, and at site QC between December 2011 and July 2012.

Table 1. NWTRC acoustic monitoring since 2004. Periods of instrument deployment analyzed in this report are shown in bold. Results of acoustic monitoring through 2011 are described in Oleson et al. (2009), Širović et al. (2011), and Širović et al. (2012). Italics show ongoing data collection.

Acoustic Monitoring Period	**Sample Rate & Duty Cycle (on/off, in min)**	**QC: Slope**	**CE: Shelf**
OCNMS01: July – October 2004	80 kHz continuous	Yes	Lost
OCNMS02: October 2004 – January 2005	80 kHz 10/20	Yes	--
OCNMS03: July 2005 – February 2006	80 kHz 6/12	Yes	--
OCNMS04: August 2006 – February 2007	80 kHz 6/12	Yes	Yes
OCNMS05: April – July 2007	80 kHz continuous	Yes	Yes
OCNMS06: July 2007 – June 2008	200 kHz 5/35	Yes	--
OCNMS07: October 2007 – June 2008	200 kHz 5/30	--	Yes
OCNMS08: June 2008 – June 2009	200 kHz 5/35	Lost	Yes
OCNMS09: December 2009 – January 2011	200 kHz 5/30	--	Lost
OCNMS12: January – October 2011	200 kHz continuous	Yes	
OCNMS13: May– November 2011	200 kHz continuous		Yes
OCNMS14: December 2011 – July 2012	**200 kHz continuous**	**Yes**	**Yes *(Dec-Jan)***
OCNMS15: September 2012 –	*200 kHz continuous*	*Yes*	*Yes*

Data Analysis

Recording over a broad frequency range up to 100 kHz allows detection of baleen whales (mysticetes), toothed whales (odontocetes) and seal and sea lion (pinniped) species. The presence of acoustic signals from multiple marine mammal species was evaluated in the data. The presence of calls from the following species was examined: blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), gray whales (*Eschrichtius robustus*), Bryde's whales (*B. edeni*), minke whales (*B. acutorostrata*), humpback whales (*Megaptera novaeangliae*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), Stejneger's beaked whale (*Mesoplodon stejnegeri*), Baird's beaked whales (*Berardius bairdii*), Cuvier's beaked whale (*Ziphius cavirostris*), Blainville's beaked whale (*Mesoplodon densirostris*), Risso's dolphins (*Grampus griseus*), and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*). Additionally, pinniped and porpoise sounds were also identified in the data, as was the daily presence of anthropogenic noise such as shipping, naval sonar, echosounders, and explosions. A few call types were detected automatically in the data, including blue, fin, and humpback whale calls. In addition, all data were analyzed by visually scrutinizing long term spectral averages (LTSAs) in appropriate frequency bands for calls of other species. When a sound of interest was identified in the LTSA, examining the waveform or spectrogram at the point of interest allowed for the identification of particular sounds to species or source, as necessary. Acoustic classification was carried out either from comparison to species-specific spectral characteristics or through analysis of the time and frequency characters of individual sounds.

To document the data analysis process, we describe the major classes of marine mammal calls and anthropogenic sounds in the NWTRC, 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 presence of sounds from an appropriate subset of species or sources. The three frequency bands are as follows: (1) low frequencies, between 10 – 1,000 Hz, (2) mid frequencies, between 10 – 5,000 Hz, and (3) high frequencies, between 1 – 100 kHz. LTSAs are created by calculating frequency spectra for all the data and each of the three frequency bands. For the analysis of the mid-frequency recordings, data were decimated by a factor of 20, while for the low-frequency analysis they were decimated by a factor of 100. The LTSAs were created using a 5 s time average with 100 Hz frequency resolution for high-frequency, 10 Hz resolution for mid-frequency, and 1 Hz resolution for low-frequency data analysis. Blue, fin, Brydes's, and gray whale sounds were classified as low frequency. Humpback, minke, killer whale whistles and pulsed calls, pinnipeds, shipping, mid-frequency active sonar, echosounders, and explosions were classified as mid-frequency. The remaining odontocete sounds were considered high-frequency. We describe the calls and procedures separately for each frequency band.

In this report, we summarize acoustic data collected between December 2011 and January 2012 at site CE and between December 2011 and July 2012 at site QC. We discuss seasonal occurrence and relative abundance of calls for different species that can be consistently identified in the acoustic data in the context of earlier visual and acoustic data collections (Oleson et al. 2009, 2010; Širović et al. 2011, 2012).

Low Frequency Marine Mammals

The hourly presence of blue whale D, fin whale 40 Hz, Bryde's whale Be4, and gray whale M3 calls was determined by manual scrutiny of low-frequency LTSAs (5 s temporal and 1 Hz frequency resolution) using custom software program *Triton* (Wiggins and Hildebrand 2007). Blue whale B calls and fin whale 20 Hz pulses were detected automatically using computer algorithms described below in each corresponding section.

The same LTSA and spectrogram parameters were used for manual detection of all call types. During scrutiny of the data, the LTSA frequency was set to display between 1-500 Hz. To observe individual calls, spectrogram windows were typically set to 120 seconds by 200 Hz. The FFT was generally set between 1,500 and 2,000 data points, yielding about 1 Hz frequency resolution, with an 85-95% overlap. When a call of interest was identified in the LTSA or spectrogram, its presence during that hour was logged using *Triton*.

Blue Whales

Blue whales produce a variety of calls worldwide (McDonald et al. 2006), but in the eastern North Pacific, B calls (Figure 2) are their most commonly recorded call (Oleson et al. 2007a). These low frequency (15-50 Hz), long duration (20 s) calls can be produced as repetitive sequences (song) or as singular calls and are produced exclusively by males, likely in association with mating behavior (Oleson et al. 2007b). The call generally contains multiple, harmonically related tonals and, owing to greater noise at low frequency, is best identified based on the presence of the 3rd harmonic.

For this report, blue whale B calls were detected automatically using the spectrogram correlation method (Mellinger and Clark 1997). The kernel was based on frequency and temporal characteristics measured from 41 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 10 s. The frequency ranged over those time periods from 47.48 to 47.09; 47.09 to 46.65; 46.65 to 46.37; and 46.37 to 45.93 Hz. The kernel bandwidth was 2 Hz. A similar detector has been used by Oleson et al. (2007a), but the frequency characteristics were adjusted to account for the annual shift in frequency of blue whale B calls (McDonald et al. 2009). The performance of the detector was tested against two weeks of manual hourly picks of blue whale B calls and we found that hourly false alarm rates were between 8.5 and 9.5 % and missed detection rates were between 9 and 11.5 %, depending on the site. In addition, automatic detections during months when blue whales are not common in this area (March through July for site QC) were manually reviewed and false alarms during this period were removed from further analysis. Detections were binned into 1 hour bins for consistent result reporting.

Blue whales also produce D calls, which are down-swept in frequency (100-40 Hz) with duration of several seconds (Figure 3). These calls are similar worldwide and are associated with feeding animals; they may be produced as call-counter call between multiple animals (Oleson et al. 2007b). Blue whale D calls were detected manually by human analysts.

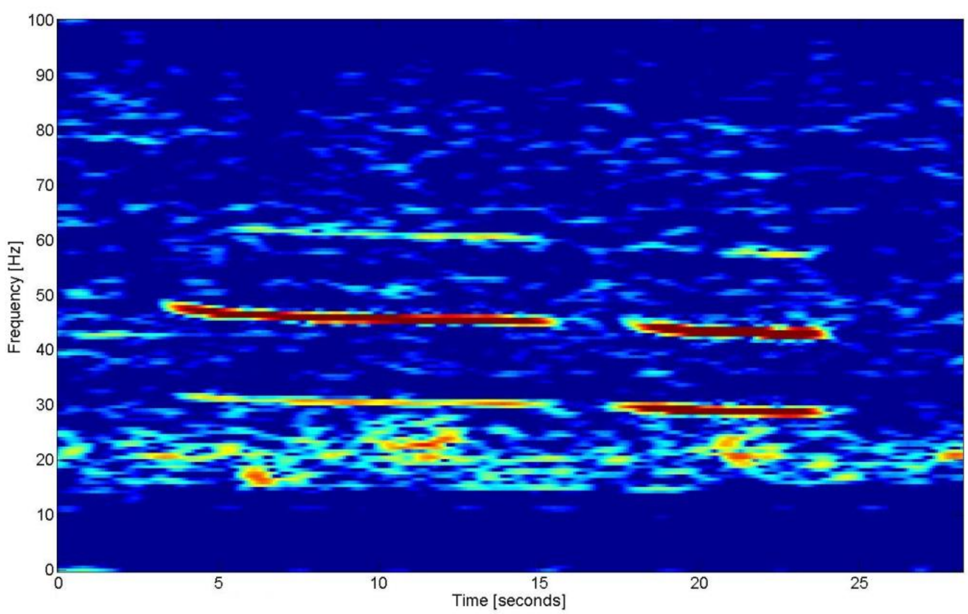


Figure 2. Blue whale B call showing harmonic tones with frequency step near the end of the call (3,500-point FFT, 95% overlap).

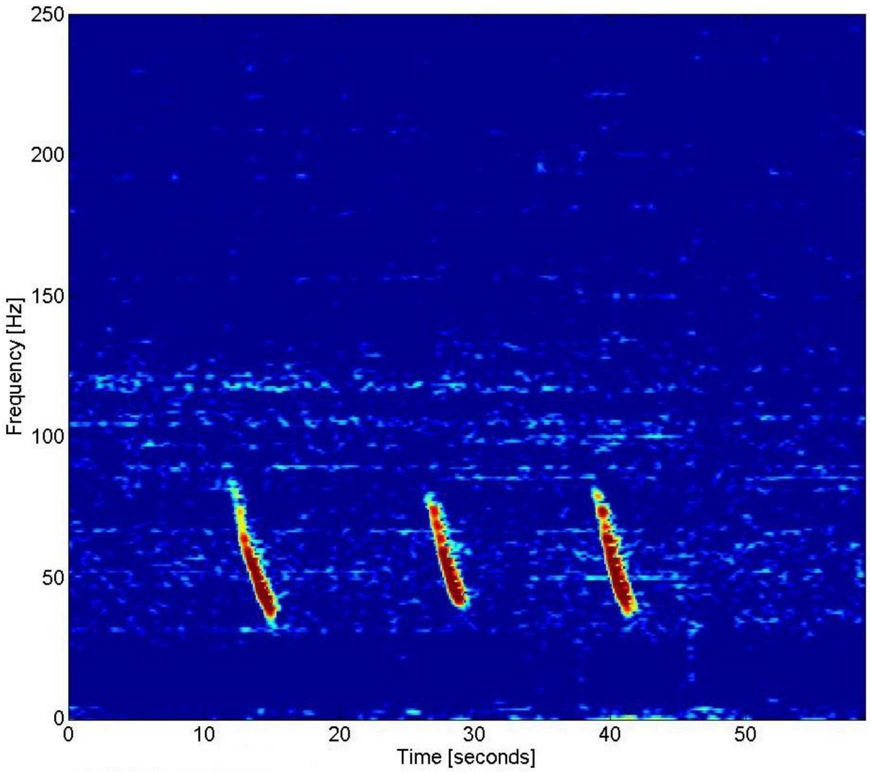


Figure 3. Spectrogram of blue whale D calls (2,000-point FFT and 90% overlap).

Fin Whales

Fin whales produce two types of short (approximately 1 s duration), low-frequency downswept calls: those that downsweep in the frequency from 30 – 15 Hz, called 20 Hz calls (Figure 4), and downsweeps from 75 – 40 Hz, called 40 Hz calls (Watkins 1981, Širović et al. 2013). 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). 40 Hz calls most often occur in irregular patterns.

For this report, fin whale 20 Hz calls were detected automatically using an energy detection method. The method used a difference in acoustic energy between signal and noise at different frequencies, calculated from 5 s LTSA with 1 Hz resolution. The frequency at 22 Hz was used as the signal frequency, while noise was calculated as the average energy between 10 and 34 Hz. All calculations were performed on the logarithmic scale. The performance of the detector was tested to find the optimal rate of false positives and missed detections, which was 19.4 % and 19.8 %, respectively. Beginning with the first day with fewer than 6 h with detections in the spring, the remainder of the automatic detections though July were manually verified for the presence of 20 Hz calls. False alarms during this period were removed from further analysis. Detections were binned into 1 hour bins for consistent reporting.

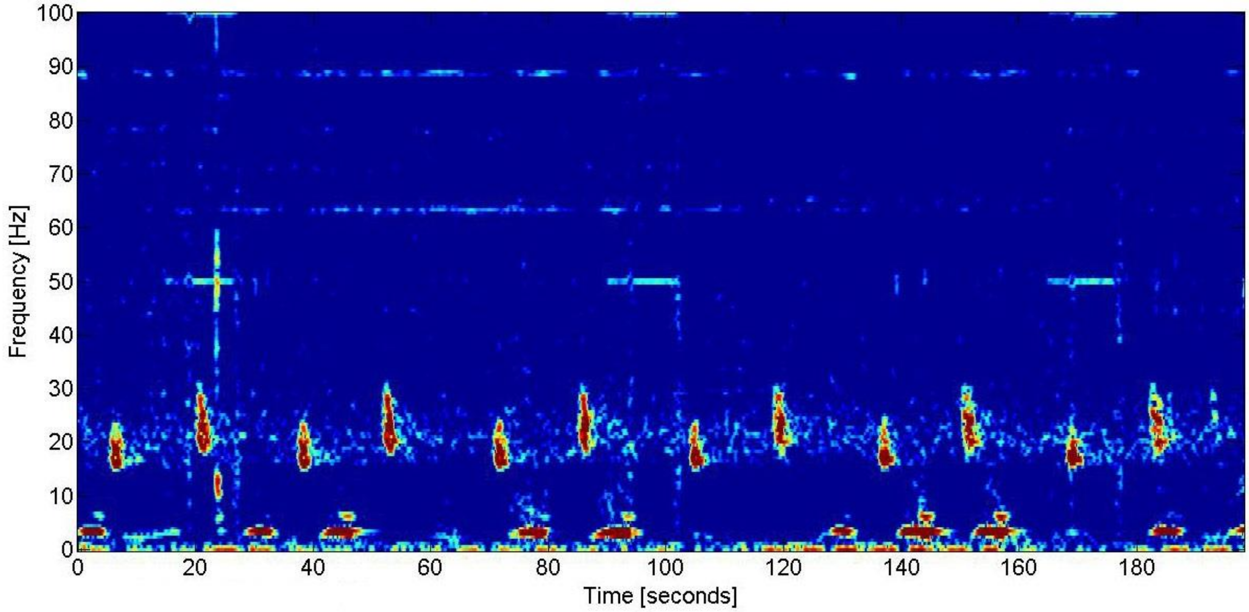


Figure 4. Fin whale 20 Hz pulsed calls, created in a regular pattern or song.

In addition to the automatic detection of 20 Hz calls, for this report, fin whale 40 Hz calls (Figure 5) were detected in the data via manual scanning of the LTSA and subsequent verification from a spectrogram of the frequency and temporal characteristics of the calls.

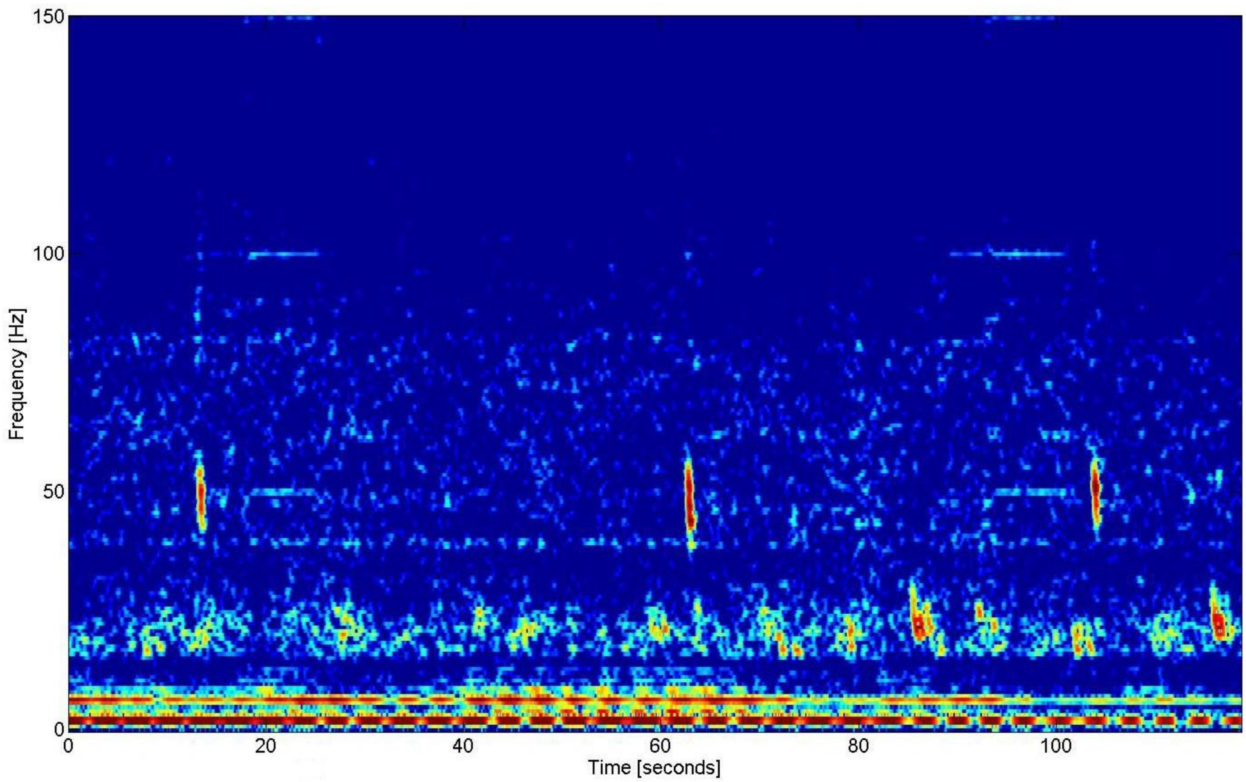


Figure 5. Fin whale 40 Hz call (2,500-point FFT and 95% overlap).

Bryde's Whales

Bryde's whales generally inhabit the warm waters of the eastern tropical Pacific and the Gulf of California, Mexico (Leatherwood et al. 1988, Tershy et al. 1991). The NWTRC region is considered beyond their northerly range limit, although there have been two recent strandings off Washington (J. Calamokidis, pers. comm). The Be4 call is one of several call types in the Bryde's whale repertoire and it is commonly recorded in the eastern North Pacific (Oleson et al. 2003, Kerosky et al. 2012). The Be4 call consists of a short, slightly upswept tone between 50 and 60 Hz. The low frequency data were monitored for the presence of this call.

Gray Whales

Gray whales produce low frequency sounds and four types of sounds have been described along their migration route between Baja California and the Bering Sea (Crane and Lashkari 1996). Call M1 consists of pulses and bonging signals. M3, the most commonly recorded call on the migration route, consists of low frequency moans. M4 are grunts and M5 are subsurface exhalations. Presence of M3 calls was monitored in the data. Classification of gray whale vocalizations is made more complex when humpback whale song and social calls are present, owing to the overlap in call frequencies and the large volume of calls associated with humpback call production versus few sounds produced by migrating gray whales.

Mid-Frequency Marine Mammals

Mid-frequency marine mammal sounds monitored in this report include: minke whale boings, humpback whale calls, killer whale whistles and pulsed calls, and pinniped calls. The LTSA search parameters used to detect each sound are given in Table 2. Humpback whale sounds were detected automatically, as described below. The start and end of each encounter was logged and their durations were added to estimate cumulative hourly presence of each mid-frequency sound source in the two datasets.

Table 2. Mid-frequency data analysis parameters.

Species / Sound type	LTSA Search Parameters Plot length (hr)	Frequency range (Hz)
Minke	0.5	1,000-2,000
Killer whale	0.75	10-5,000
Pinniped	0.75	200-700

Humpback Whale

Humpback whales produce song or non-song calls. The song is categorized by the repetition of units, phrases and themes of a variety of calls as defined by Payne and McVay (1971). Non-song vocalizations such as social and feeding sounds consist of individual units that can last from 0.2 to 2.5 seconds (Dunlop et al. 2007, Stimpert et al. 2011). Most humpback whale vocalizations are produced between 100-3,000 Hz (Figure 6). For this report we detected humpback calls (both song and non-song) using an automatic detection algorithm based on the generalized power law algorithm (see Helble et al. 2012 for a detailed description of the detection algorithm). The detections were subsequently verified for accuracy by a trained analyst.

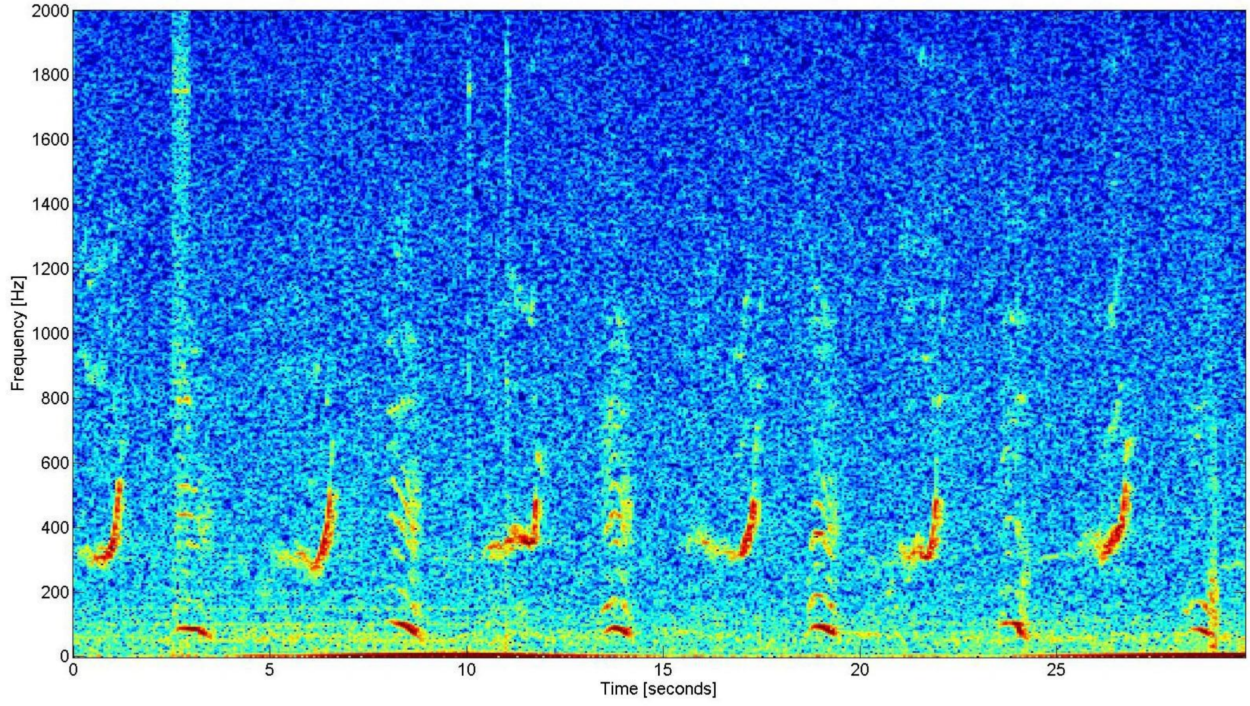


Figure 6. Spectrogram of humpback whale song segment, showing multiple units forming a phrase and a theme.

Minke Whale

Minke whale "boings" consist of 2 parts, beginning with a burst followed by a long buzz, with the dominant signal band just below 1400 Hz. A typical minke boing recorded in the eastern Pacific has an average duration of 3.6 seconds and a pulse repetition rate of 92 Hz (Rankin and Barlow 2005). Presence of minke boings was analyzed manually.

Pinniped

Most pinniped sounds off Washington are barking vocalizations, occurring between 400 and 600 Hz, and of short duration (< 1 s). However, pinniped barking bouts can last several hours at a time. As they are easily confused with humpback vocalizations in the LTSA, it was necessary to examine a short-term spectrogram view to confirm presence of pinnipeds in the data.

High Frequency Marine Mammals

High-frequency, species-specific sounds monitored in this report include: Risso's and Pacific white-sided dolphins, killer whale, sperm whale, Stejneger's beaked whale, Baird's beaked whale, Cuvier's beaked whale, and Blainville's beaked whale. Also monitored were narrow-band high frequency clicks from unidentified porpoise, and other whistles and echolocation clicks that cannot be attributed to a single species at this time. The start and end of each acoustic encounter was logged and their durations were added to estimate cumulative hourly presence of each high-frequency sound source in the two datasets.

