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Blue Whale (*Balaenoptera musculus*) Diel Call Patterns Offshore of Southern California

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Abstract

Diel and seasonal calling patterns for blue whales (*Balaenoptera musculus*) were observed in coastal waters off southern California using seafloor-mounted autonomous acoustic recording packages (ARPs). Automated call counting from spectrogram cross-correlation showed peak seasonal calling in late summer/early fall. When call counts were organized by daily time intervals, calling peaks were observed during twilight periods, just after sunset and before sunrise. Minimum calling was observed during the day. Nighttime calling was greater than daytime calling, but also showed a minimum between the dusk and dawn calling peaks. These peaks correlate with the vertical migration times of krill, the blue whales' primary prey. One hypothesis to explain these diel variations is that blue whale calling and foraging may be mutually exclusive activities. Fewer calls are produced during the day while prey are aggregated at depth and foraging is efficient. More calls are produced during the twilight time periods when prey are vertically migrating and at night when prey are dispersed near the sea surface and foraging is less efficient.

Key Words: blue whale, *Balaenoptera musculus*, whale call, diel, diurnal, acoustic, southern California, northeast Pacific

Introduction

Acoustic monitoring of calling whales provides a means for estimating relative abundance and seasonal distributions of these highly mobile animals. Abundance estimates from acoustic monitoring require consideration of the whales' calling behavior, however. Diel and seasonal variations in call characteristics and call occurrence exist for many species and may be correlated with various behaviors (e.g., Au et al., 2000; Carlstrom, 2005; Klinowska, 1986). Calling and quiet period statistics are needed to provide call-to-whale correction factors. In this paper, we examine temporal patterns in blue whale (*Balaenoptera musculus*) calling from acoustic monitoring offshore of southern California to provide a better understanding of calling behavior.

Diel rhythms in cetaceans have been documented in the wild, although much less frequently than for terrestrial animals because of the difficulty of studying these animals for extended periods (Klinowska, 1986). Sleep and resting, tidal or lunar influences, and feeding are typical causes for diel rhythm activity in marine species (e.g., Palmer, 1976). Many fish species are most acoustically active for a brief period shortly after sunset (Connaughton & Taylor, 1995; Mann & Lobel, 1995; Rountree & Bowers-Altman, 2002). Several cetacean species are known to call more often at night, including common dolphins (*Delphinus delphis*) (Goold, 2000), North Atlantic right whales (*Eubalaena glacialis*) (Matthews et al., 2001), and harbor porpoises (*Phocoena phocoena*) (Carlstrom, 2005). Studies of humpback whale (*Megaptera novaeanglia*) song in Hawaii found no diel variation (Helweg & Herman, 1994); however, later work in a nearby area where higher humpback whale densities occur found significant diel variation (Au et al., 2000).

Blue whales off California's coast are some of the best studied, owing to their accessibility (Barlow, 1995; Calambokidis et al., 1999). The population of blue whales off southern California is estimated to number about 2,000 (Calambokidis & Barlow, 2004; Forney et al., 2000). Based on photo-identification, satellite-tagging, and acoustic-recordings, these blue whales migrate north as far as the Gulf of Alaska in the summer for feeding (Stafford, 2003), and as far south as the Costa Rica Dome in the winter, presumably for calving and mating (Calambokidis et al., 1999; Mate et al., 1999; Stafford et al., 1999).

Blue whales produce simple, high-intensity, low-frequency, acoustic calls (Cummings & Thompson, 1971). Although blue whale call characteristics off California have remained consistent over the past 40 years, the function of calling is not understood well. Repetitive call sequences appear to be made only by males (McDonald et al., 2001; Oleson et al., 2004). These calls may be associated with mate attraction, similar to the closely related fin whale (*B. physalus*) in which males produce loud songs to attract distant females (Croll et al., 2002). By observing the daily patterns in the cycle of calling, a better understanding of the function and behavioral context of calling may be realized.