Unidentified Dolphin

Delphinid sounds can be categorized as whistles, buzz or burst pulses, or echolocation clicks. Dolphin echolocation clicks are broadband impulses with the dominant energy between 20 and 60 kHz. Buzz or burst pulses are rapidly repeated clicks that have a creak or buzz-like sound quality; they are in approximately the same frequency band as the echolocation clicks. Dolphin whistles are tonal calls predominantly between 5 and 20 kHz that vary in their degree of frequency modulation as well as duration. Some delphinid sounds are not yet distinguishable to species based on the character of their clicks, buzz or burst pulses or whistles (Roch et al. 2007, 2011). Northern right whale dolphins (*Lissodelphis borealis*), short-beaked common dolphin (*Delphinus delphis*), bottlenose dolphins (*Tursiops truncatus*), and striped dolphins (*Stenella coeruleoalba*) make clicks and whistles that are thus far not definitively classifiable to species level and may all be encountered in this area (Jefferson et al. 2008), although only northern right whale dolphin sightings have been confirmed (Oleson et al. 2009). Since these signals are easily detectable in an LTSA as well as the spectrogram (Figure 7), they were monitored during this analysis effort and are characterized as unidentified dolphin signals.

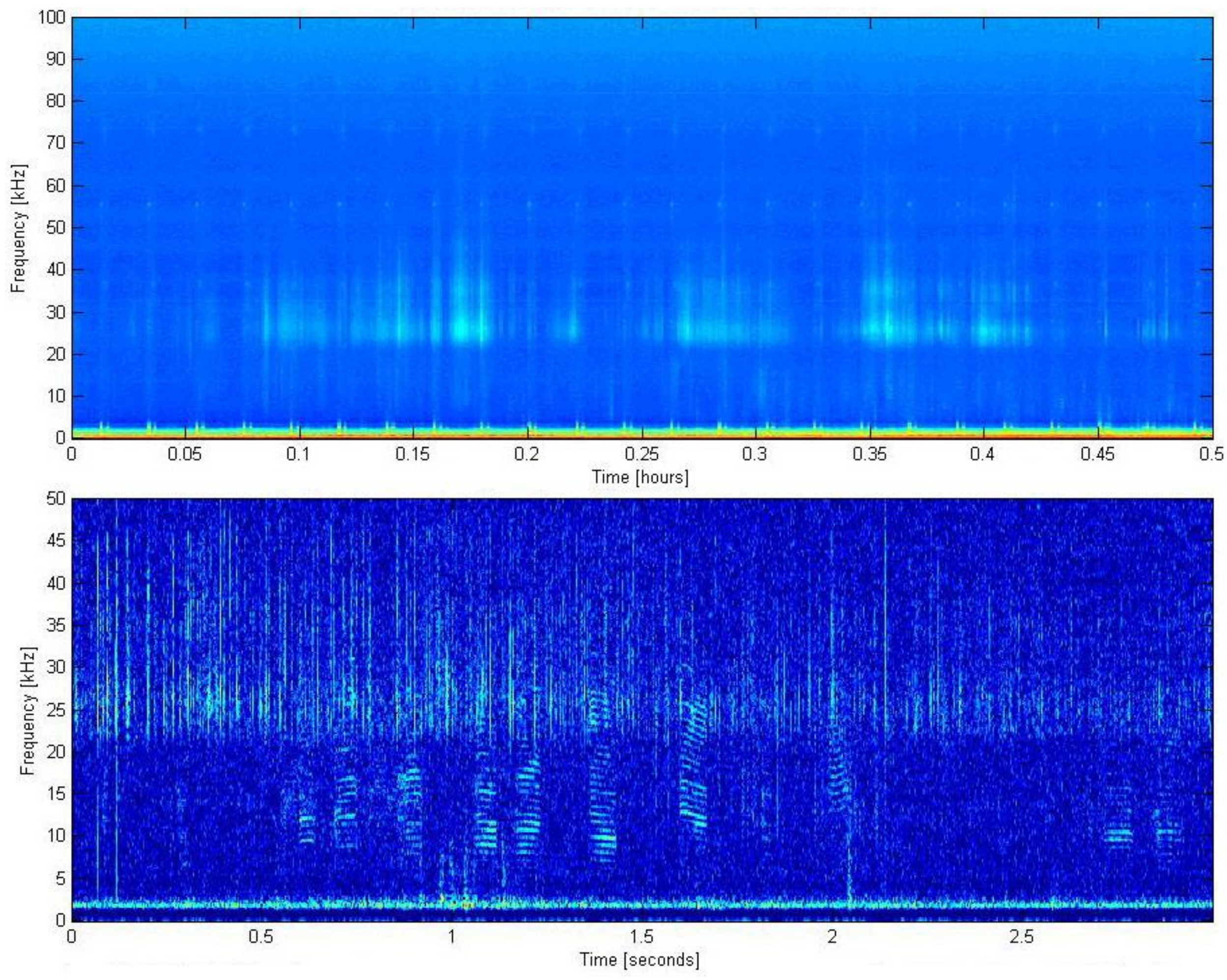


Figure 7. LTSA (top) and spectrogram (bottom; 1,000 point FFT and 50% overlap) of unidentified odontocete signals.

Risso's Dolphin

Risso's dolphin echolocation clicks can be identified to species by their distinctive banding patterns observable in the LTSA (Figure 8). Risso's dolphin echolocation clicks recorded offshore southern California have energy peaks at 22, 26, 30, and 39 kHz (Soldevilla et al. 2008), and it is expected that their energy peaks will be similar in the NWTRC area.

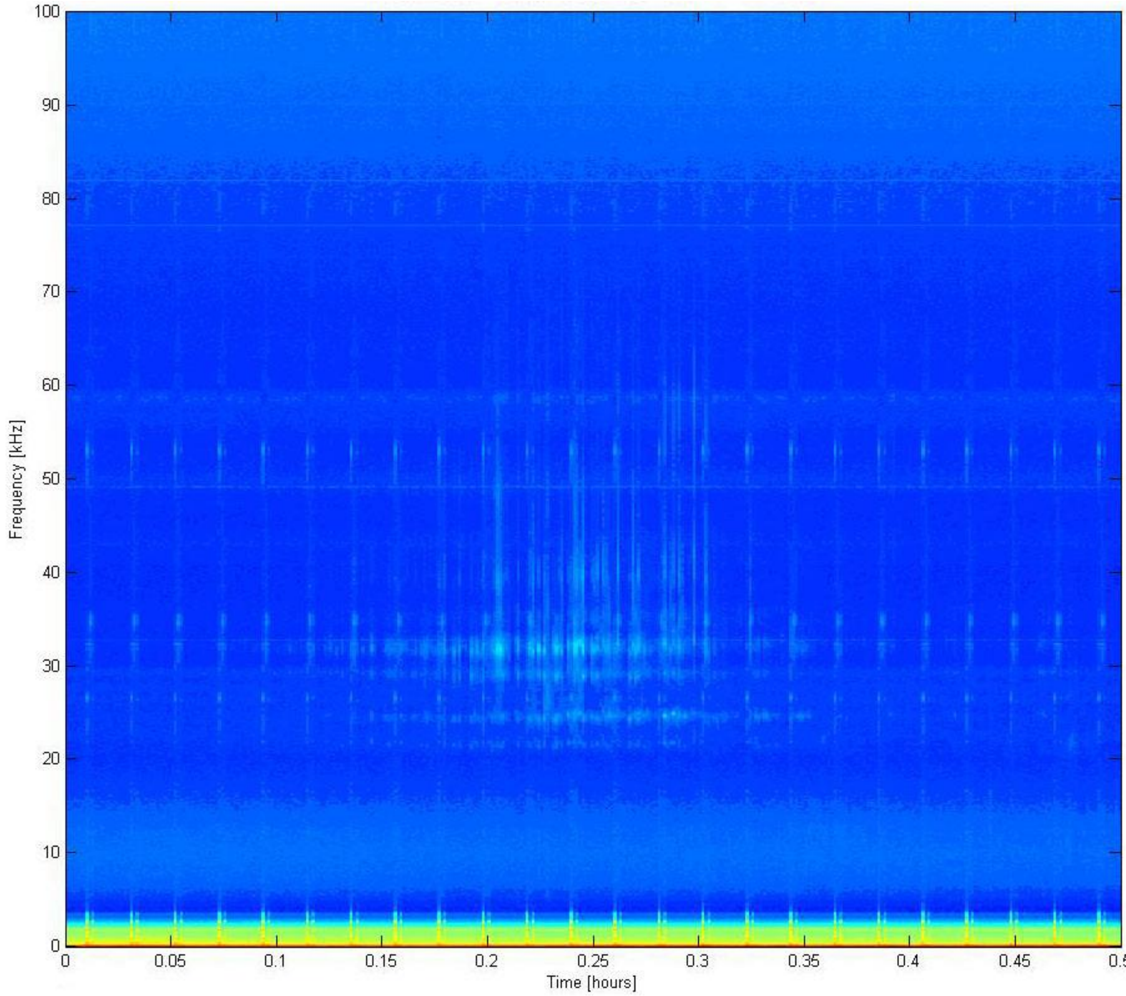


Figure 8. Risso's dolphin click bout in a LTSA. Note a distinctive banding pattern.

Pacific White-Sided Dolphin

Pacific white-sided dolphin echolocation clicks also can be identified to species by their distinctive banding patterns (Figure 9). Pacific white-sided dolphin echolocation clicks recorded offshore southern California have two distinctive patterns of energy peaks, designated type A and type B (Soldevilla et al. 2010). The type A group occupies the northern portion of the southern California Bight, whereas both groups are known from the southern portion of the Bight. Since Pacific white-sided dolphins are thought to seasonally migrate, the type A group is more likely to be found within the NWTRC. The type A dolphins' echolocation clicks have energy peaks at 22, 27, 33, and 37 kHz (Soldevilla et al. 2008).

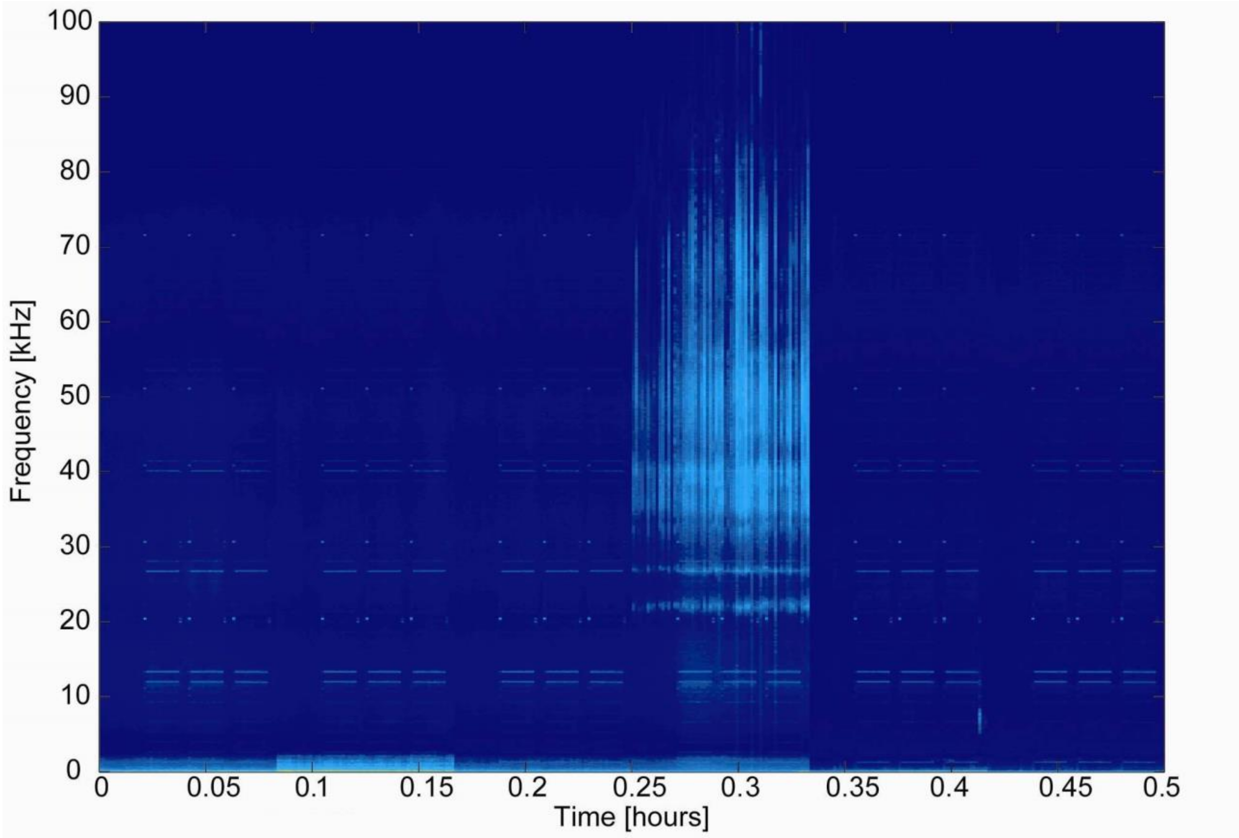


Figure 9. Pacific white-sided dolphin echolocation clicks in a LTSA.

Killer Whale

Killer whales are known to produce four call types: echolocation clicks, low frequency whistles, high-frequency modulated signals, and pulsed calls (Ford et al. 1989, Samarra et al. 2010, Simonis et al. 2012). Killer whale pulsed calls are well documented and are the best described of all killer whale 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 et al. 1989). High frequency modulated (HFM) signals have only recently been attributed to killer whales in both the northeast Atlantic (Samarra et al. 2010) and the northeast Pacific (Simonis et al. 2012). These signals have fundamental frequencies between 17 and 75 kHz, the highest of any known delphinid tonal calls. Pulsed calls and the HFM signals were used for killer whale species identification in this analysis.

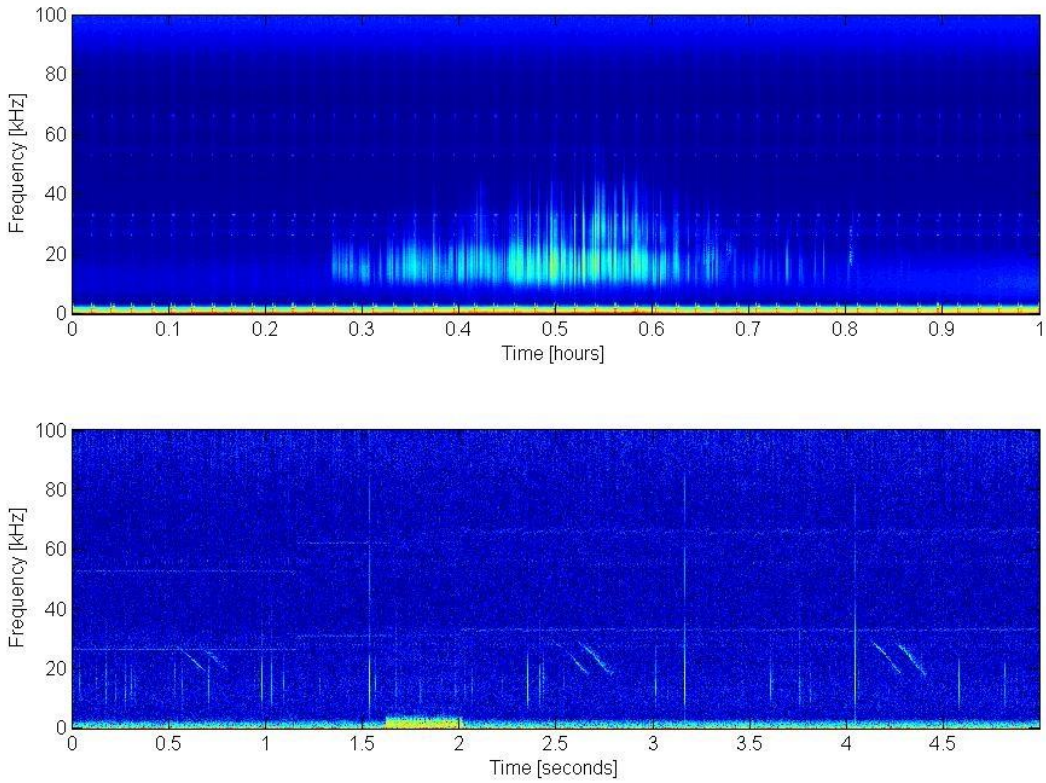


Figure 10. Killer whale echolocation clicks and HFM signals in a LTSA (top) and spectrogram (bottom).

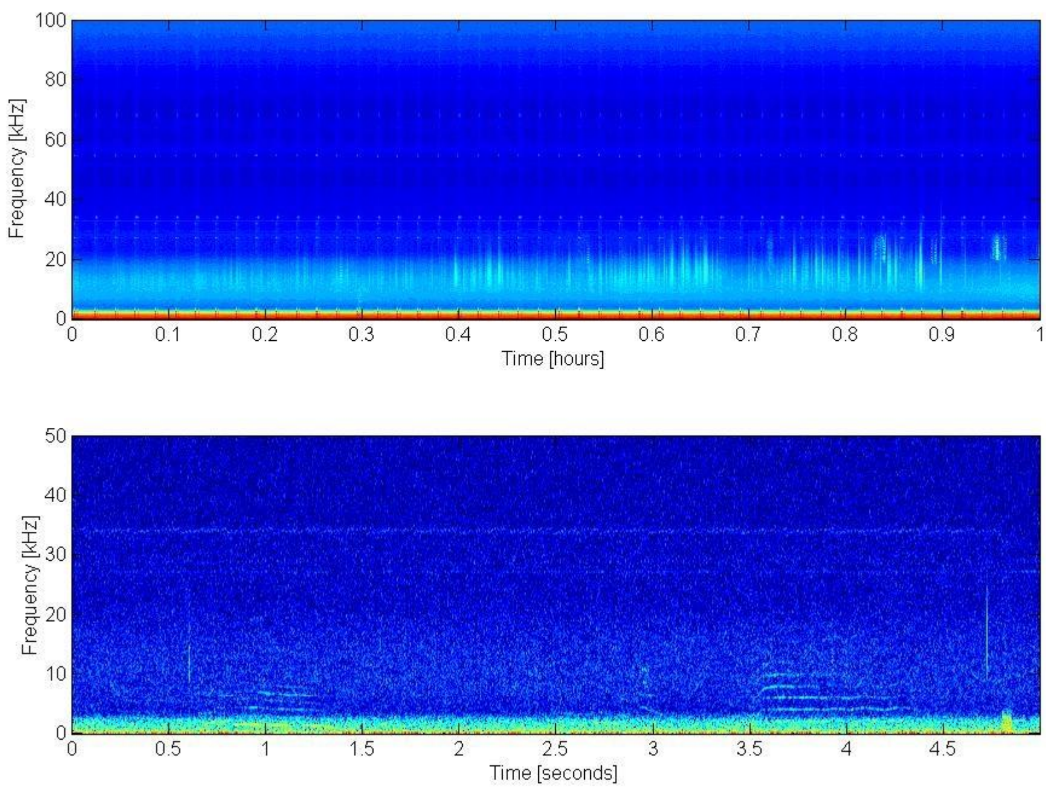


Figure 11. Killer whale pulsed calls in a LTSA (top) and spectrogram (bottom).

Sperm Whale

Sperm whale clicks generally contain energy from 2-20kHz, with the majority of energy between 10-15 kHz (Møhl et al. 2003). Regular clicks, observed during foraging dives, demonstrate a uniform inter-click interval from 0.25-2 seconds (Goold and Jones 1995, Madsen et al. 2002, Møhl et al. 2003). Short bursts of closely spaced clicks called creaks are observed during foraging dives and are believed to indicate a predation attempt (Watwood et al. 2006). Sperm whales also produce other clicks, which can be classified as slow clicks and codas. Slow clicks are used only by males and are more intense than regular clicks with long inter-click intervals (Madsen et al. 2002). Codas are stereotyped sequences of clicks which are less intense and contain lower peak frequencies than regular clicks (Watkins and Schevill, 1977). Multiple foraging dives and rest periods are often observed over a long period of time in the LTSA. Although ship noise can be confused with sperm whales in the LTSA, in the finer resolution of a spectrogram, the erratic impulses from mechanical noise and propeller cavitation can be easily distinguished from the continuous, regular sperm whale clicks.

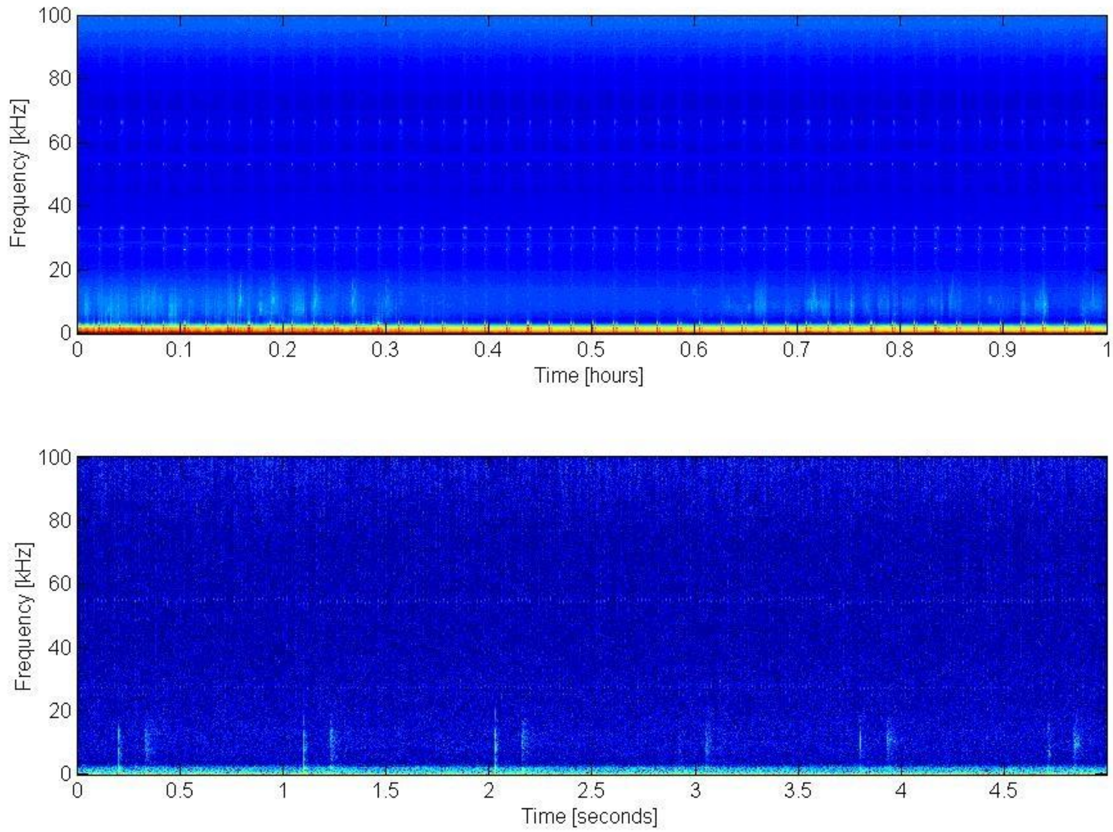


Figure 12. Sperm whale echolocation clicks in a LTSA (top) and spectrogram (bottom).

Stejneger's Beaked Whale

Stejneger's beaked whales are known to occur with some regularity in the northern Pacific Ocean. Their echolocation signals are easily distinguished from other species' acoustic signals; they have the typical beaked whale polycyclic structure and frequency-modulated (FM) pulse upsweep with a peak frequency above 50 kHz and uniform inter-pulse interval around 0.1s (Figure 13; Baumann-Pickering et al. 2012).

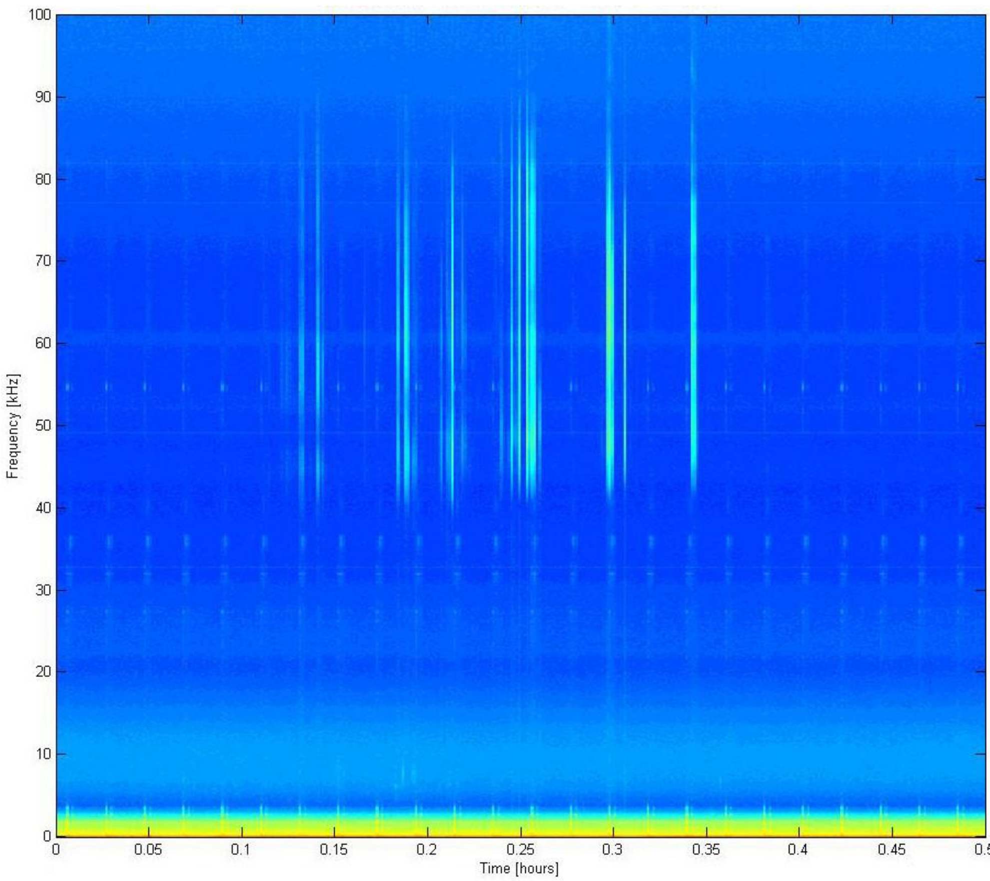


Figure 13. Stejneger's beaked whale FM pulses in a LTSA.

Baird's Beaked Whale

Baird's echolocation signals are distinguishable from other species' acoustic signals and one of their signal types demonstrates the typical beaked whale polycyclic, FM pulse upsweep (Dawson et al 1998). These FM pulses are easily identifiable because they are lower frequency than other beaked whale signals. Spectral peaks are notable around 15, 30 and 50 kHz (Figure 14).

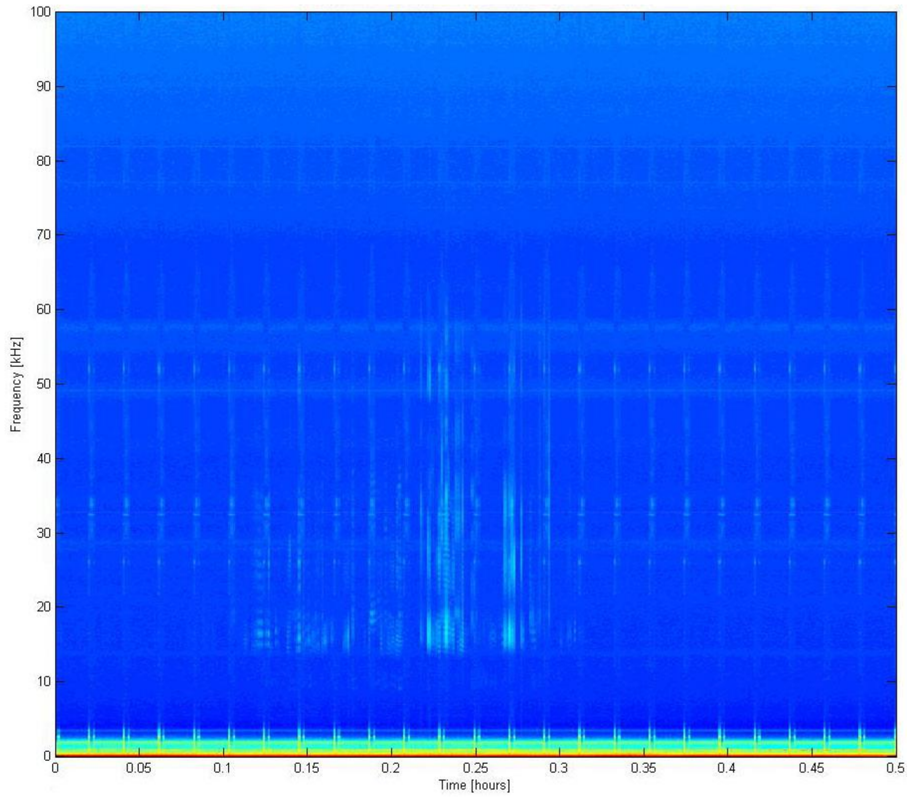


Figure 14. Baird's beaked whale FM pulses in a LTSA.

Cuvier's Beaked Whale

Cuvier's echolocation signals are also 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 0.4s (Johnson et al. 2004, Zimmer et al. 2005). An additional feature that helps with the identification of Cuvier's FM pulses is that they have two characteristic spectral peaks around 17 and 23 kHz (Figure 15).

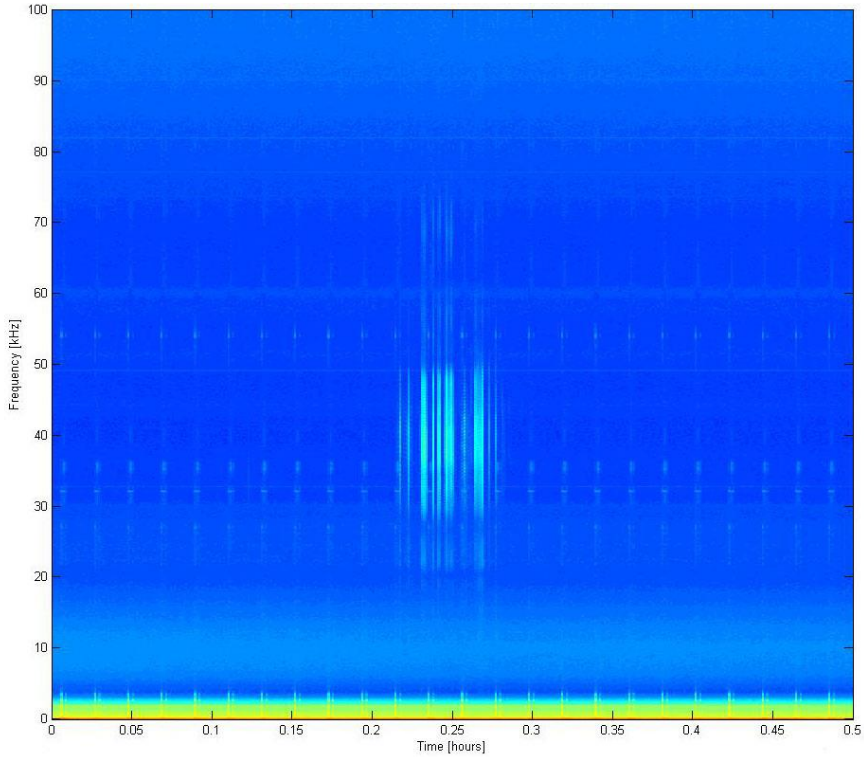


Figure 15. Cuvier's beaked whale FM pulses in a LTSA.

Blainville's Beaked Whale

Blanville's beaked whales produce a distinctive echolocation signal with a typical wide FM pulse upsweep with a -10 dB bandwidth from 26-51 kHz, a well differentiated sharp cut-off below 25 kHz, and a peak frequency around 30 kHz (Figure 16). These FM pulses also have a regular inter-pulse interval of about 0.3 s (Johnson et al. 2006).

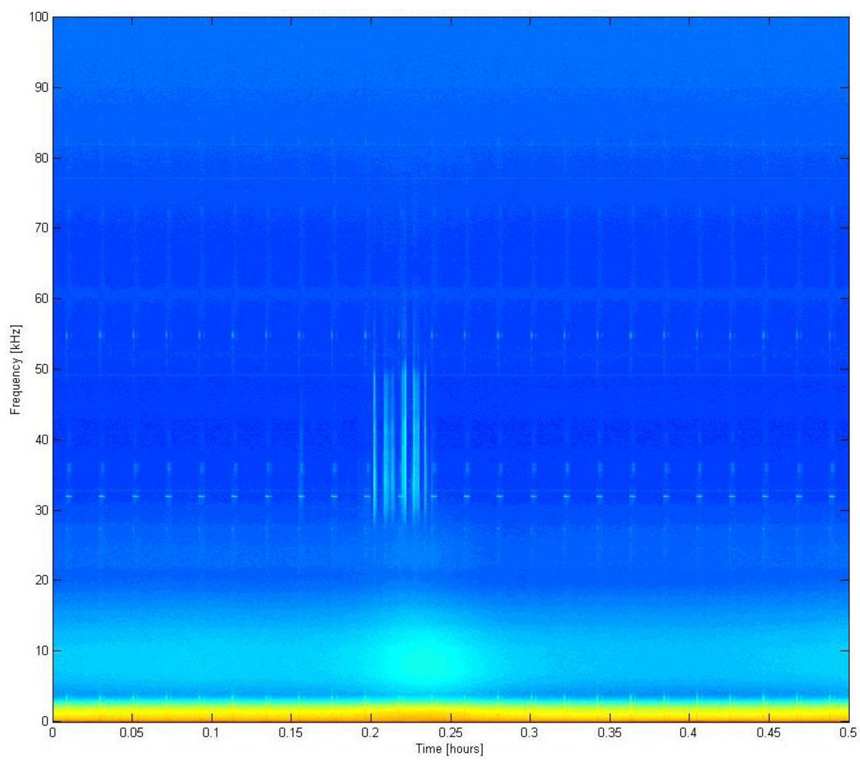


Figure 16. Blainville's beaked whale FM pulse in LTSA.

Unidentified Beaked Whale

All other beaked whale-type FM pulses that had a constant inter-pulse interval, but their signal quality was not sufficient for species identification, would have been categorized and logged as unidentified beaked whale signals, but no such signals were detected in these deployments.

Unidentified Porpoise

Harbour porpoises (*Phocoena phocoena*) and Dall's porpoises (*Phocoenoides dalli*) were the most frequently sighted marine mammals during visual surveys in the area (Oleson et al. 2009, 2010). Both Dall's and harbour porpoises produce clicks that contain energy from 115-150 kHz (Verboom and Kastelein 1995), higher frequency than the bandwidth of these recordings. Narrow-banded high frequency (NBHF) clicks, with energy from 55-85 kHz and a narrower bandwidth than typical delphinid clicks, were frequently identified in this dataset (
Figure 17). There is no known cetacean in the study area which produces echolocation clicks of this description and these NBHF clicks are most likely a result of spectral aliasing (mirroring of energy from above the recording band into the recording band) of porpoise clicks produced with high source levels in very close proximity to the recorder.

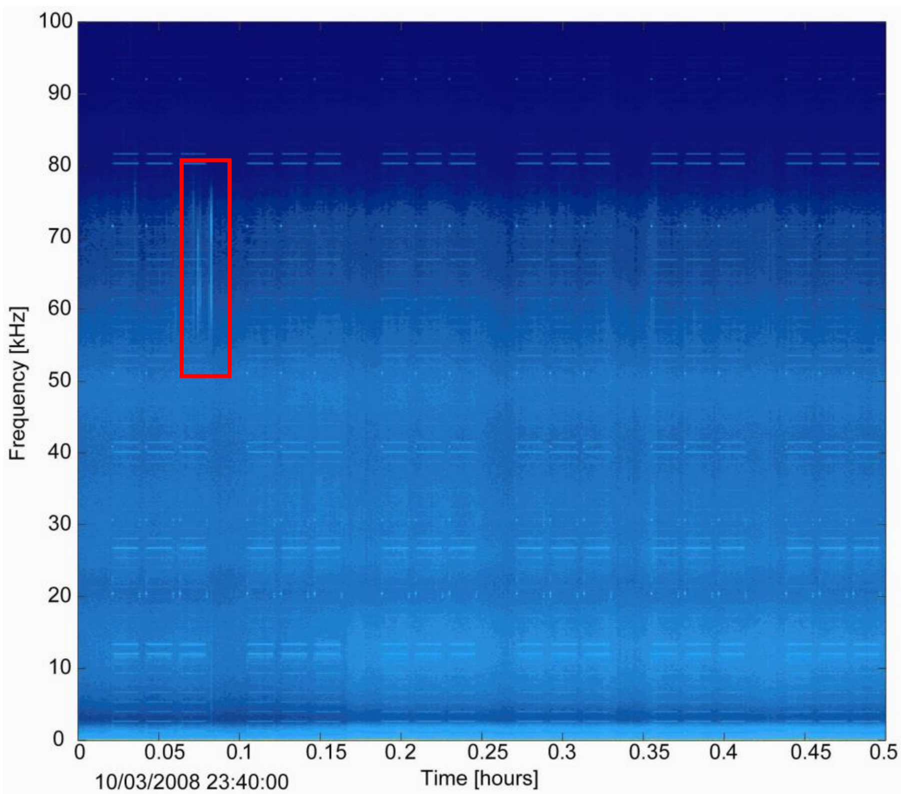


Figure 17. LTSA of narrow-banded high frequency (NBHF) pulses (outlined by a red box), likely aliased porpoise pulses recorded at site CE.

Anthropogenic Sounds

Several anthropogenic sounds occurring at mid-frequency ranges (<5 kHz) were also monitored for this report: broadband ship noise, mid- frequency active (MFA) sonar, and explosions. The LTSA search parameters used to detect each sound are given in Table 3. The start and end of each sound or session was logged and their durations were added to estimate cumulative hourly presence of each mid-frequency sound source in the two datasets.

Table 3. Mid-frequency anthropogenic sound data analysis parameters.

Species / Sound type	LTSA Search Parameters Plot length (hr)	Frequency range (Hz)
Broadband Ship Noise	3.0	10-5,000
MFA Sonar	0.75	1,000-5,000
Echosounders	0.75	10-5,000
Explosions	0.75	10-5,000

Broadband Ship Noise

Broadband ship noise occurs when a ship passes relatively close to the HARP. 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. 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 HARP (Figure 18). This noise can extend to well above 10 kHz, though typically falls off above a few kHz.

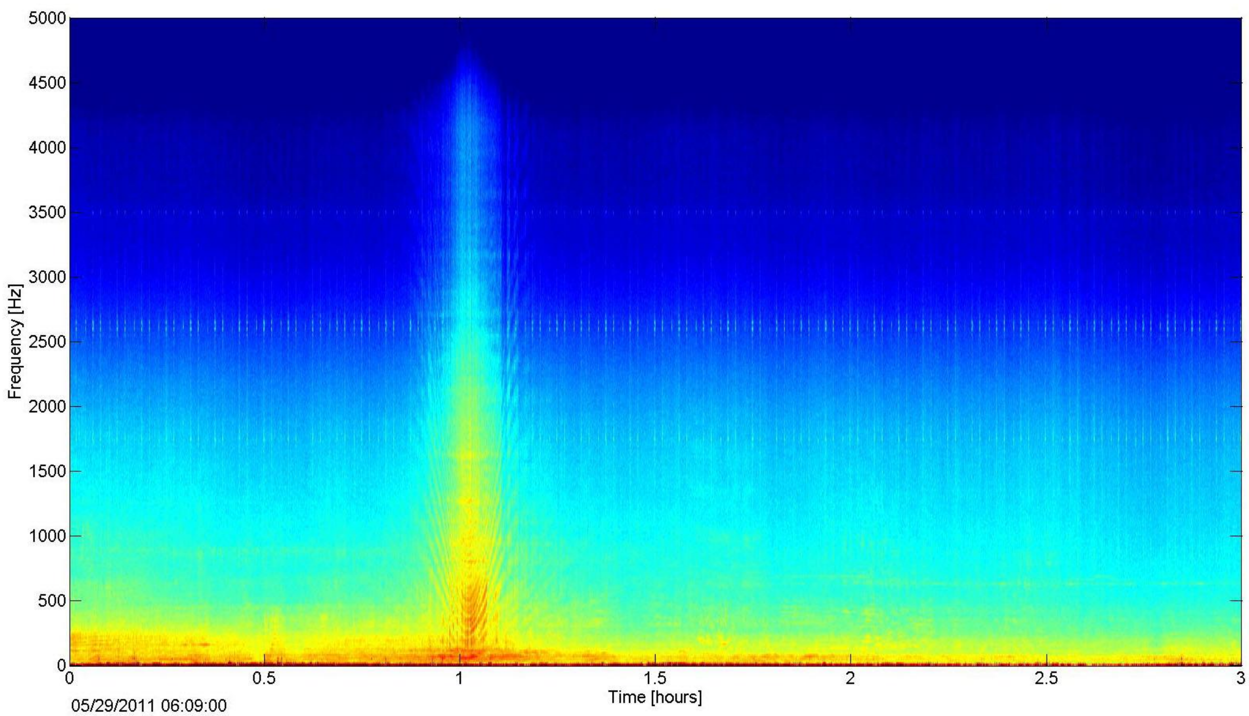


Figure 18. Broadband ship noise in the LTSA.

Mid-Frequency Active (MFA) Sonar

Sounds from MFA sonar vary in frequency and duration and can be used in a combination of frequency modulated (FM) sweeps and continuous wave (CW) tones. While they can span frequencies from about 1 kHz to over 50 kHz, many are between 2.0 and 5.0 kHz and are more generically known as '3.5 kHz' sonar. In this section, we describe the process for identifying sessions or events of MFA sonar in recordings from HARPs and how pings from these sessions were analyzed, including counts and distributions of sonar levels.

The first step in analyzing MFA sonar was conducted by visual scanning of LTSAs for periods of sonar activity. Individual MFA sonar pings typically span 1 - 3 s, but are intense enough to show up as 'pulses' in LTSA plots. Start and end times of MFA sonar events were logged manually to provide target periods for automatic detections. A custom-developed MATLAB routine was used to detect sonar pings and calculate peak-to-peak (PP) received sound pressure levels using manually picked target periods. For this detector, a sonar ping was defined as the presence of sonar within 5 s. The average spectrum level across the frequency band from 2.4 to 4.5 kHz for each 5 s time bin was calculated. This provides a time series of the average received levels in that frequency band. Minimum values were noted for each 15 time bins, and used as a measure of background noise level over the sonar event period. Spectral bins that contained system noise (disk writing) were eliminated to prevent contamination in the results. Each of the remaining average spectral bins was compared to the background minimum levels. If levels were more than 3 dB above the background, then a detection time was noted. These detection times were used to index to the original time series to calculate peak-to-peak (PP) levels. Received PP levels were calculated by differencing the maximum and minimum amplitude of the time series in the 5 s window. The raw time series amplitudes are in units of analog-to-digital converter (ADC) counts. These units were corrected to µPa by using the HARP calibrated transfer function for this frequency band. The HARP response is not flat over the 2.4 – 4.5 kHz band, so a middle value at 3.5 kHz was used. The transfer function value used was 84.3 dB re $\mu Pa^2/counts^2$. For sonar pings less than this middle frequency, the levels are overestimated up to about 7 dB and for higher frequency sonar the levels are underestimated up to about 1 dB.

Echosounders

Echosounding sonars transmit short pulses or frequency sweeps, typically in the mid- or high frequency ranges. 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 mid-frequency.

Explosions

Explosive sounds logged in the HARP data can include 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 which, when expanded in the spectrogram, has a sharp onset with a reverberant decay (Figure 19). These sounds have peak bandwidth as low as 10 Hz but often extend over 2,000 Hz, lasting for a few seconds including the reverberation.

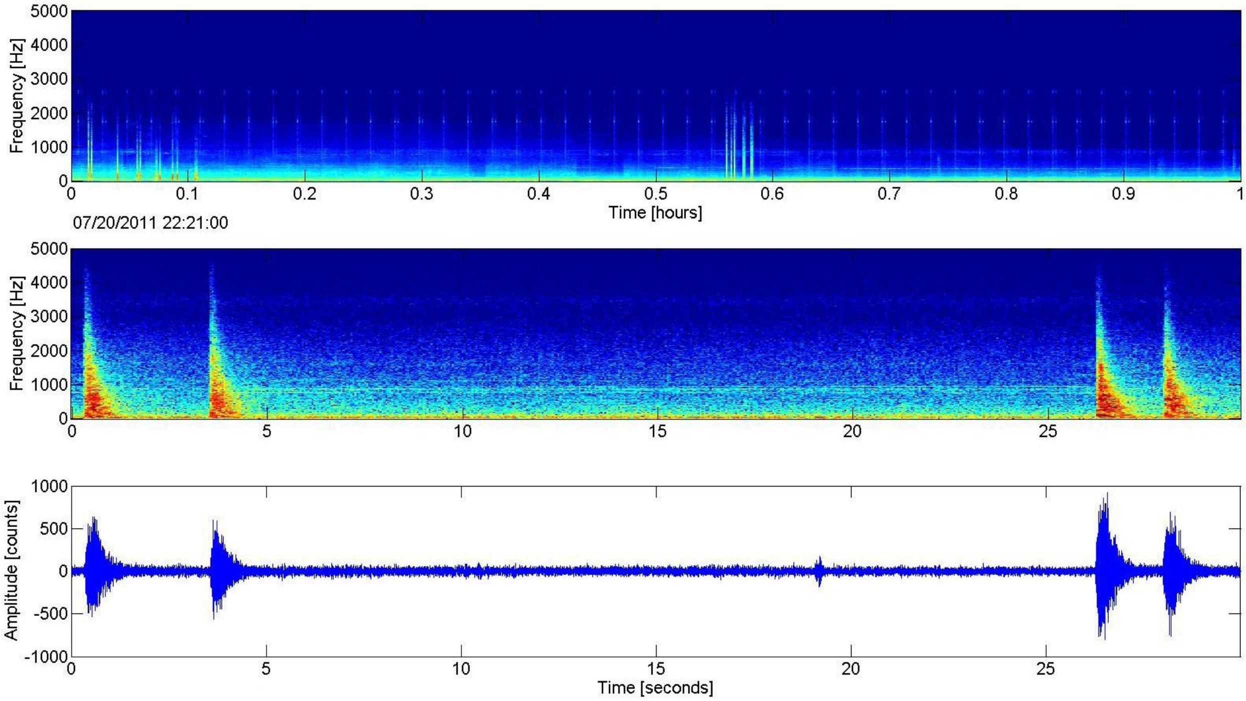


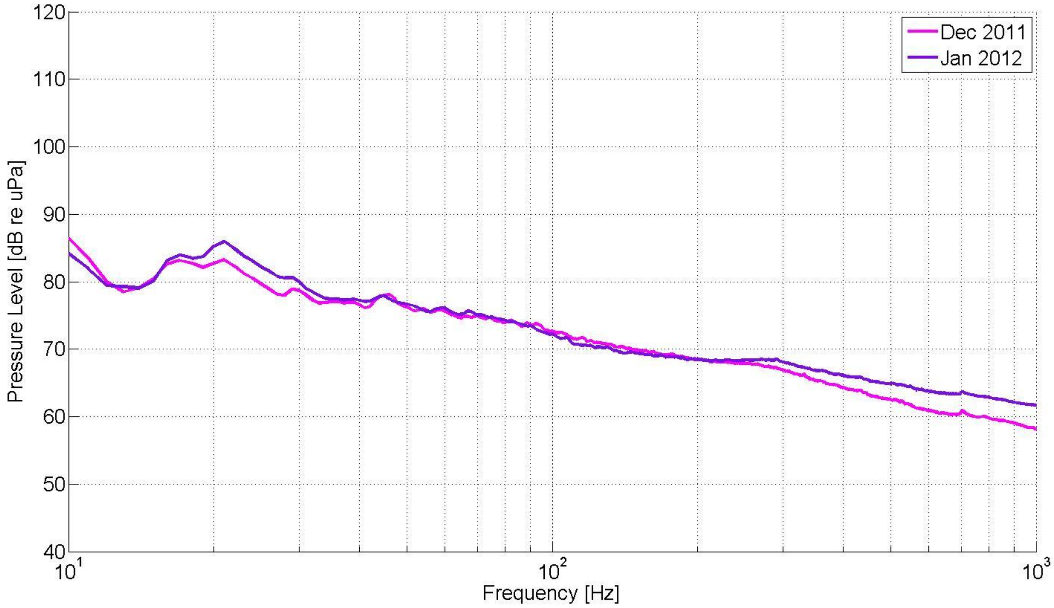
Figure 19. Multiple explosions are seen in the LTSA (top) and four individual events of these are expanded in the spectrogram (middle) and time series (bottom).

Results

This report summarizes the results of acoustic data collection in the NWTRC at site CE (shelf) from December 2011 through January 2012, and site QC (slope) from December 2011 through July 2012. We present ambient noise levels and the seasonal occurrence of marine mammal species and anthropogenic sounds recorded at these two locations.

Ambient Noise

Ambient noise at sites CE (shelf) and QC (slope) are presented in Figure 20. There was a significant amount of system-induced noise in the recordings from site CE, possibly due to strumming of the instrument cable during intense current flow on the continental shelf. Periods of high system noise were removed from analysis in order to accurately measure ambient noise. At site CE, 75 percent of the data was excluded. Both sites display a prominent seasonal peak at 15-30 Hz during the winter, indicative of the presence of fin whale calls. This peak is more pronounced at site QC and consistent with fin whale spatial preference determined from call detection at both sites, presented herein. At frequencies above 200 Hz, local wind and waves dominate the noise (Hildebrand 2009) and are generally lower during the summer, as demonstrated at site QC. The jagged appearance of the spectra during the summer at site QC and frequencies <200 Hz may be indicative of higher local boating activity.



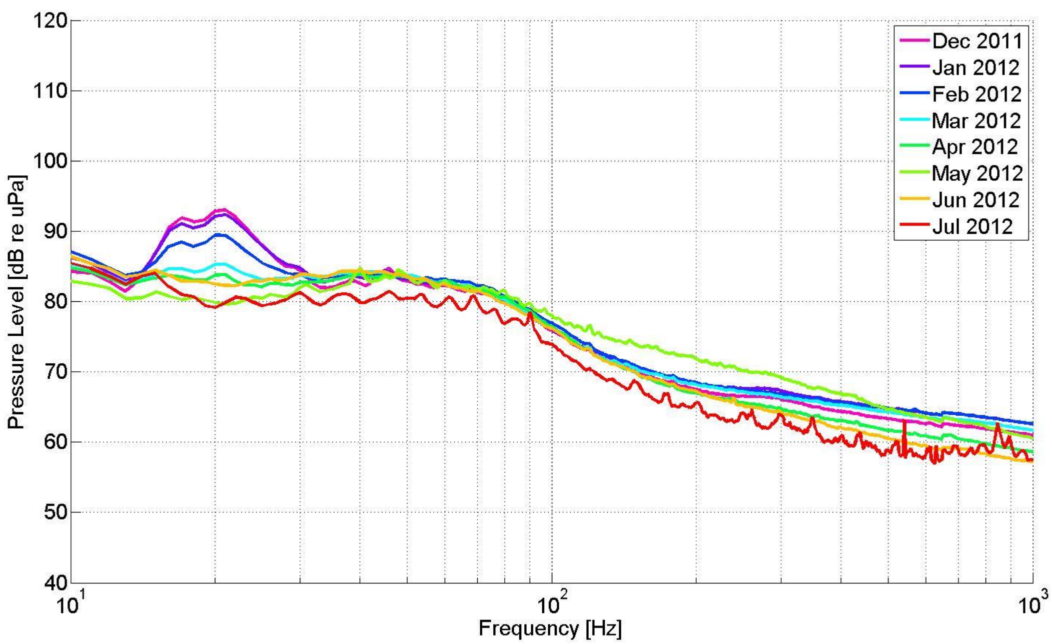


Figure 20. Monthly averages of ambient noise at site CE from December 2011 to January 2012 (top) and site QC from December 2011 to July 2012 (bottom). Legend gives color-coding by month.

Mysticetes

Four baleen whale species were detected in December 2011 and during 2012 at sites CE and QC: blue whales, fin whales, gray whales, and humpback whales. Relative hourly calling abundance varied among sites and species. Blue whale calls (B and D) were detected at both sites, but B calls were more common on the shelf site CE. Fin whale calls were more common on the slope site QC, and gray whale calls were more common closer to shore at site CE. Humpback whale calls were present at both sites. No Bryde's or minke whale calls were detected at either site. More details of each species' presence at these sites are given below.

Blue Whales

Blue whale B calls were detected at both sites during this monitoring period. Peaks in hours with detections occurred in December at site CE, and in January at site QC (Figure 21). No calls were detected between April and July.

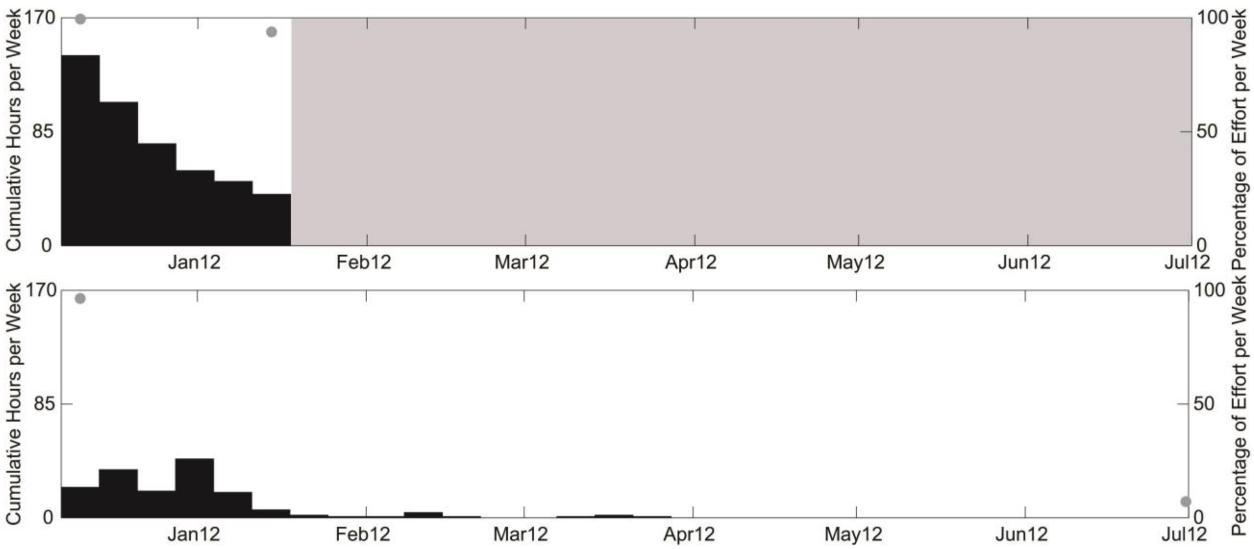


Figure 21. Weekly presence of blue whale B calls (black bars) at sites CE (top) and QC (bottom) between December 2011 and July 2012. Gray dot represents percent of effort per week in weeks with less than 100% recording effort and gray shading marks show periods with no recording effort. Where gray dots or shading are absent, full recording effort occurred for the entire week.

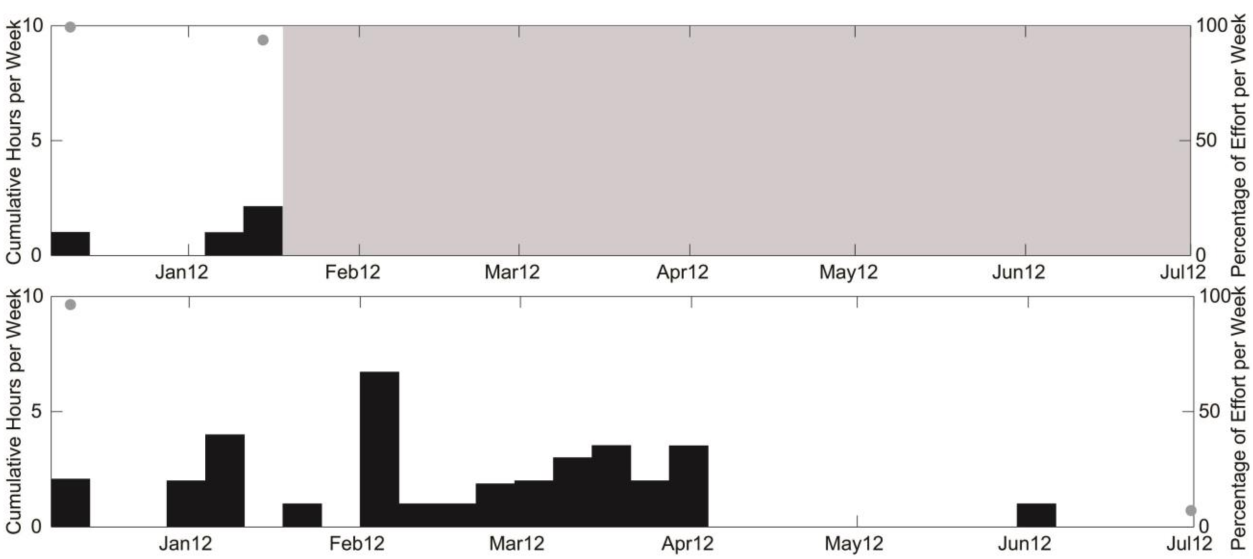


Figure 22. Weekly presence of blue whale D calls (black bars) at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Blue whale D calls were recorded at both sites in December and January, and were detected until April at site QC (Figure 22). No D calls were detected in May, but one hour of D call presence was detected in June. Overall, this seasonal presence is consistent with previously reported seasonal occurrence of blue whale calls off Washington (Watkins et al. 2000, Burtenshaw et al. 2004, Širović et al. 2011, 2012).

Fin Whales

Fin whales were the most common acoustically detected baleen whale at both sites and their calls were detected at both sites with peak calling in winter and spring and low calling during the summer (Figure 23 and Figure 24). At site CE, 20 Hz calls were present throughout December and January, peaking in mid-January. At site QC, high numbers of hours with 20 Hz calls were detected from January through April, tapering off in May (Figure 23). Farther offshore in the eastern North Pacific, fin whale calls are generally detected from October through April (Watkins et al. 2000), corresponding to the pattern we observed at our sites.

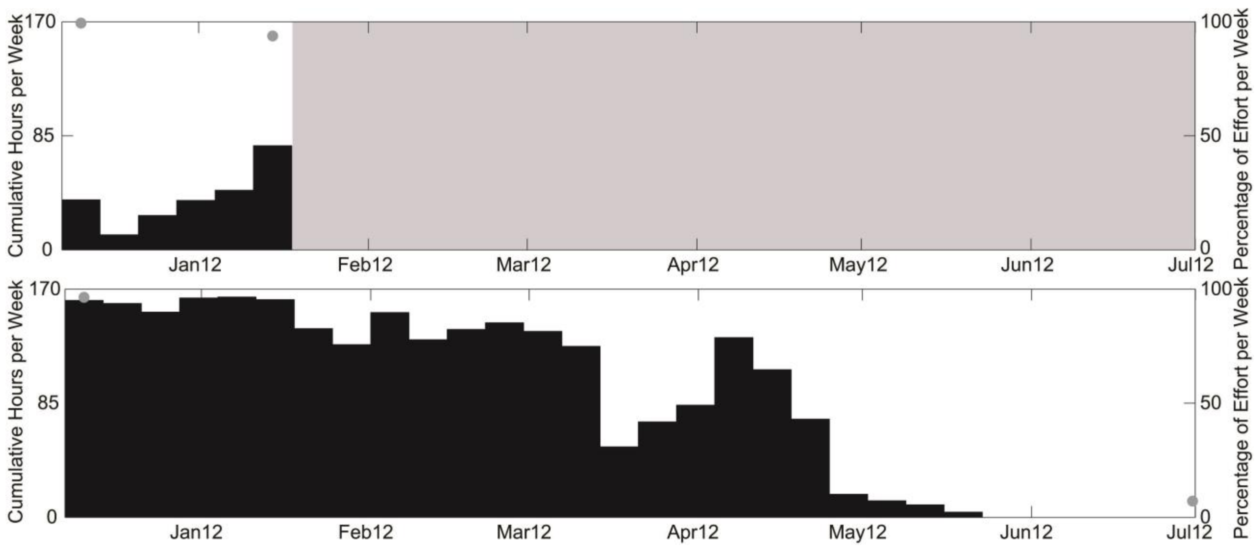


Figure 23. Weekly fin whale 20 Hz call presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

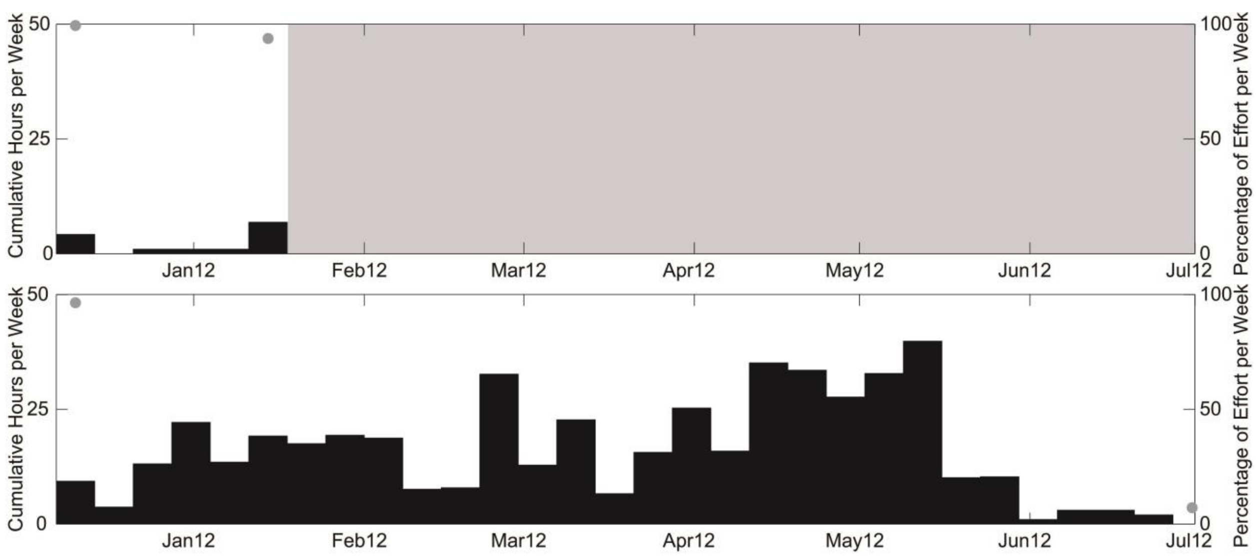


Figure 24. Weekly fin whale 40 Hz call presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Fin whale 40 Hz calls were recorded at both sites (Figure 24). In general, there were fewer hours with 40 Hz calls than the 20 Hz calls. As with 20 Hz calls, 40 Hz calls were present from December to June. Peaks in the number of hours with 40 Hz calls occurred March through May, whereas peaks in 20 Hz calling hours occurred December through April. Differences in the timing of peak calling presence per call type may indicate distinct behavioral functions associated with these call types (Širović et al. 2013).

Bryde's Whales

No Bryde's whale calls were detected at either of the sites during the monitoring period. While there have been a few recent strandings of Bryde's whales off Washington, this area is generally beyond their traditional range (Kerosky et al. 2012).

Gray Whales

Gray whale M3 calls were detected at both sites in December and January (Figure 25). These calls were more commonly detected at the inshore site (CE), and are consistent with the coastal migration patterns of southbound gray whales traveling from feeding grounds in the Bering and Chukchi Seas to breeding grounds off Baja California.

Identification of gray whale calls was difficult due to the abundance of humpback whale social sounds during most of the recording period at site CE. These humpback sounds covered much of the same bandwidth as gray whale M3 calls. More details on the acoustic repertoire of the gray whale populations, as well as details of social call structure by humpback whales in this region would be beneficial for future efforts of gray whale call detection at these sites.

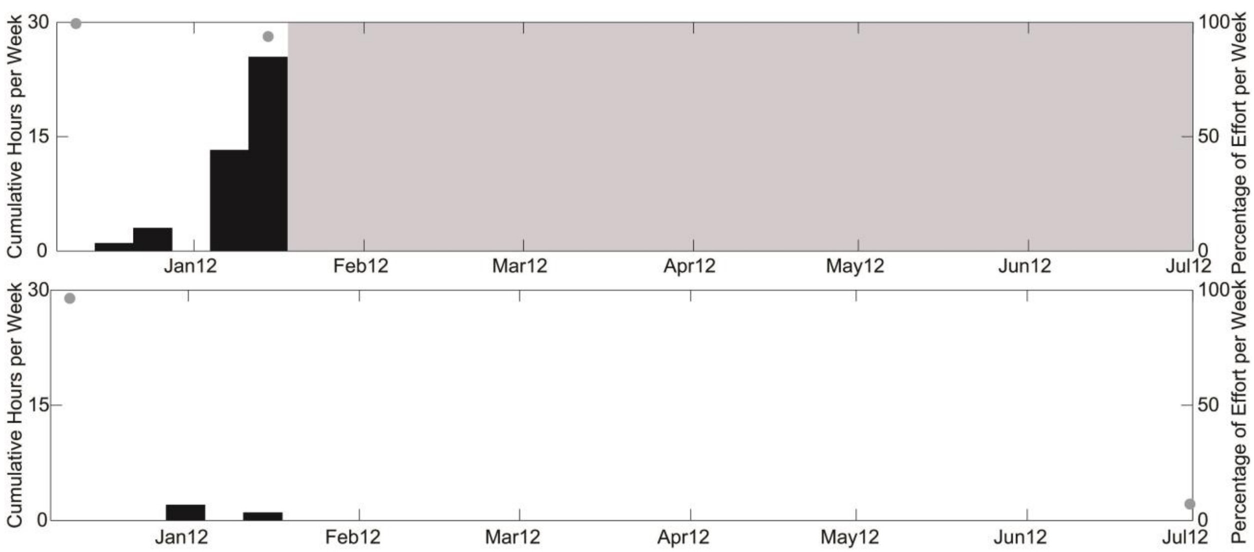


Figure 25. Weekly gray whale M3 call presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Humpback Whales

Both song and non-song call types were grouped for this analysis of humpback whale presence. Humpback whale calls were detected at high rates from December through February (Figure 26), which is consistent with previous recordings showing overwintering presence at this site (Oleson et al. 2009, Širović et al. 2011, 2012). This time is the peak time for humpback singing (Širović et al. 2011) so it is likely that a large portion of the hourly detections were songs. The lower level of calling from February through July is also consistent with previous findings (Oleson et al. 2009, Širović et al. 2011, Širović et al. 2012). Visual and acoustic detections of humpback whales in this area do not fully overlap (Oleson et al. 2010), which is likely due to the difference in the availability of animals for different types of surveys based on their behavioral state.

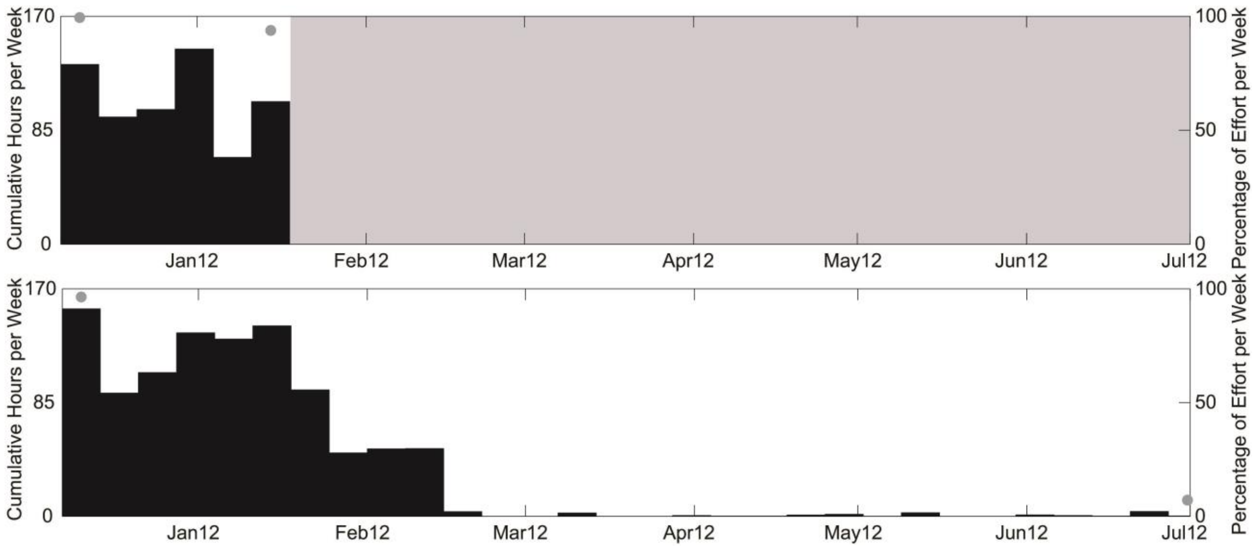


Figure 26. Weekly presence of all humpback whale calls at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Minke Whales

No minke whale boings were detected at either of the monitored sites. This is consistent with the results of previous monitoring efforts in this area (Širović et al. 2011, 2012).

Pinnipeds

No pinniped vocalizations were detected at site CE between December 2011 and January 2012, or at site QC between December 2011 and July 2012.

Odontocetes

Unidentified Dolphin

A number of odontocete echolocation clicks, buzz, and whistle detections were classified as "unidentified dolphin." Unidentified dolphins were detected throughout the year, but there were a larger number of unidentified dolphin vocalizations in December at site CE (Figure 27). These detections at the inshore site (CE) were most likely short-beaked common dolphins, northern right whale dolphins, or bottlenose dolphins. Detections at the offshore site (QC) were most likely either short-beaked common dolphins or northern right whale dolphins.

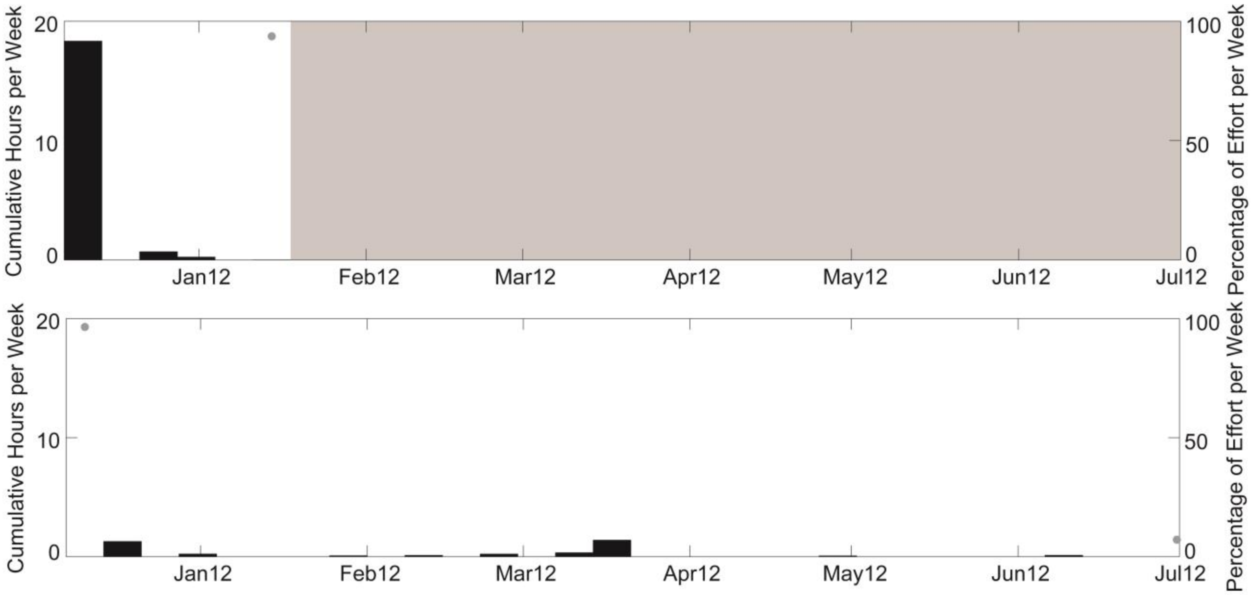


Figure 27. Weekly unidentified odontocete whistles, buzz pulses, and echolocation click presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Risso's Dolphin

Risso's dolphin echolocation clicks were detected at the offshore site (QC) during late winter and early summer (Figure 28). There was a diel pattern in their echolocation clicks, with higher activity at night indicating nighttime foraging (see Appendix). This diel activity is consistent with previous reports in other areas (Soldevilla et al. 2010). Risso's acoustic presence and visual sightings were less common in previous years at the offshore site (Oleson et al. 2009, Širović et al. 2011).

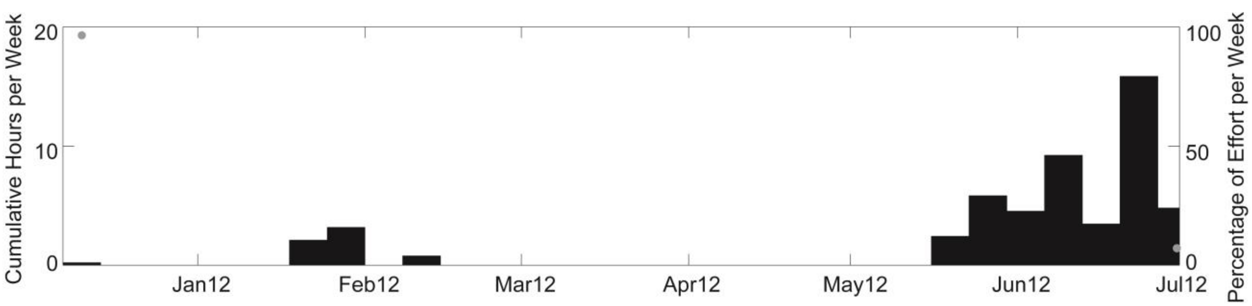


Figure 28. Weekly Risso's dolphin echolocation click presence at sites QC between December 2011 and July 2012. No Risso's dolphin clicks were detected at site CE. Effort markings are as described in Figure 21.

Pacific White-Sided Dolphin

After a decrease in Pacific white-sided dolphin echolocation clicks at site CE in 2008 and 2009 (Oleson et al. 2009), there were a larger number of detections in 2011 (Širović et al. 2012), including December 2011 and January 2012 (Figure 29). Pacific white-sided dolphin clicks were also detected at site QC, but in fewer numbers and more sporadically. All echolocation clicks attributed to Pacific white-sided dolphins demonstrated nighttime preference (see Appendix).

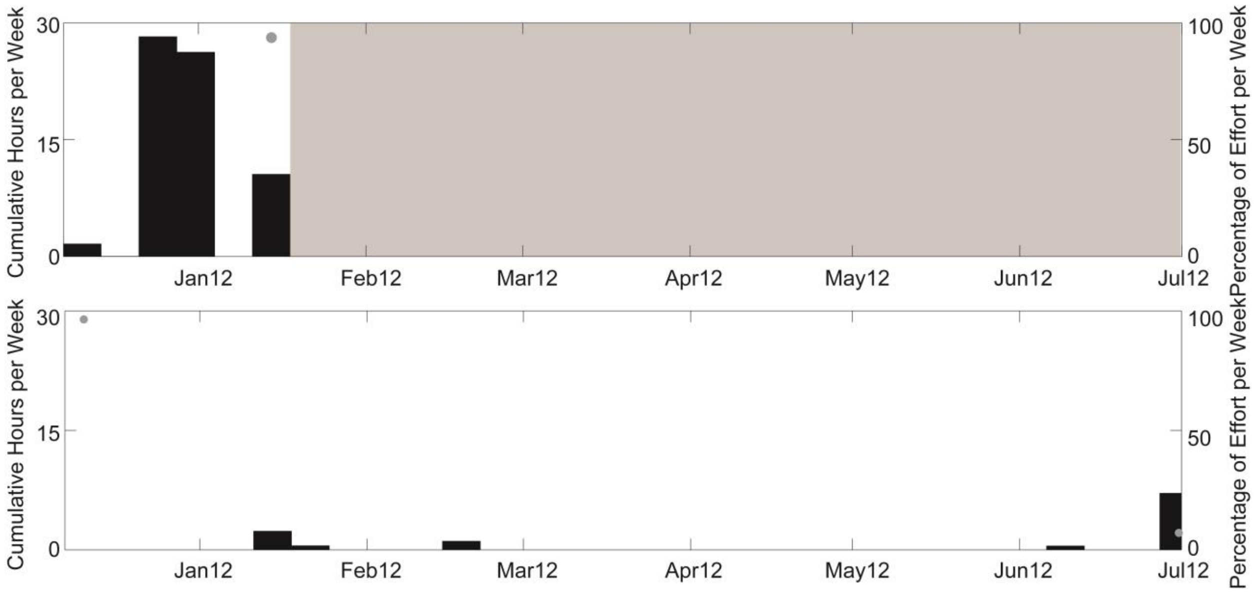


Figure 29. Weekly Pacific white-sided dolphin echolocation click presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Killer Whale

Killer whale vocalizations were very commonly detected at site CE in December and January and they were detected intermittently throughout the year at site QC (Figure 30), which is consistent with previous reports of killer whale calling in this area (Oleson et al. 2009, Širović et al. 2011, 2012). Most detections at site CE occurred during night (Appendix). Further analyses are required to attribute the detected calls to specific killer whale ecotypes.

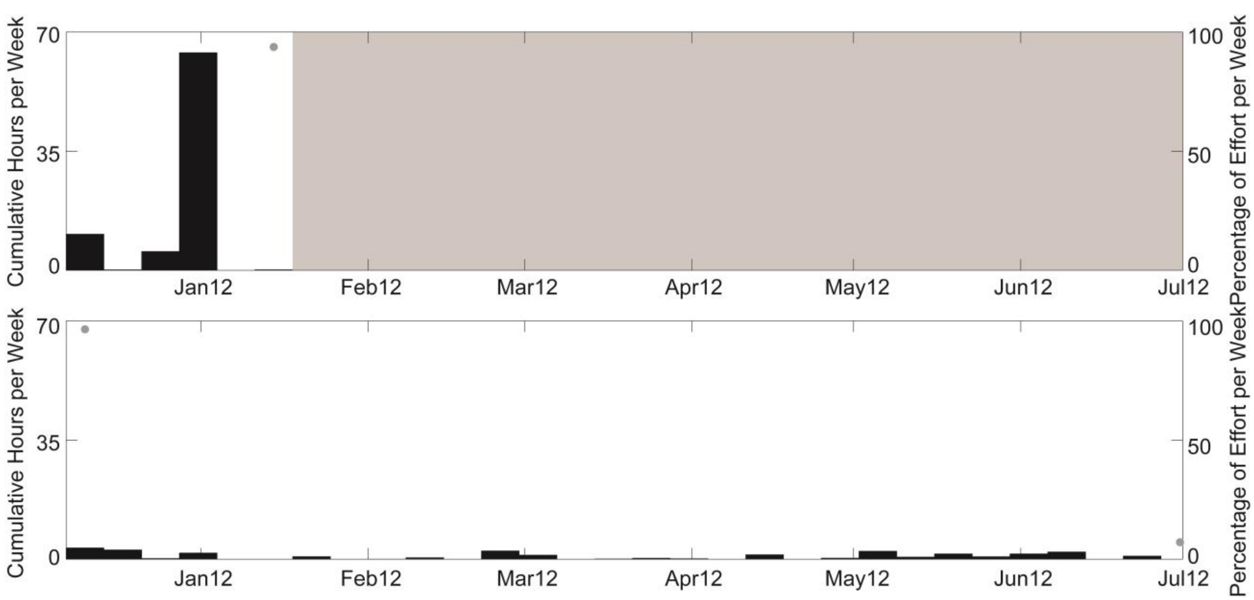


Figure 30. Weekly killer whale whistle, pulsed call, and echolocation click presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Sperm Whale

Sperm whale echolocation clicks were detected consistently throughout the deployment period at site QC, though they were also detected at site CE in December and January (Figure 31), consistent with previous reports (Oleson et al. 2009). Previous reports from this area have suggested the possibility of a diel preference in sperm whale echolocation clicks (Širović et al. 2011); more recently, however, no clear pattern has been determinable (Širović et al. 2012). In the context of this report, sperm whale echolocation clicks detected at the offshore site (QC) show no clear diel preference, while sperm whales clicks detected at the inshore site (CE) suggest a nighttime preference (see Appendix).

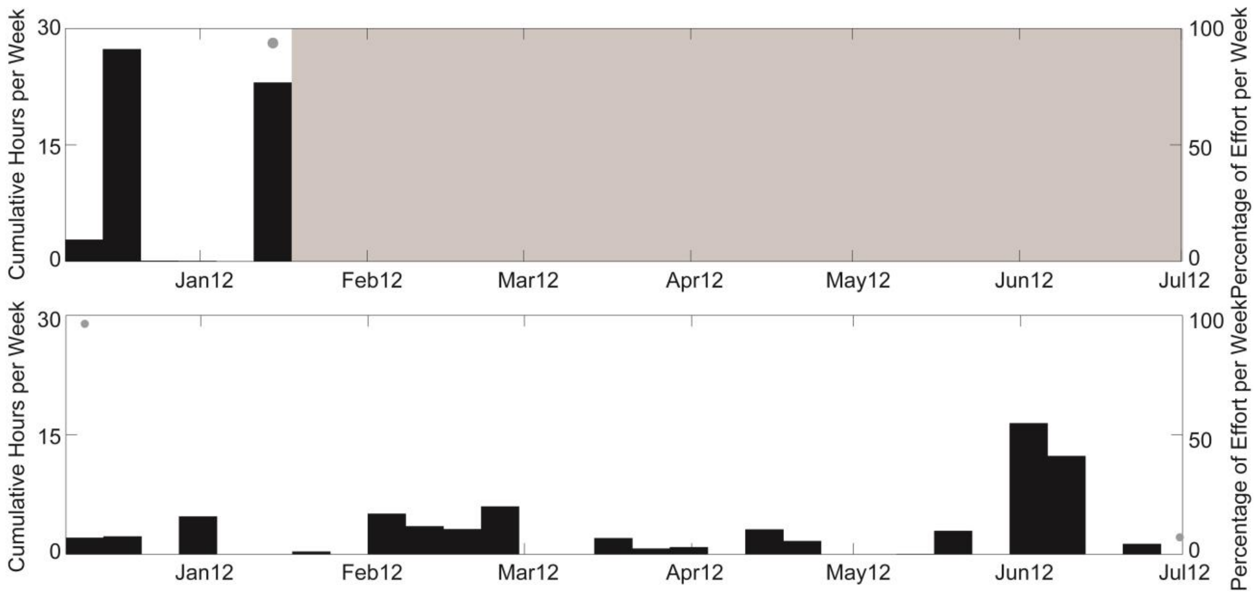


Figure 31. Weekly sperm whale echolocation click presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Stejneger's Beaked Whales

Even though Stejneger's beaked whales were only detected at site QC, they were the most consistently detected beaked whale off Washington. Calls were detected between December and June (Figure 32), demonstrating seasonality consistent with previously reported detections for this species at this site (Širović et al. 2012). It is possible that these animals move to areas further north during summer months.

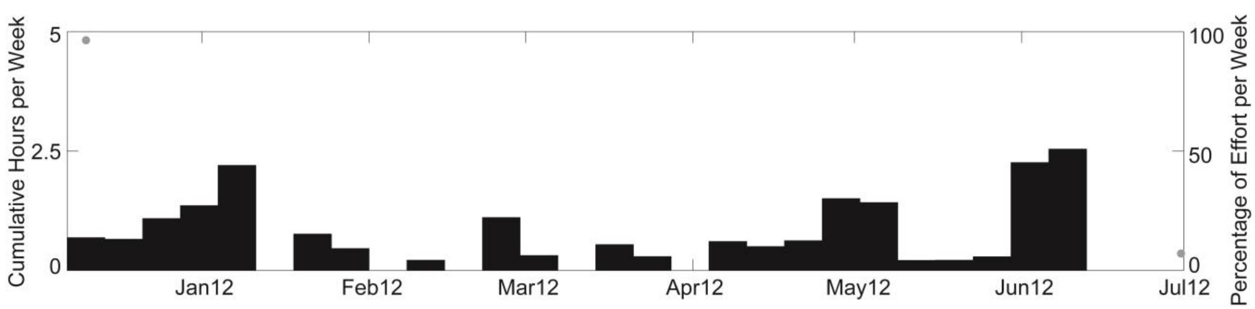


Figure 32. Weekly Stejneger's beaked whale frequency modulated pulse presence at site QC during between December 2011 and July 2012. No Stejneger's beaked whale signals were detected at site CE. Effort markings are as described in Figure 21.

Baird's Beaked Whale

Baird's beaked whale FM pulses were detected at both sites (Figure 33), showing peaks in winter and summer consistent with previously reported peak acoustic presence (Širović et al. 2012). While overall they were not detected as frequently as Stejneger's beaked whales, in the winter at CE and the summer at QC, their echolocations were more common than any other beaked whale signals recorded during this monitoring period off Washington. There was no apparent diel pattern in their pulses during this period.

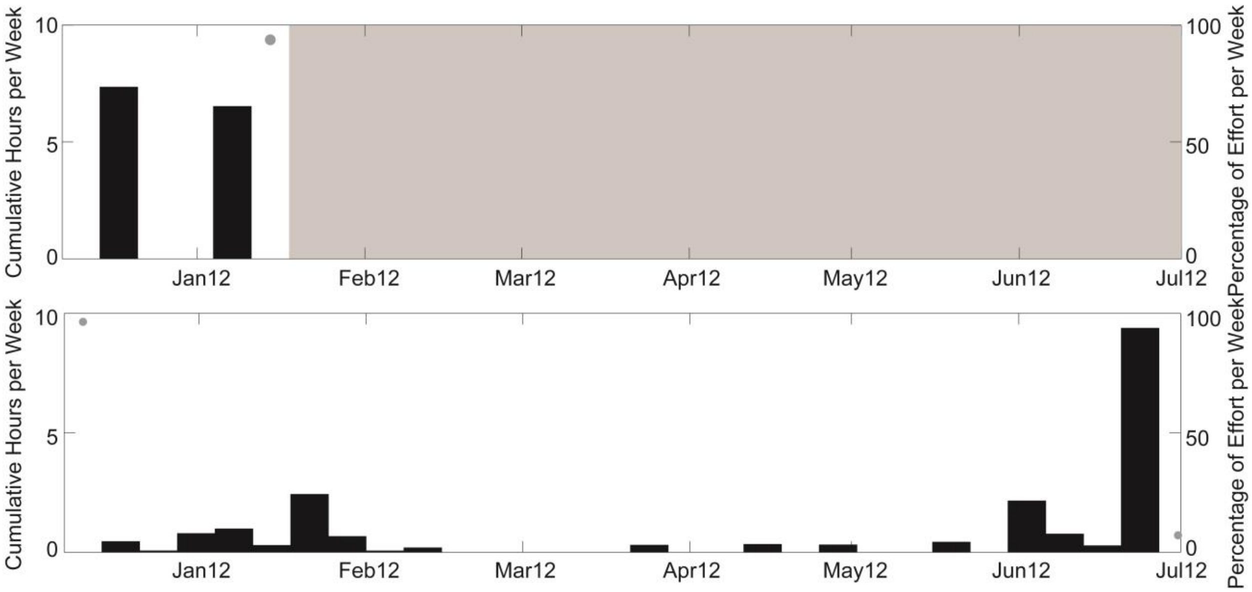


Figure 33. Weekly Baird's beaked whale frequency modulated pulse and click presence at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Cuvier's Beaked Whale

Cuvier's beaked whales were detected throughout the year at low levels, but only at site QC (Figure 34). There was no diel preference for echolocation click detections.

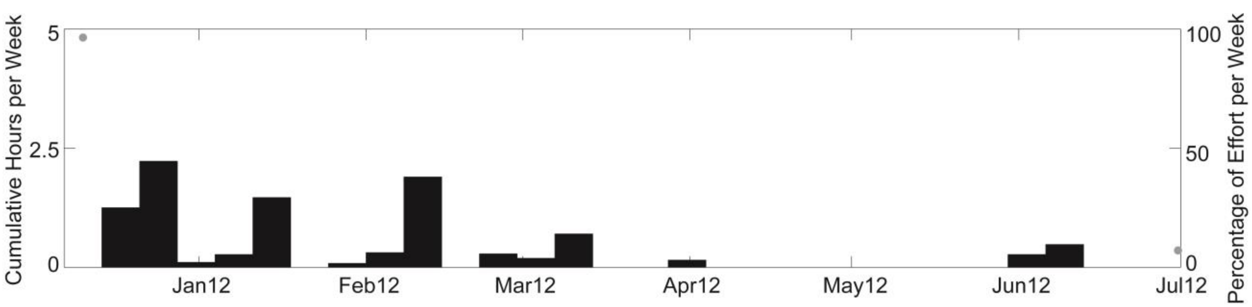


Figure 34. Weekly Cuvier's beaked whale frequency modulated pulse presence at site QC between December 2011 and July 2012. No Cuvier's beaked whale signals were detected at site CE. Effort markings are as described in Figure 21.

Blainville's Beaked Whale

No Blainville's beaked whale signals were detected at either site CE between December 2011 and January 2012 or site QC between December 2011 and July 2012.

Unidentified Porpoise

Narrowband high frequency clicks were recorded at site CE only and classified as unidentified porpoise, most likely either Dall's porpoise or harbor porpoise. Dall's porpoises are more frequently sighted in the vicinity of the CE site on the shelf (Oleson et al. 2009). No recordings are available during known presence of either species, so it is impossible as yet to confirm the species. In previous years, peak presence of NBHF clicks occurred in the fall (Oleson et al. 2009, Širović et al. 2011); click presence during 2011, however, was relatively constant and continued into January 2012 (Širović et al. 2012, Figure 35). Most of the acoustic activity occurred during the night (see Appendix).

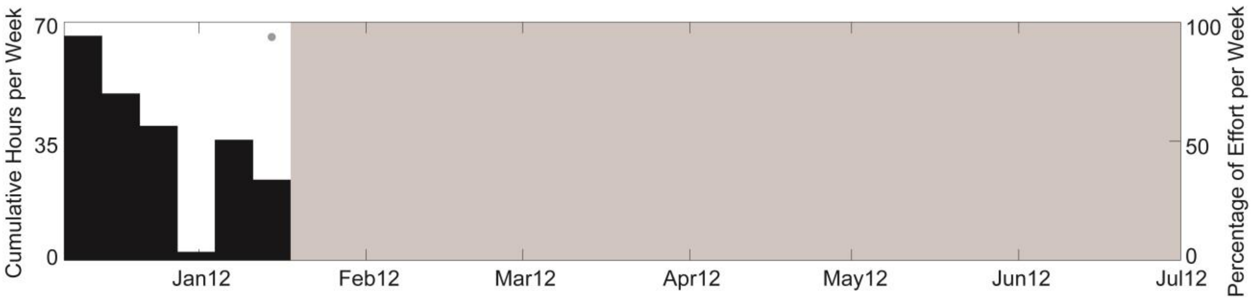


Figure 35. Weekly unidentified NBHF porpoise click presence at site CE between December 2011 and January 2012. No porpoise clicks were detected at site QC. Effort markings are as described in Figure 21.

Anthropogenic Sounds

Broadband Ship Noise

Ship noise was detected at high rates throughout the recording period at site QC, and it was less consistent at site CE, with a noticeable dip in late December and early January (Figure 36).

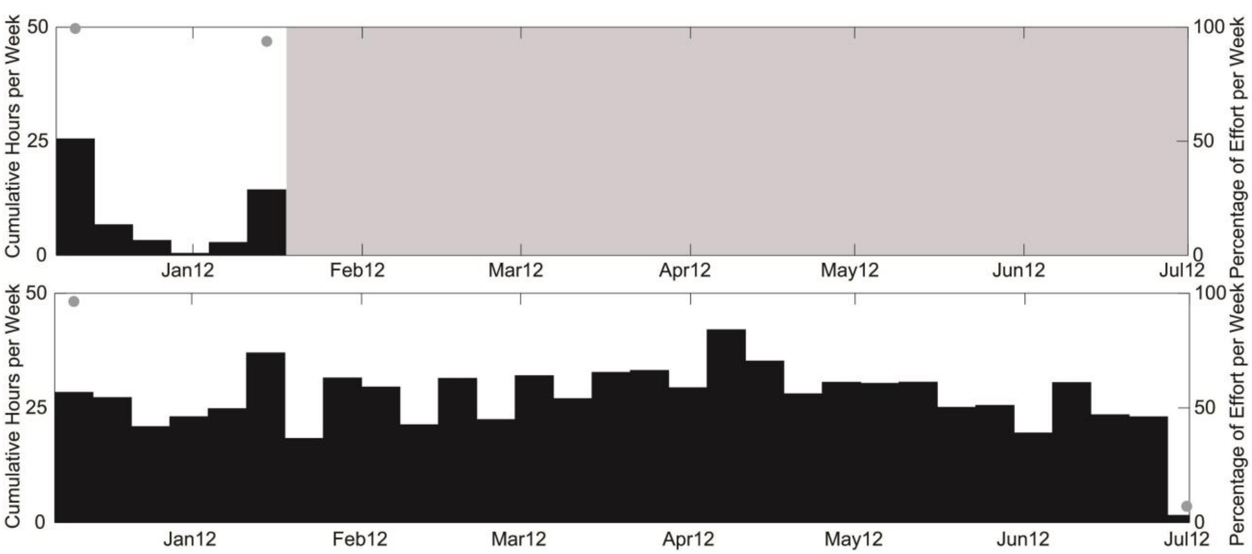


Figure 36. Weekly hours with broadband ship noise at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

Mid-Frequency Active Sonar

During our recording period at site QC between December 2011 and July 2012, there were 4 days with MFA events (Figure 37). No MFA sonar was detected between December 2011 and January 2012 at site CE. Total time over which the events occurred at QC was 2 hrs 19 mins (Appendix). At site QC, 59 MFA sonar pings were detected, ranging from 2400 to 4500 Hz and 108 to 127 dB pp re: 1 µPa with the mean level 118 dB pp re: 1 µPa (Figure 38). The minimum value in this distribution is likely a threshold limit based on the automatic detection methods used. All pings detected were below 130 dB pp re: 1 µPa (Figure 39).

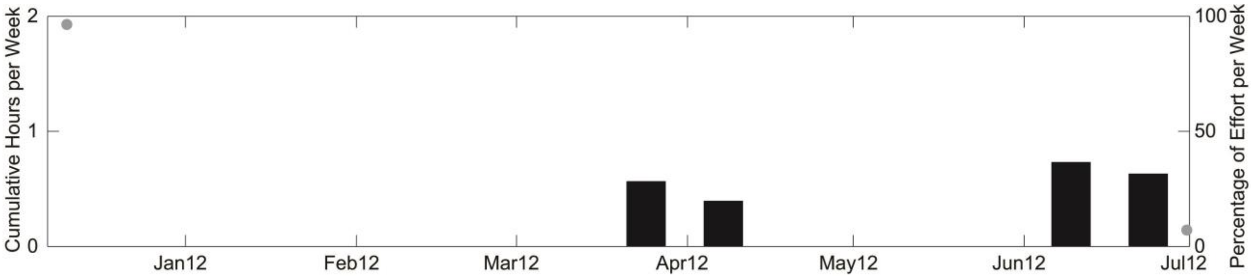


Figure 37. Weekly mid-frequency active (MFA) sonar presence at sites QC between December 2011 and July 2012. No MFA was detected at site CE. Effort markings are as described in Figure 21.

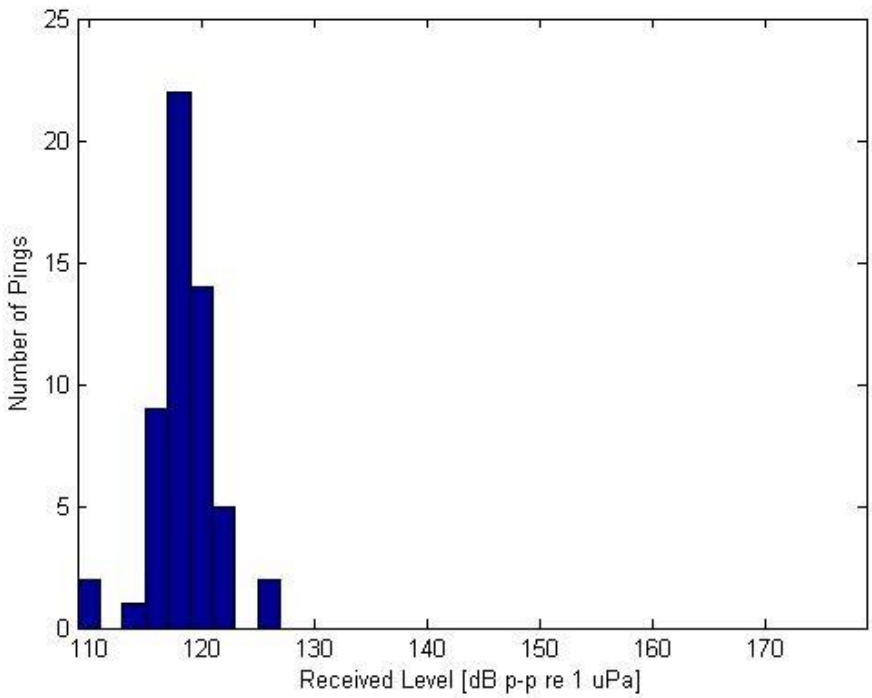


Figure 38. Distribution of the number of MFA sonar pings by received levels at site QC in 1 dB bins. Minimum level (108 dB pp re: 1 µPa) is likely related to the detection threshold.

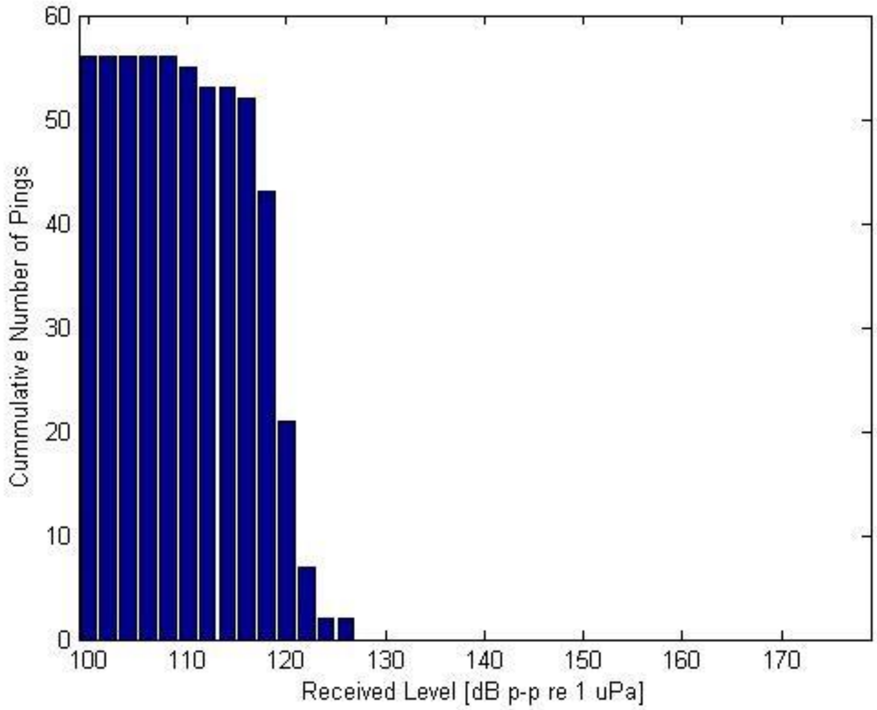


Figure 39. Cumulative distribution of the number of MFA sonar pings detected at site QC by received level in 1 dB bins.

Echosounders

Echosounder pings were detected at site QC only (Figure 40), most commonly around 3 kHz. Cumulative time over which echosounding events occurred was 1 hr 56 min.

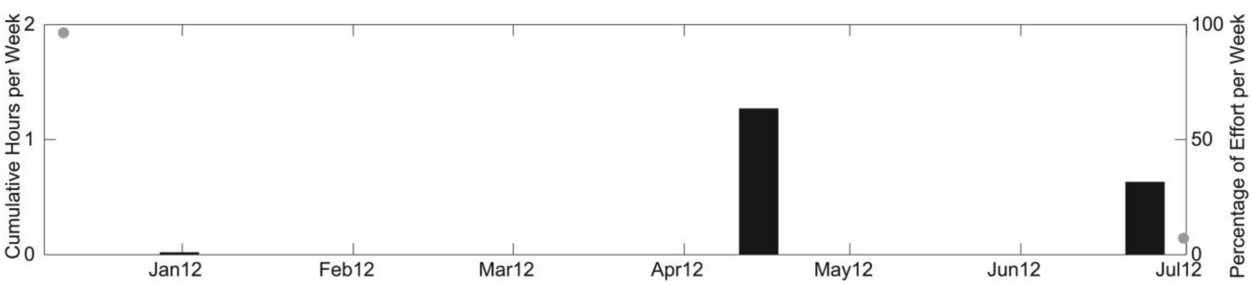


Figure 40. Weekly echosounder ping presence at site QC between December 2011 and July 2012. Effort markings are as described in Figure 21.

Explosions

Explosions were detected at both sites CE and QC, including a significant explosion event at site QC over the span of a few weeks in mid to late June (Figure 41; see also Appendix). While most sporadic explosions around these sites are likely from seal-bombs associated with fishing, the detections at QC in June is attributable to air-guns associated with seismic surveys conducted in the area at the time (http://blogs.ei.columbia.edu/tag/cascadia-in-motion/).

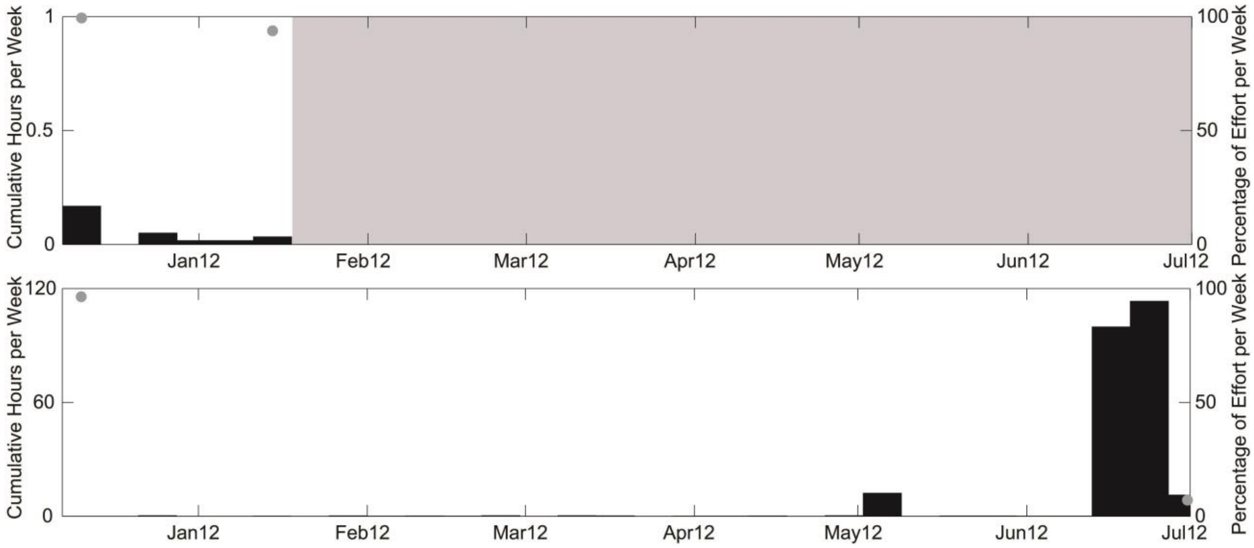


Figure 41. Weekly hours with explosions at sites CE (top) and QC (bottom) between December 2011 and July 2012. Effort markings are as described in Figure 21.

References

Baumann-Pickering, S., A.E. Simonis, S.M. Wiggins, R.L. Brownell Jr., J.A. Hildebrand (2012) Aleutian Islands beaked whale echolocation signals. Mar. Mamm. Sci. DOI: 10.1111/j.1748-7692.2011.00550.x

Burtenshaw, J.C., E.M. Oleson, J.A. Hildebrand, M.A. McDonald, R.K. Andrew, B.M. Howe, J.A. Mercer. (2004) Acoustic and satellite remote sensing of blue whale seasonality and habitat in the Northeast Pacific. Deep-Sea Research II 51: 967-986

Crane, N. L. and K. Lashkari (1996). Sound production of gray whales, *Eschrichtius robustus*, along their migration route: A new approach to signal analysis. Journal of the Acoustical Society of America 100: 1878-1886.

Dawson, S., J. Barlow, D. Ljungblad (1998) Sounds recorded from Baird's beaked whale, *Berardius bairdil*. Marine Mammal Science, 14: 335–344.

Dunlop, R., M. Noad, D. Cato, D. Stokes (2007). The social vocalization repertoire of east Australian migrating humpback whales (*Megaptera novaeangliae*), Journal of the Acoustical Society of America 122: 2893-2905.

Ford, J.K.B. (1989). Acoustic Behavior of Resident Killer Whales (*Orcinus-Orca*) Off Vancouver Island, British-Columbia. Canadian Journal of Zoology 67: 727-745.

Goold, J.C. and S. E. Jones (1995) Time and frequency domain characteristics of sperm whale clicks. Journal of the Acoustical Society of America 98: 1279–129.

Helble, T.A., G.R. Ierley, G.L. D'Spain, M.A. Roch, J.A. Hildebrand (2012) A generalized power-law detection algorithm for humpback vocalizations, Journal of the Acoustical Society of America 131: 2682-2699.

Hildebrand, J A. (2009) Anthropogenic and Natural Sources of Ambient Noise in the Ocean. Marine Ecology Progress Series 395: 5-20.

Jefferson, T.A., M.A. Webber, R.L. Pitman (2008) Marine mammals of the world – A comprehensive guide to their identification. Elsevier, London, UK.

Johnson, M., P.T. Madsen, W.M.X. Zimmer, N.A. de Soto, P.L. Tyack (2004) Beaked whales echolocate on prey. Proceeding of the Royal Society B: Biological Sciences 271: S383–S386.

Kerosky, S.M., A. Širović, L.K. Roche, S. Baumann-Pickering, S.M. Wiggins, J.A. Hildebrand (2012) Bryde's whale seasonal range expansion and increasing presence in the Southern California Bight from 2000 to 2010. Deep-Sea Research I 65: 125-132.

Leatherwood, S., R.R. Reeves, W.F. Perrin, W.E. Evans (1988) Whales, dolphins, and porpoises of the eastern North Pacific and adjacent Arctic waters: A guide to their identification. Dover Publishing, New York, NY.

Madsen, P.T., M. Wahlberg, B. Møhl (2002) Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: implications for echolocation and communication. Behavioral Ecology and Sociobiology 53: 31–41.

McDonald, M.A., J.A. Hildebrand, S.C. Webb (1995) Blue and fin whales observed on a seafloor array in the Northeast Pacific. Journal of the Acoustical Society of America 98: 712-721.

McDonald, M.A., S.L. Mesnick, J.A. Hildebrand (2006) Biogeographic characterisation of blue whale song worldwide: using song to identify populations. Journal of Cetacean Research and Management 8: 55-65

McDonald, M.A., J.A. Hildebrand, S. Mesnick (2009) Worldwide decline in tonal frequencies of blue whale songs. Endangered Species Research 9:13-21.

Mellinger, D.K. and C.W. Clark. (1997) Methods of automatic detection of mysticete sounds. Marine and Freshwater Behaviour and Physiology 29: 163-181.

Møhl, B., M. Wahlberg, P.T. Madsen, A. Heerfordt, A. Lund (2003) The monopulsed nature of sperm whale clicks. Journal of the Acoustical Society of America 114: 1143-115.

Oleson, E.M., J. Barlow, J. Gordon, S. Rankin, J.A. Hildebrand (2003) Low frequency calls of Bryde's whales. Marine Mammal Science 19: 406-419.

Oleson, E.M., S.M. Wiggins, J.A. Hildebrand (2007a) Temporal separation of blue whale call types on a southern California feeding ground. Animal Behaviour 74: 881-894.

Oleson, E.M., J. Calambokidis, W.C. Burgess, M.A. McDonald, C.A. LeDuc, J.A. Hildebrand (2007b) Behavioral context of call production by eastern North Pacific blue whales. Marine Ecology Progress Series 330: 269-284.

Oleson, E.M., J. Calambokidis, E. Falcone, G. Schorr, J.A. Hildebrand (2009) Acoustic and visual monitoring of cetaceans along the outer Washington Coast. Technical Report for grant N0002407WX12527. Report # NPS-OC-09-001 issued by Naval Postgraduate School, Monterey, CA. 45 pp.

Oleson, E.M., J. Calambokidis, R. Baird, E. Falcone, G. Schorr, A. Douglas, D. Webster, D. McSweeney, J.A. Hildebrand (2010) Marine mammal demographics off the outer Washington coast and near Hawaii. Technical Report for grant # N002440810023. 21 pp.

Payne, R. and S. McVay (1971) Songs of humpback whales. Science 173: 585-597.

Rankin, S. and J. Barlow (2005) Source of the North Pacific "boing" sound attributed to minke whales, Journal of the Acoustical Society of America 118: 3346-3351.

Roch, M.A., M.S. Soldevilla, J.C. Burtenshaw, E.E. Henderson, J.A. Hildebrand (2007) Gaussian mixture model classification of odontocetes in the Southern California Bight and the Gulf of California, Journal of the Acoustical Society of America 121: 1737-1748.

Roch, M.A., H. Klinck, S. Baumann-Pickering, D.K. Mellinger, S. Qui, M.S. Soldevilla, J.A. Hildebrand (2011) Classification of echolocation clicks from odontocetes in the Southern California Bight. Journal of the Acoustical Society of America 129: 467-475.

Samarra, F.I.P., V.B. Deecke, et al. (2010) Killer whales (Orcinus orca) produce ultrasonic whistles, Journal of the Acoustical Society of America 128: EL205-EL210.

Simonis, A.E., S. Baumann-Pickering, E.M. Oleson, M.L. Melcón, M. Gassmann, S.M. Wiggins, J.A. Hildebrand (2012) High-frequency modulated signals of killer whales (Orcinus orca) in the North Pacific. J. Acoust. Soc. Am. 131:EL295-EL301.

Širović, A., E.M. Oleson, J. Calambokidis, S. Baumann-Pickering, A. Cummins, S. Kerosky, L. Roche, A. Simonis, S.M. Wiggins, J.A. Hildebrand (2011) Marine Mammal Demographics of the Outer Washington Coast during 2008 – 2009. Technical report #NPS-OC-11-004CR, Naval Postgraduate School, Monterey, CA.

Širović, A., J. A. Hildebrand, S. Baumann-Pickering, J. Buccowich, A. Cummins, S. Kerosky, L. Roche, A. Simonis, S.M. Wiggins, J.A. Hildebrand (2012) Passive Acoustic Monitoring for Marine Mammals in the Northwest Training Range Complex 2011. Marine Physical Lab Technical Memorandum 535, Scripps Institution of Oceanography, La Jolla, CA.

Širović, A., L. Williams, S.M. Kerosky, S.M. Wiggins, J.A. Hildebrand (2013) Temporal separation of two fin whale call types across the eastern North Pacific. Marine Biology 160: 47-57.

Soldevilla, M.S., E.E. Henderson, et al. (2008) Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. Journal of the Acoustical Society of America 124: 609-624.

Soldevilla, M.S., S.M. Wiggins, J.A. Hildebrand. (2010) Spatio-temporal comparison of Pacific white-sided dolphin echolocation click types. Aquatic Biology 9: 49-62.

Stimpert, A., W. Au, S. Parks, T. Hurst, D. Wile (2011) Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring. Journal of the Acoustical Society of America 129: 476-482.

Tershy, B. R., D. Breese, et al. (1991) Increase in Cetacean and Seabird Numbers in the Canal-De-Ballenas During an El-Nino-Southern Oscillation Event. Marine Ecology-Progress Series 69: 299-302.

Thompson, P., L. T. Findley, et al. (1992) 20-Hz pulses and other vocalizations of fin whales, *Balaenoptera physalus*, in the Gulf of California, Mexico. Journal of the Acoustical Society of America 92: 3051 - 3057.

Verboom, W.C. and R.A. Kastelein. (1995) Acoustic signals by Harbour porpoises (Phocoena phocoena), in: Harbour Porpoises, Laboratory Studies to Reduce Bycatch, edited by P. E. Nachtigall, J. Lien, W. W. L. Au, and A. J. Read (De Spil, Woerden, The Netherlands), pp. 1–39

Watkins, W.A. (1981) Activities and underwater sounds of fin whales. Scientific Reports of the Whale Research Institute 33: 83-117.

Watkins, W.A. and W.E. Schevill (1977) Sperm whale codas. Journal of the Acoustical Society of America 26: 1485-1490.

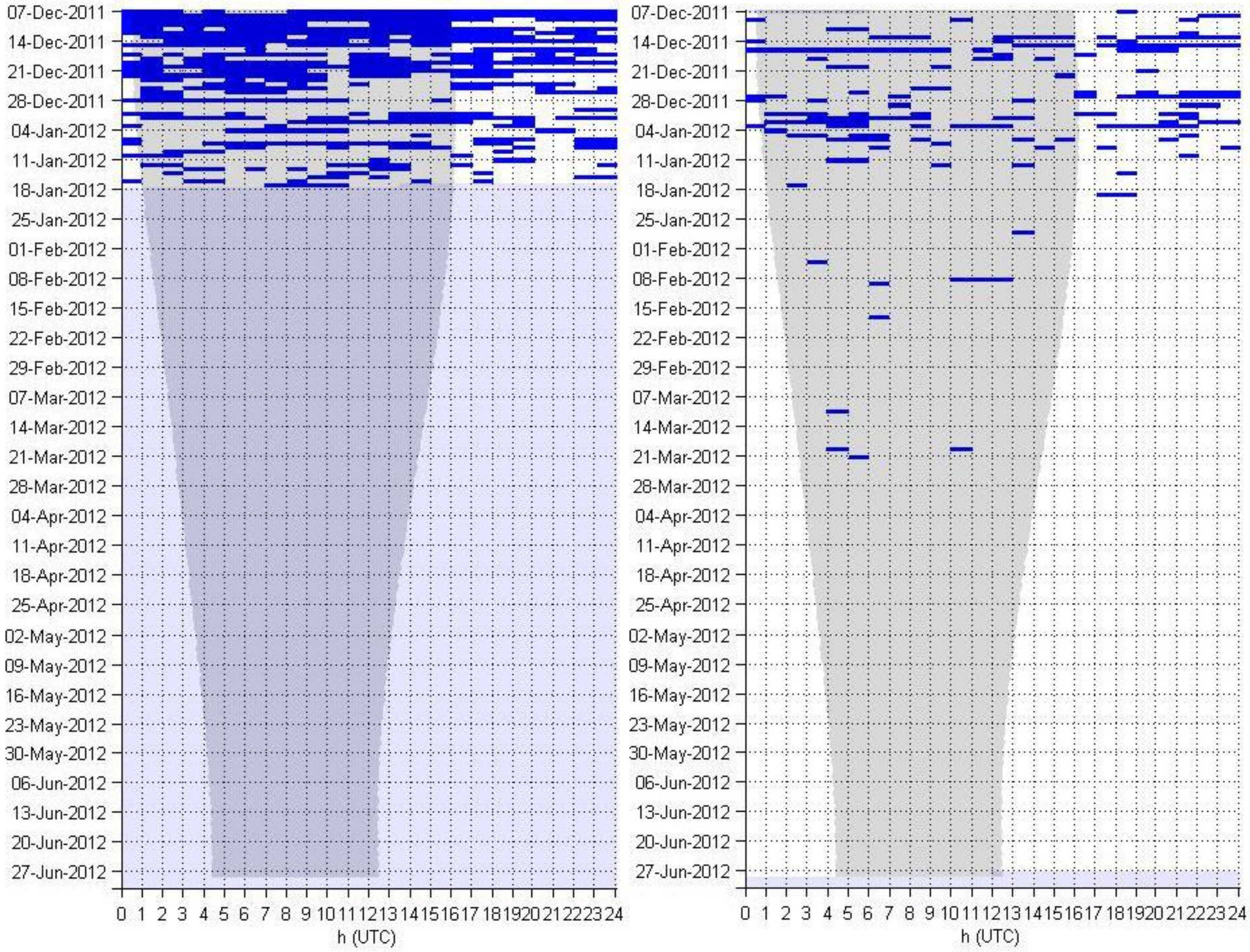
Watkins, W.A., M.A. Daher, G.M. Reppuccim, J.E. George, D.L. Martin, N.A. DiMarzio, D.P. Gannon (2000) Seasonality and distribution of whale calls in the North Pacific. Oceanography 13: 62-67.

Watwood, S.L., P.J.O. Miller, M. Johnson, P.T. Madsen, P. L. Tyack (2006) Deep-diving foraging behaviour of sperm whales (*Physeter macrocephalus*). Journal of Animal Ecology 75: 814–825.

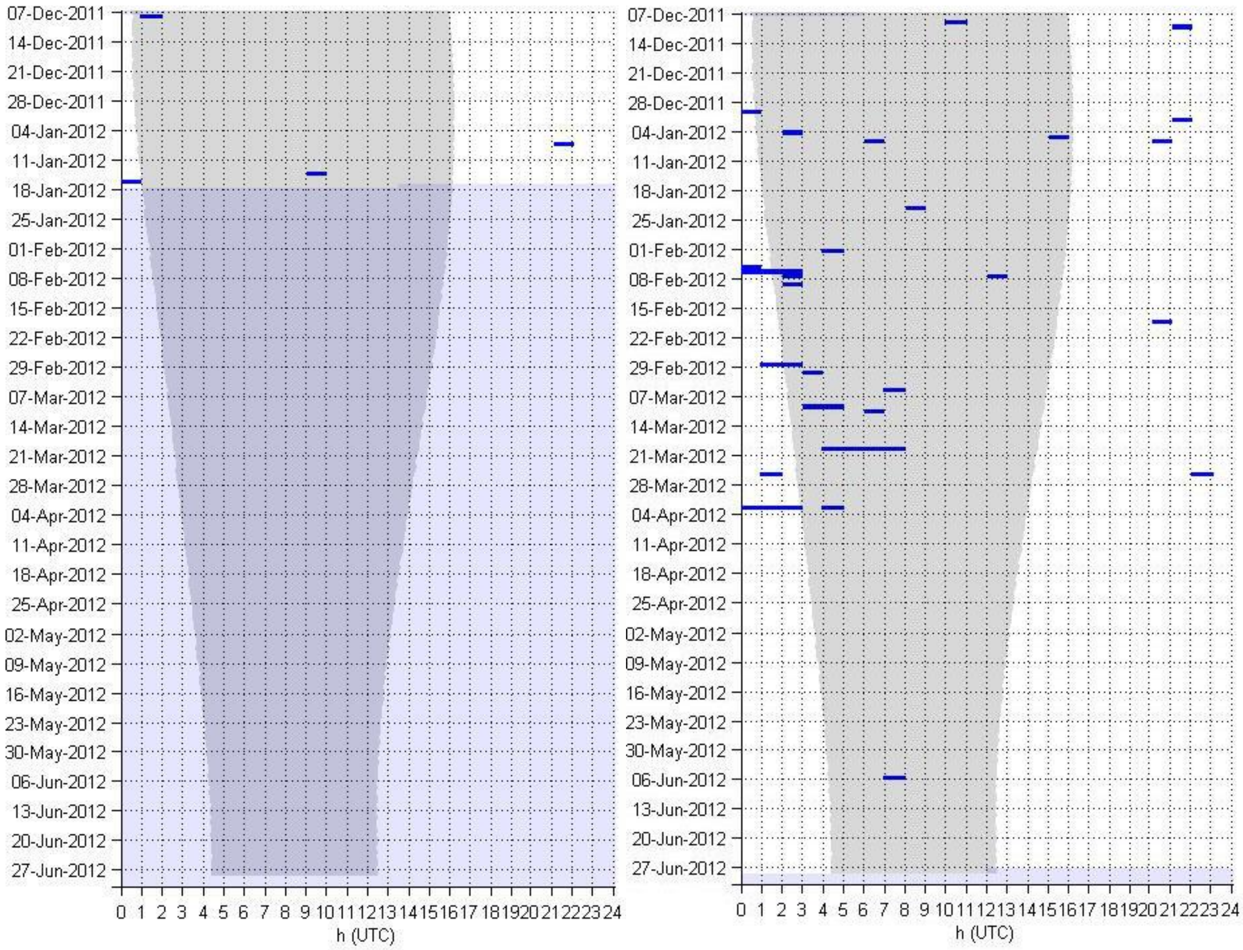
Wiggins, S.M. and J.A. Hildebrand (2007) High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring. Pages 551-557 International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables & Related Technologies 2007. Institute of Electrical and Electronics Engineers, Tokyo, Japan.

Zimmer, W.M.X., M.P. Johnson, P.T. Madsen, P.L. Tyack (2005) Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*). Journal of the Acoustical Society of America 117: 3919-3927.

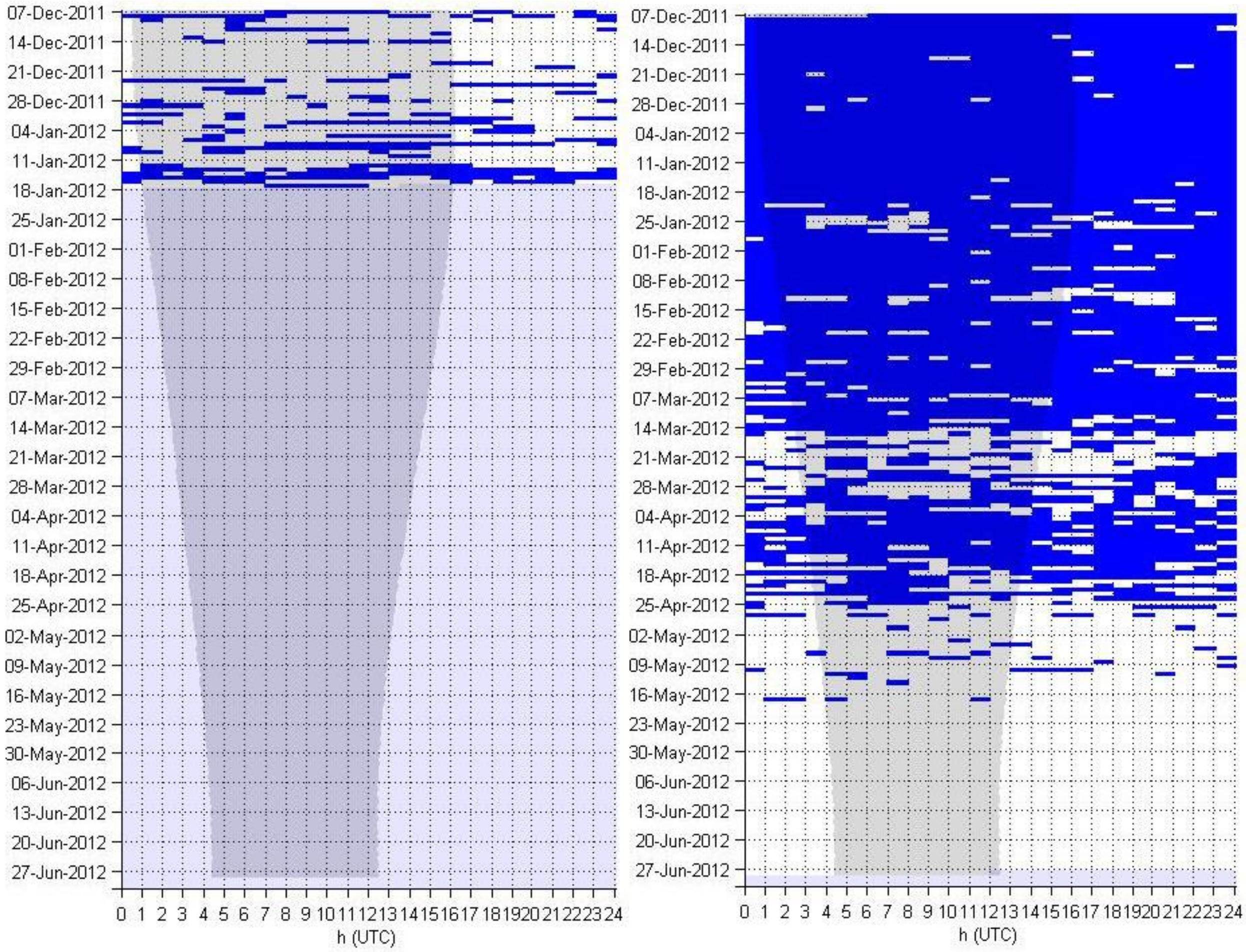
Appendix - Seasonal/Diel Occurrence Plots



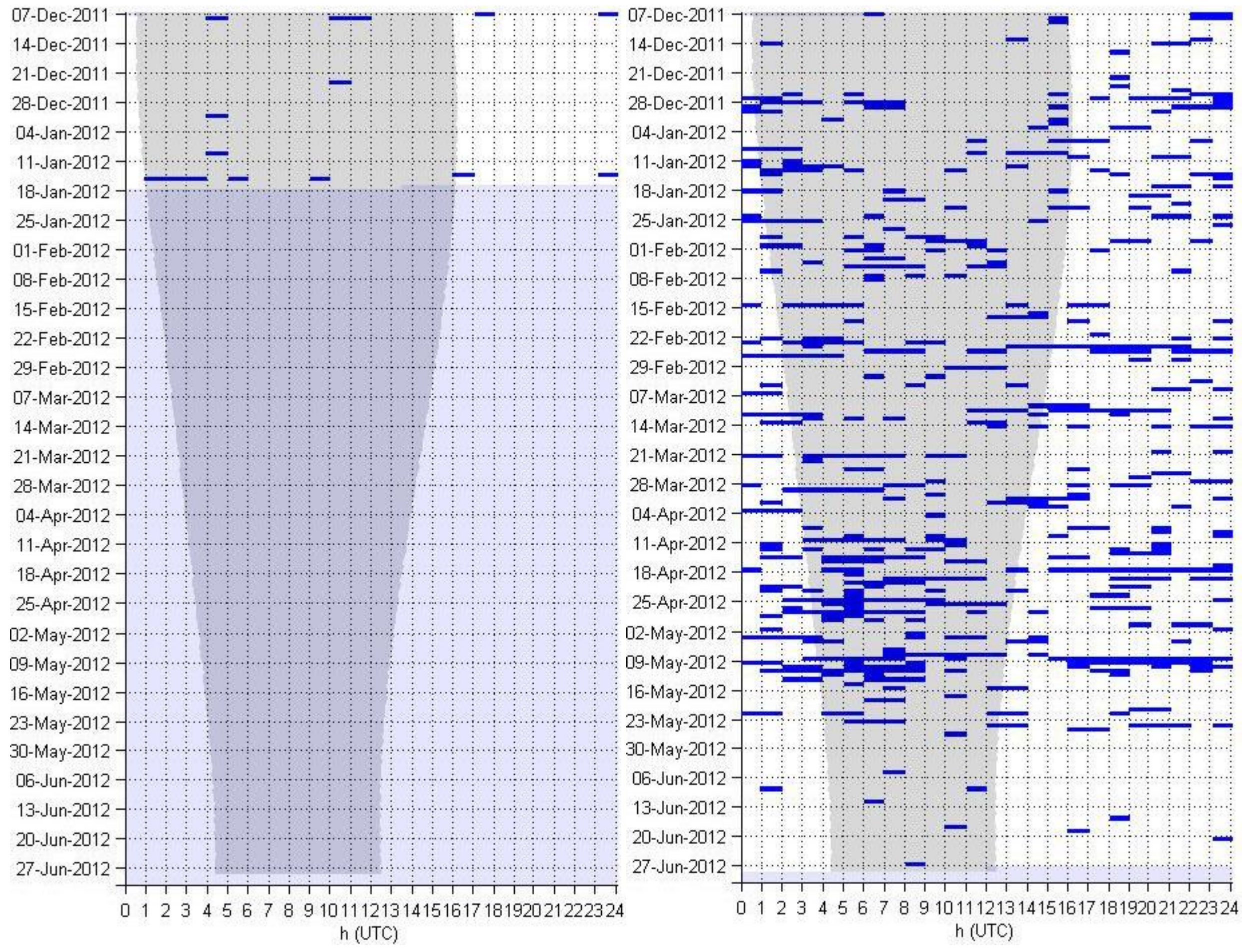
Blue whale –B call in hourly bins at sites CE (left) and QC (right).



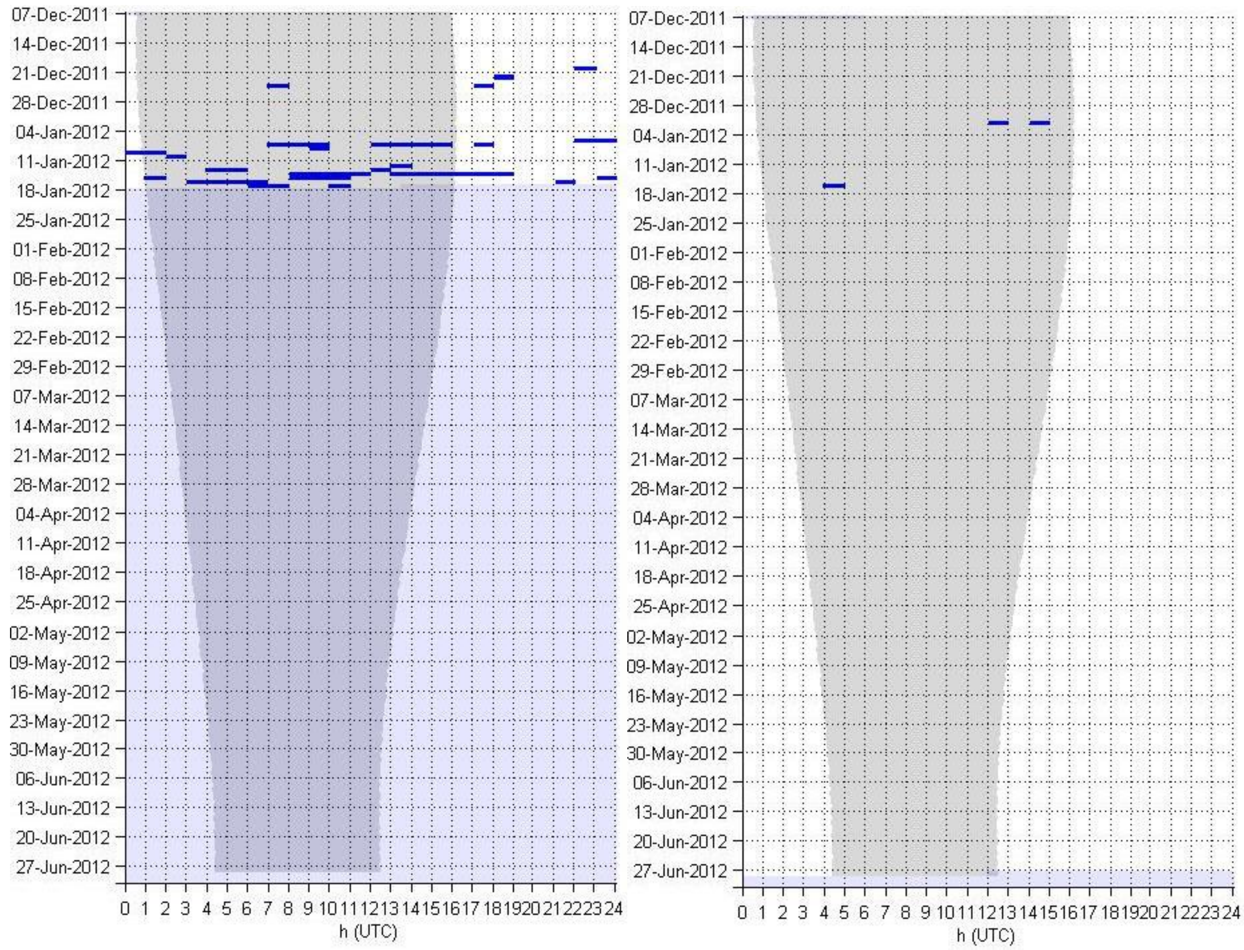
Blue whale –D call in hourly bins at sites CE (left) and QC (right).



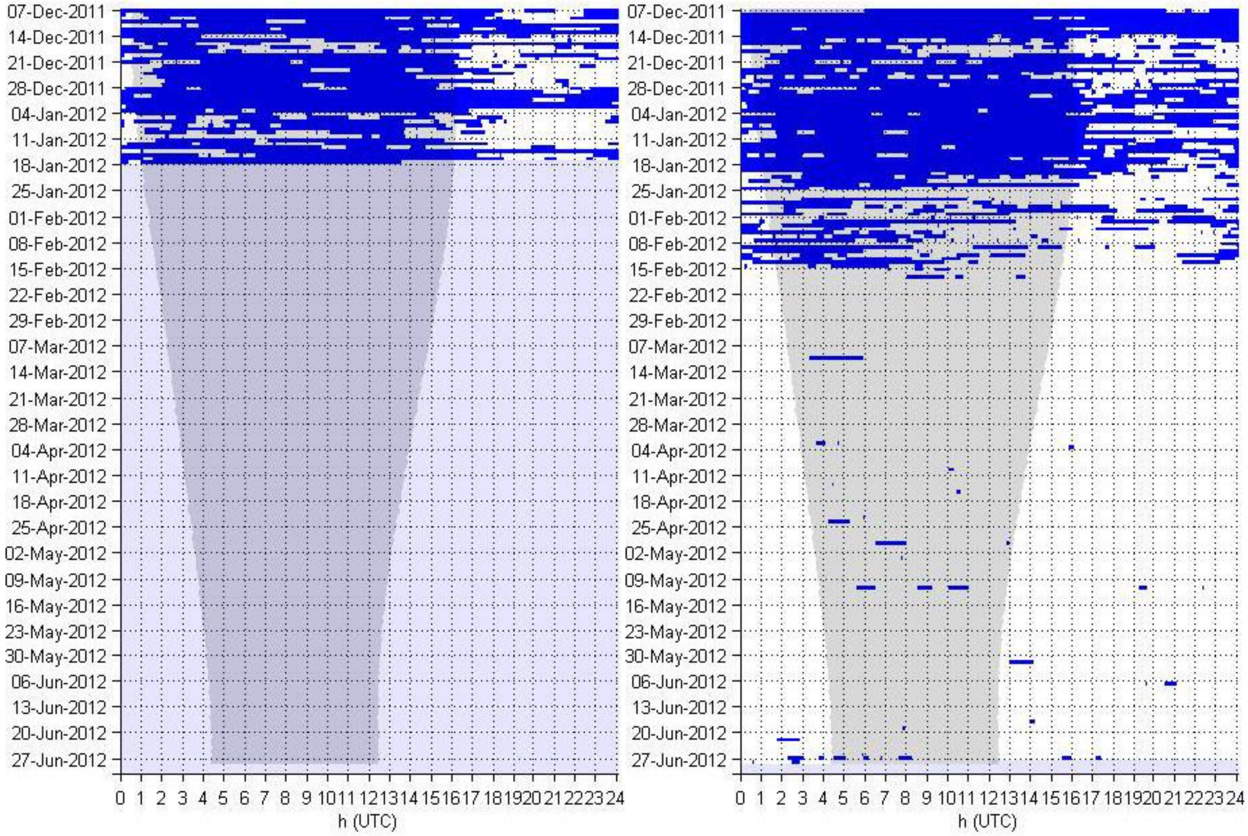
Fin whale – 20 Hz call in hourly bins at sites CE (left) and QC (right).



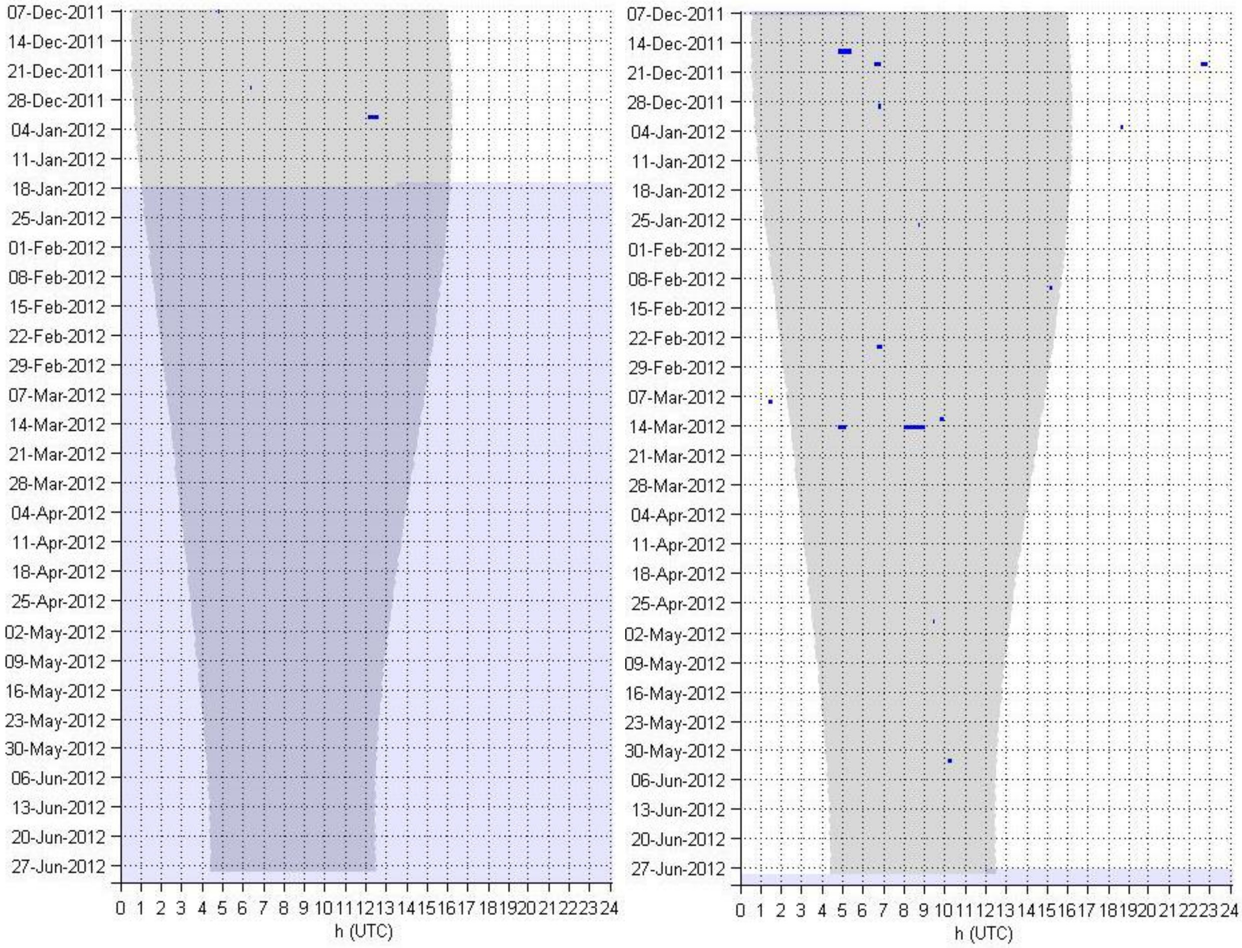
Fin whale – 40 Hz call in hourly bins at sites CE (left) and QC (right).



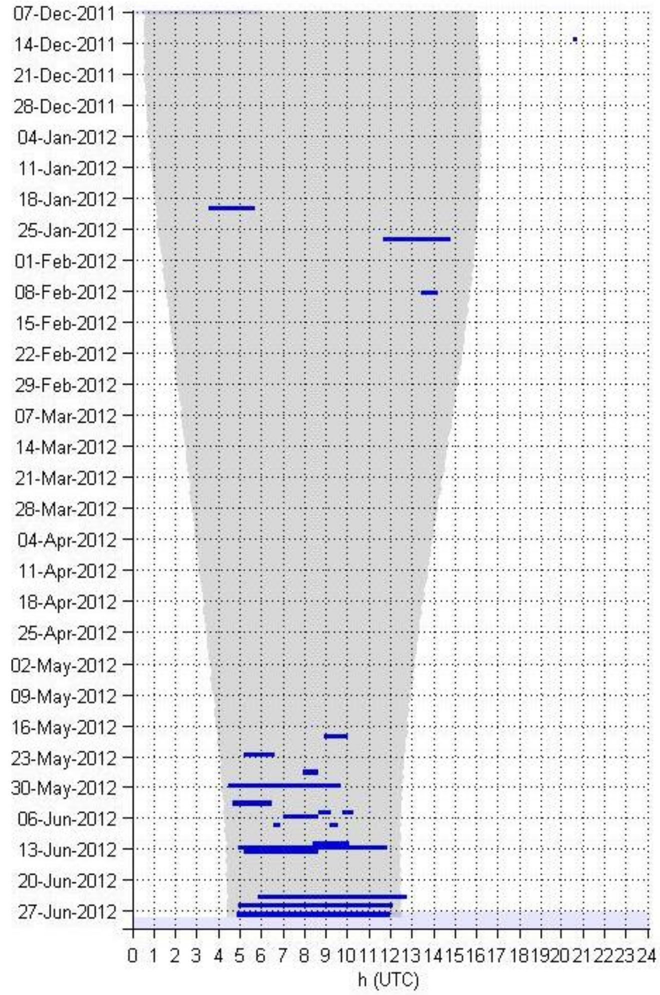
Gray whale – Calls in hourly bins at sites CE (left) and QC (right).



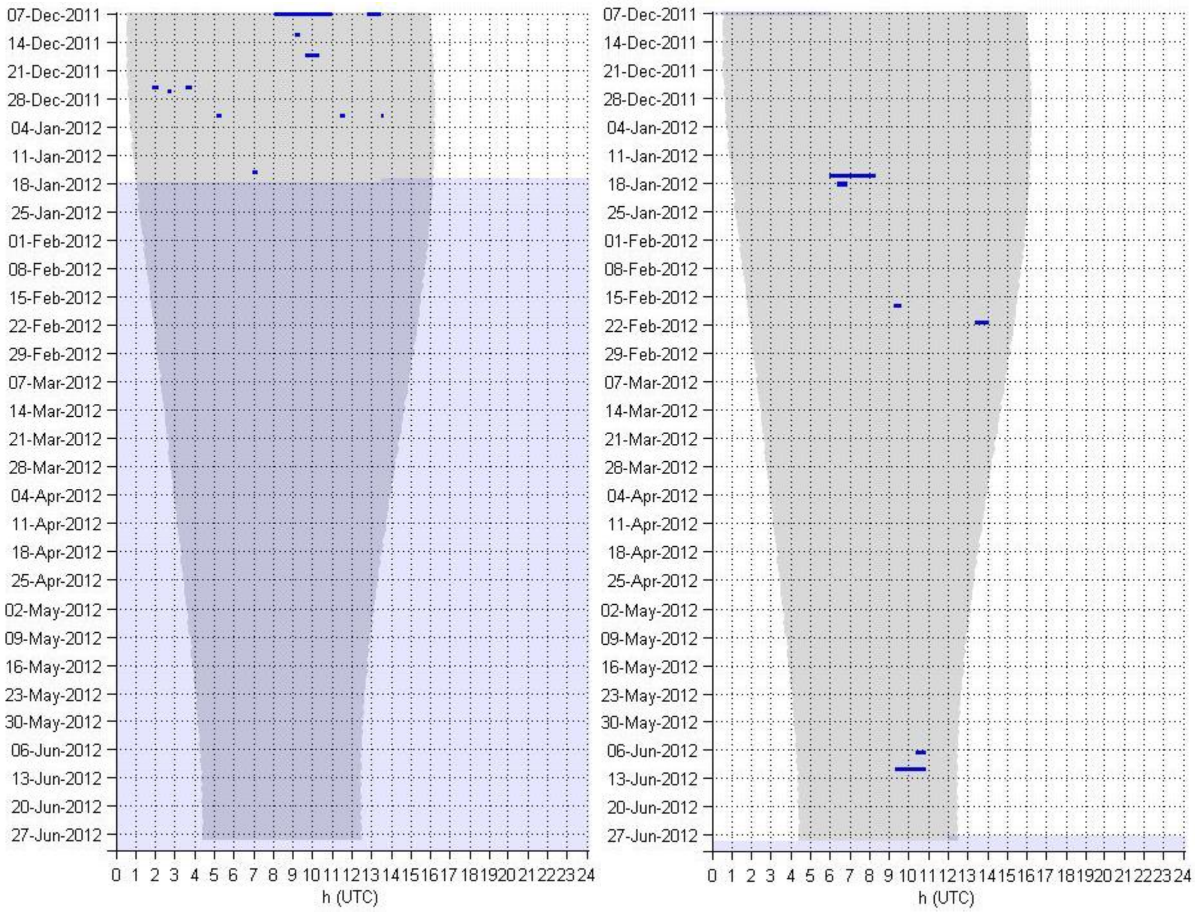
Humpback whale – Song and non-song calls in five-minute bins at sites CE (left) and QC (right).



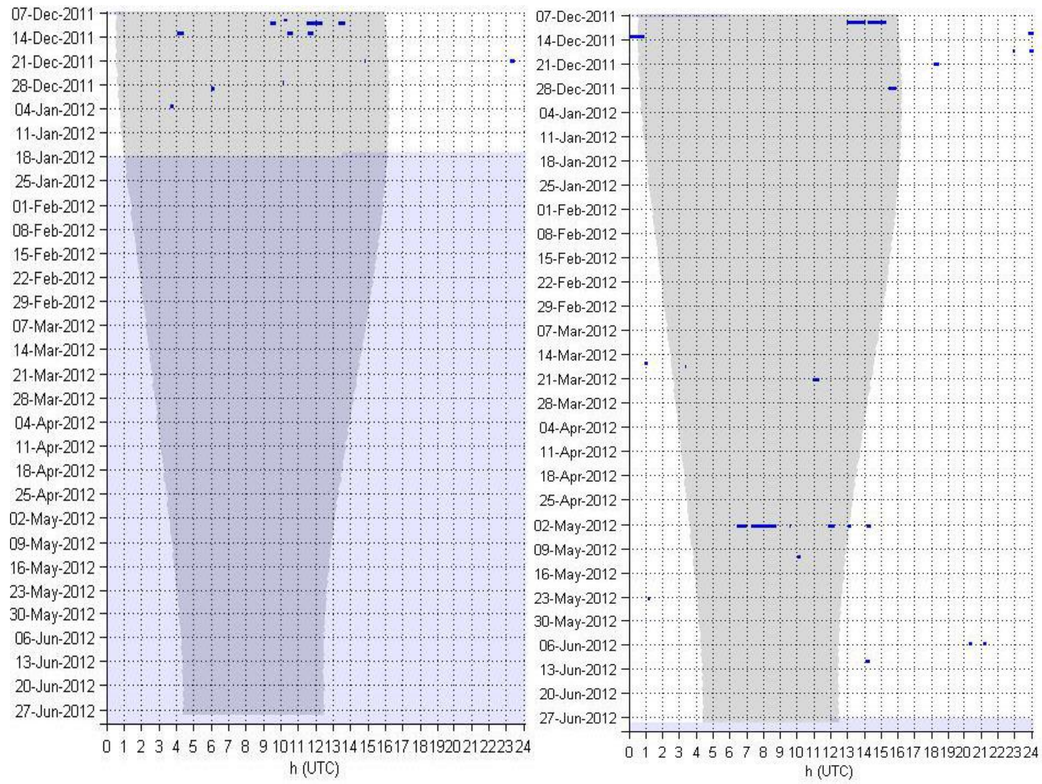
Unidentified dolphin –Whistles and echolocation clicks in five-minute bins at sites CE (left) and QC (right).



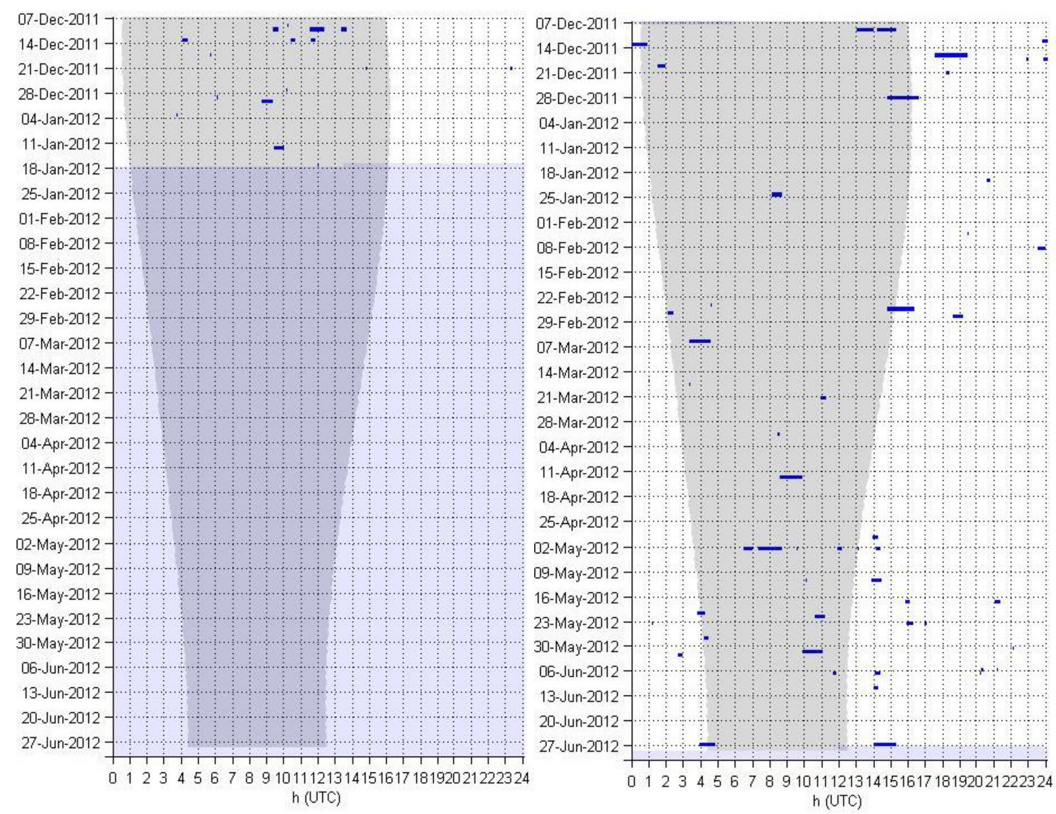
Risso's dolphin – Echolocation clicks in five-minute bins at site QC.



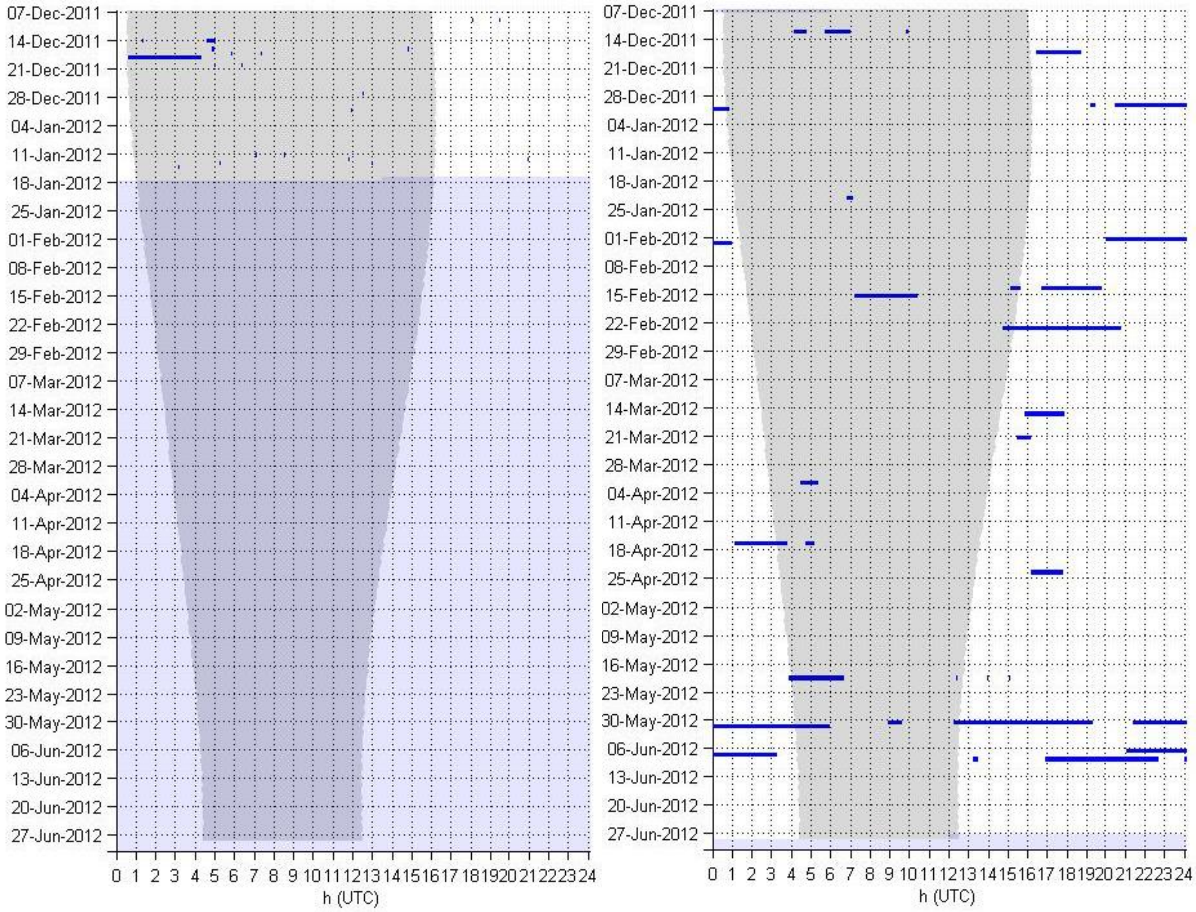
Pacific white-sided dolphin – Echolocation clicks in five-minute bins at sites CE (left) and QC (right).



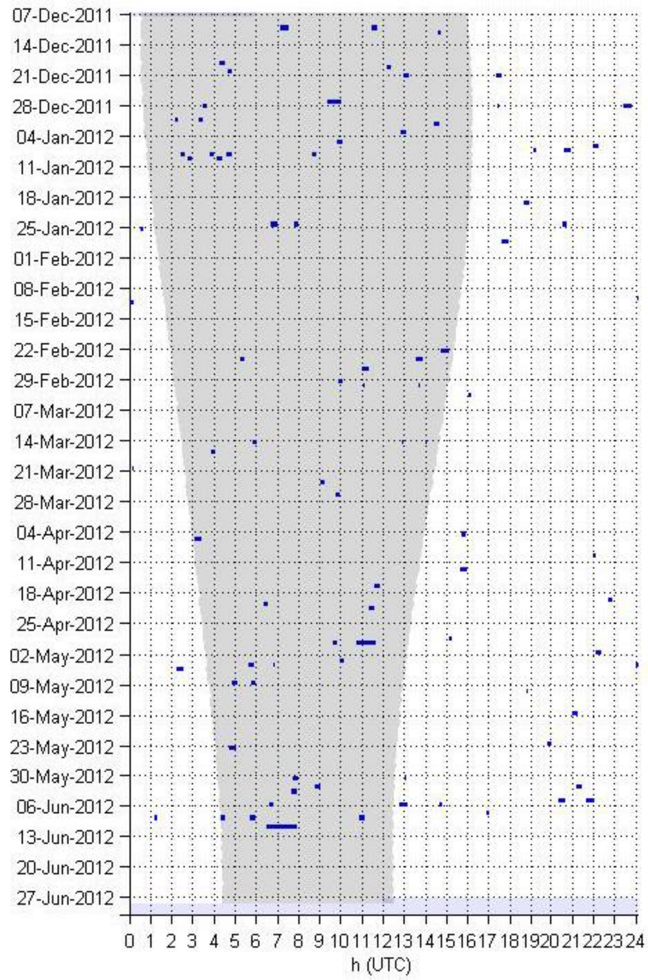
Killer whale –Whistles (<5 kHz) and pulsed calls in five-minute bins at sites CE (left) and QC (right).



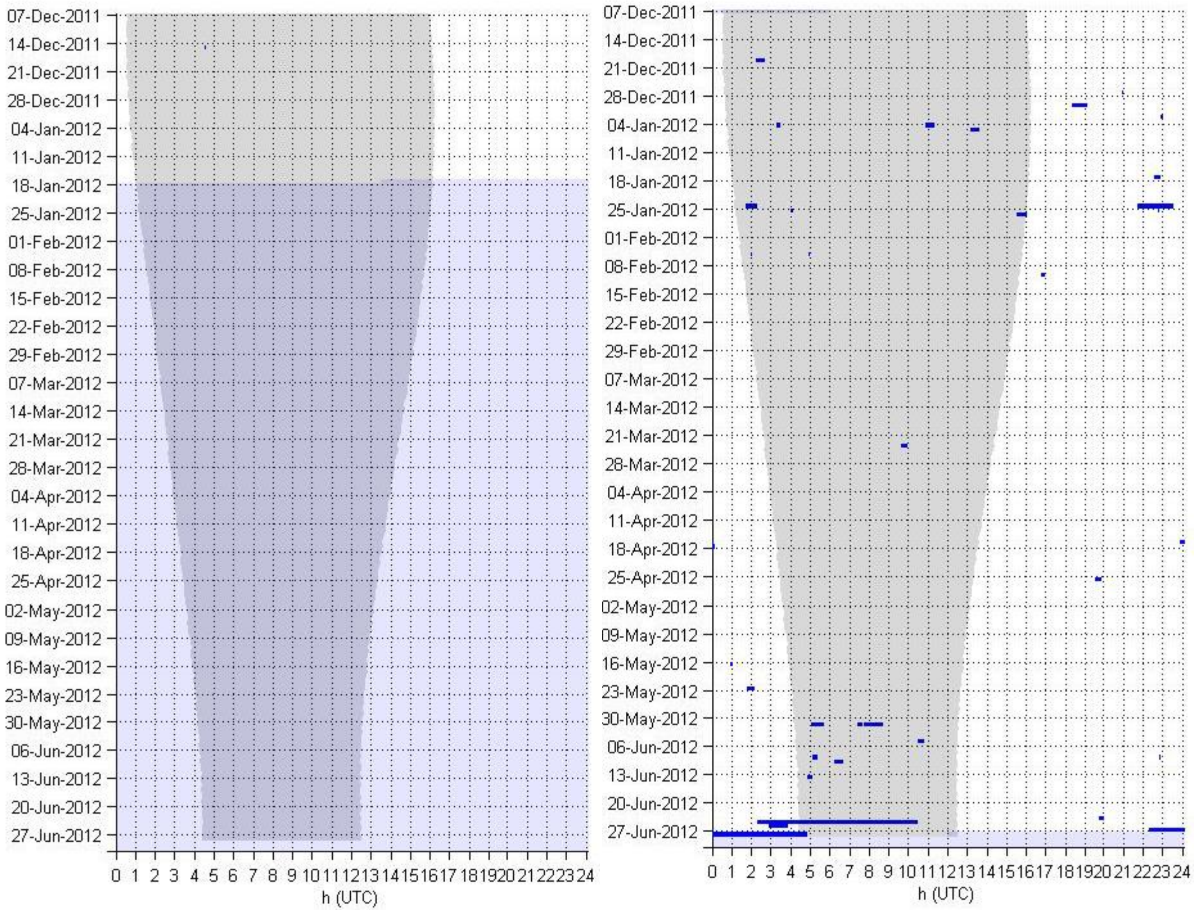
Killer whale –Whistles (>5 kHz) and echolocation clicks in five-minute bins at sites CE (left) and QC (right).



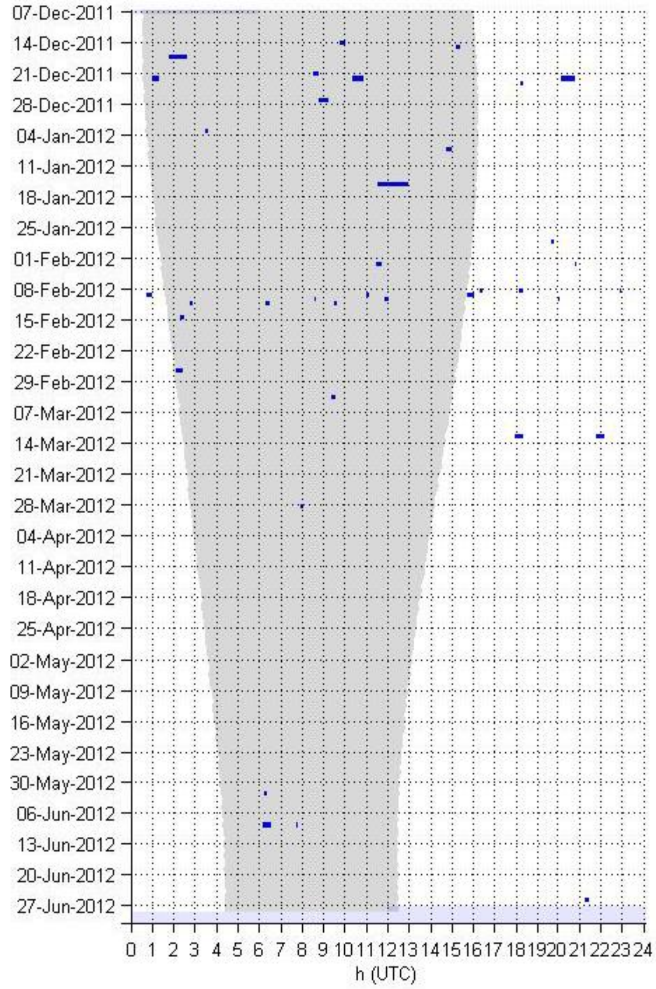
Sperm whale – Echolocation clicks in five-minute bins at sites CE (left) and QC (right).



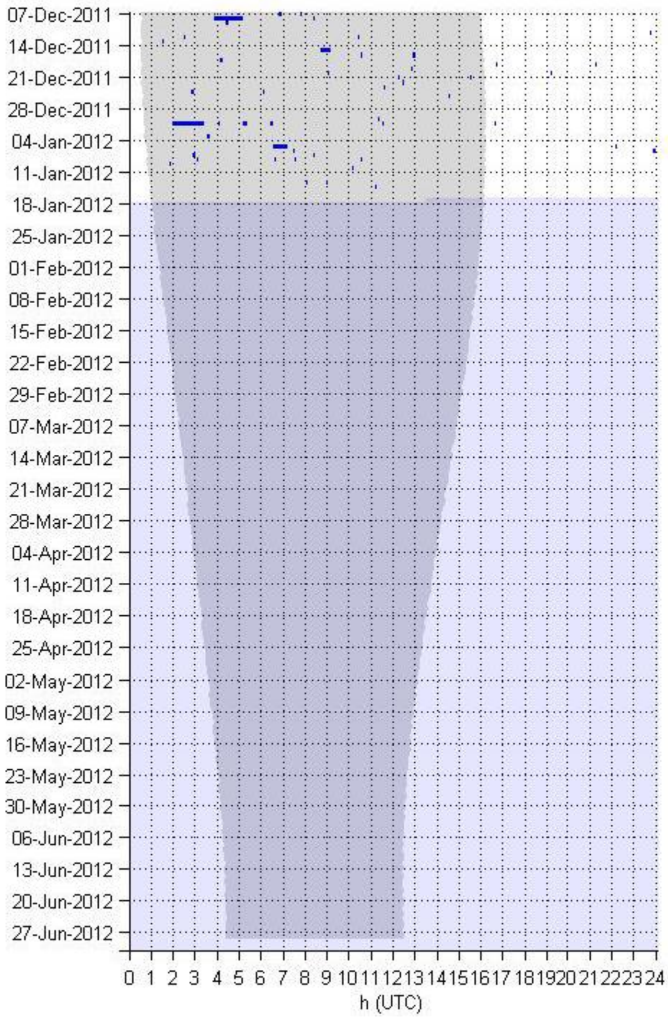
Stejneger's beaked whale – Frequency-modulated pulses in five-minute bins at site QC.



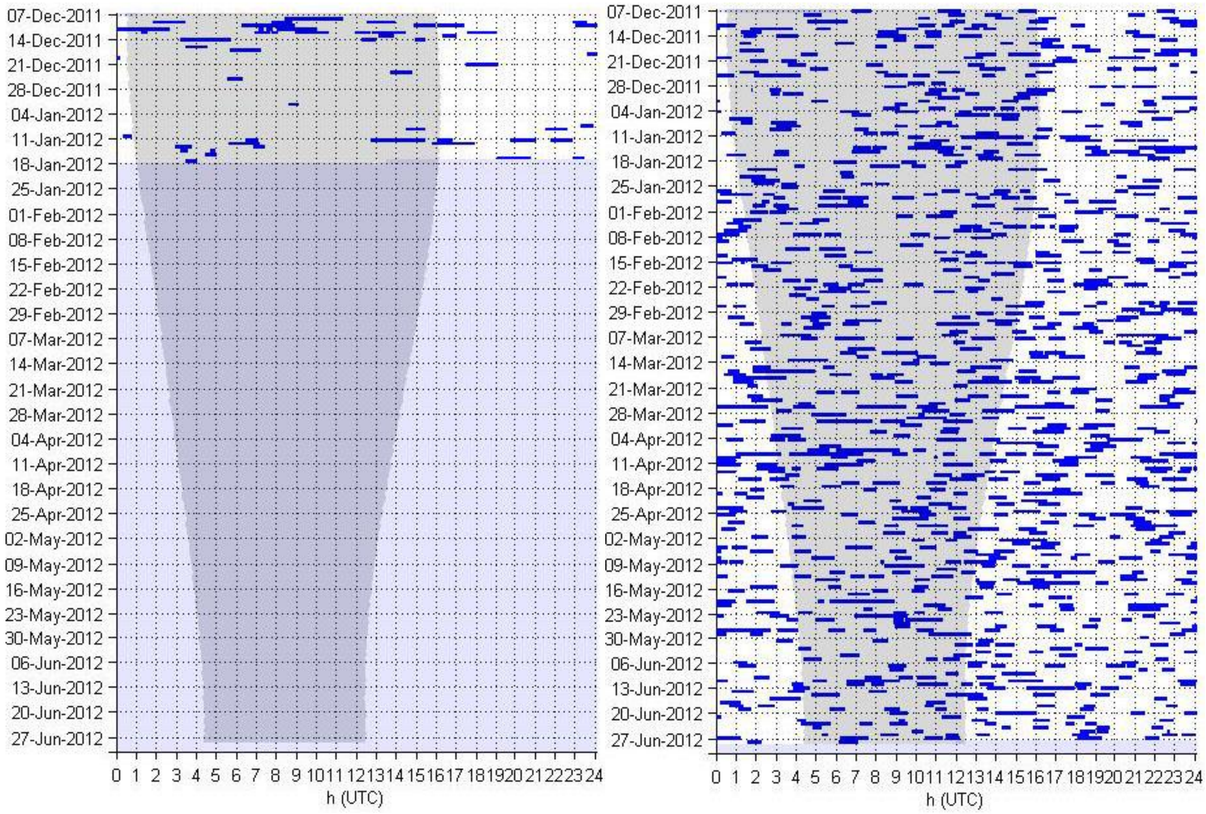
Baird's beaked whale – Frequency-modulated pulses in five-minute bins at sites CE (left) and QC (right).



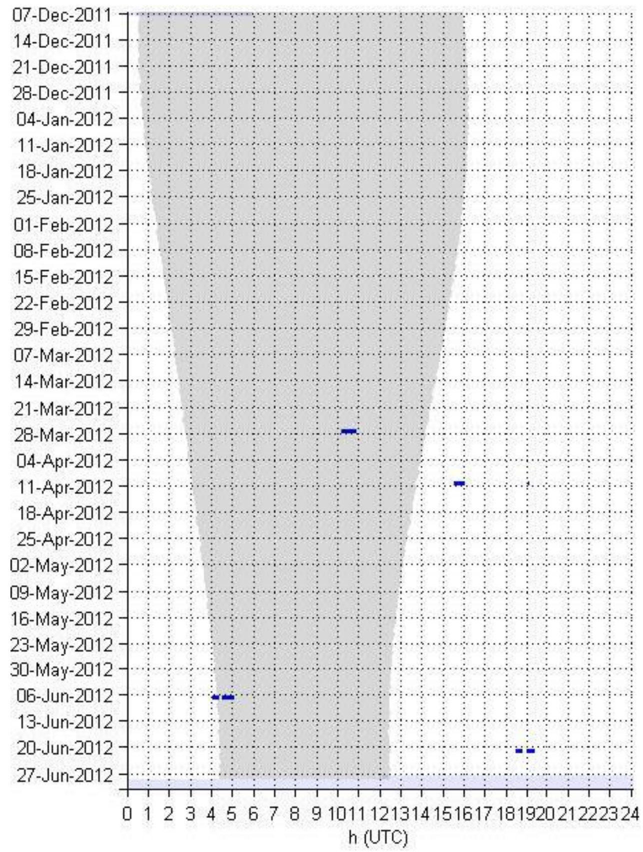
Cuvier's beaked whale - Frequency-modulated pulses in five-minute bins at site QC.



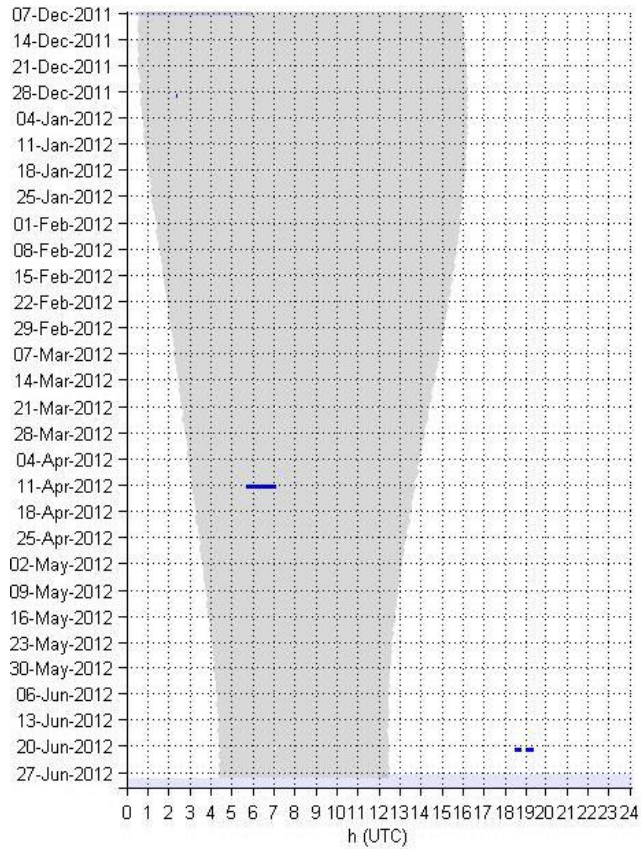
Unidentified Porpoise – Narrow-banded high-frequency pulses in five-minute bins at site CE.



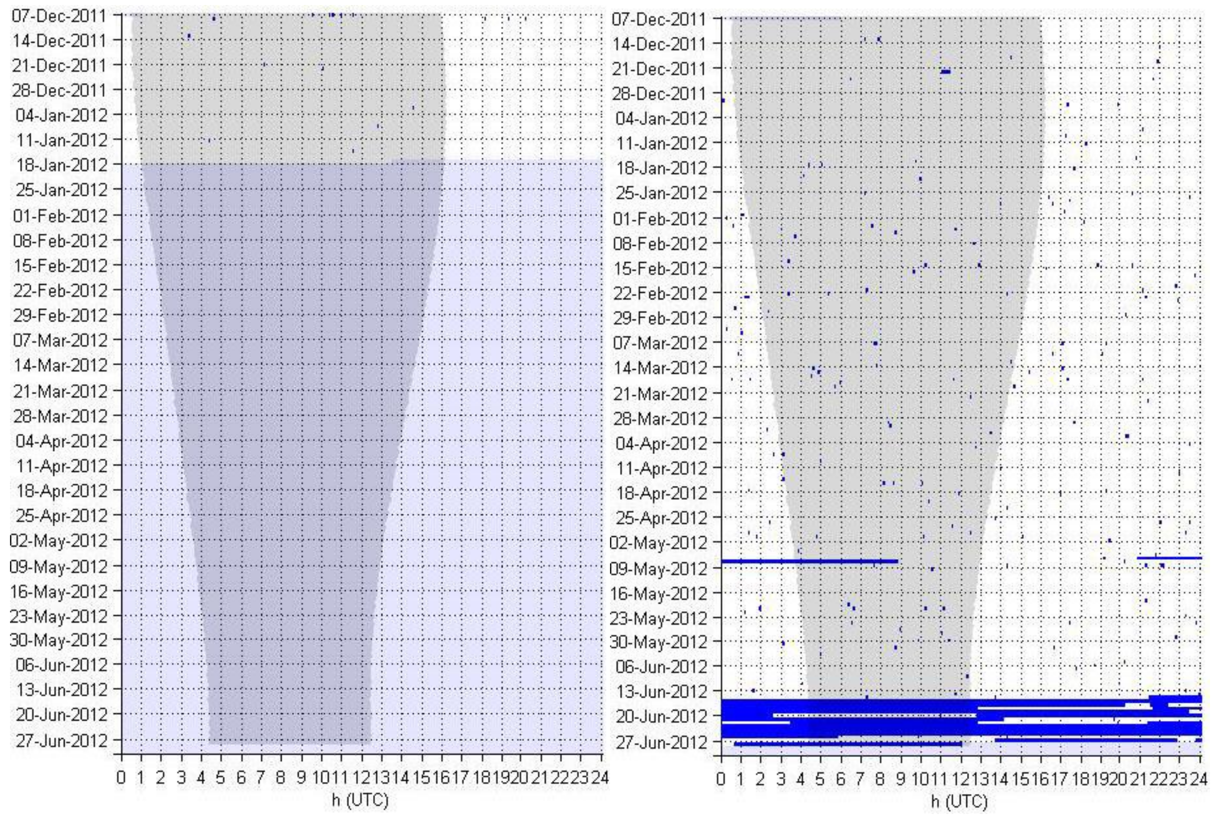
Broadband ship noise – presence in one-minute bins at sites CE (left) and QC (right).



Mid-frequency active sonar – presence in five-minute bins at site QC.



Echosounders – presence in five-minute bins at site QC.



Explosions – Presence in five-minute bins at sites CE (left) and QC (right).