There are three call types associated with northeastern Pacific blue whales (McDonald et al., 2001; Thompson et al., 1996). Two of these types, labeled "A" and "B" are produced in patterned and repetitive sequences (Figure 2). An A call is composed of a series of pulses and lasts for approximately 20 s. The fundamental frequency is approximately 15 Hz, but there are also strong overtones, especially around 90 Hz. B calls begin with a frequency-modulated (FM) up-sweep from about 10 Hz to 12 Hz for about 10 s, and continue as a down-swept tone from about 17 Hz to 16 Hz, lasting around 20 s. B calls have strong harmonics. The third harmonic (48 Hz) typically has the highest signal-noise-ratio (SNR). The third call type, which is called "D," occurs in irregular patterns, primarily as a call-counter-call between at least two individual animals (McDonald et al., 2001). In this paper, we focus on B calls and do not examine D calls.

We have been monitoring calling blue whales off the coast of southern California (Figure 1) since 2000, with the goal of using the acoustic data to investigate temporal patterns and variations in calling behavior. In this paper, we examine one year of recordings (2001) for daily call patterns and call variability throughout the year.

Materials and Methods

To monitor calling blue whales from 1 January to 31 December 2001, we deployed an array of autonomous acoustic recording packages (ARPs) in 120 m to 430 m deep water around the Cortez and Tanner Banks about 100 km west of San Diego, California (Figure 1 & Table 1). Approximately every two to three months, cruises were conducted to recover data from the ARPs,

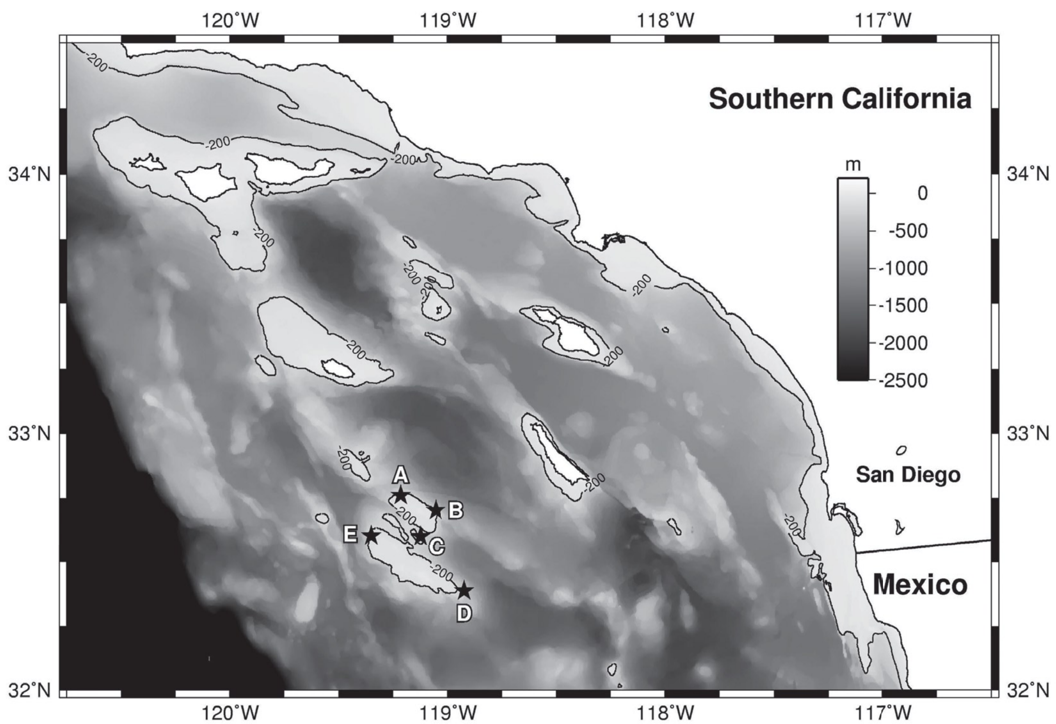

Figure 1. Southern California Bight bathymetry map with 200-m contours; the five stars depict the acoustic recording package (ARP) locations on Cortez and Tanner Banks (see Table 1).

Table 1. Seafloor ARP locations off the coast of southern California

Site	Location		Depth
A	32° 45.62' N	119° 13.00' W	120 m
B	32° 42.08' N	119° 03.24' W	250 m
C	32° 35.74' N	119° 07.58' W	150 m
D	32° 23.29' N	118° 55.42' W	430 m
E	32° 36.16' N	119° 21.15' W	150 m

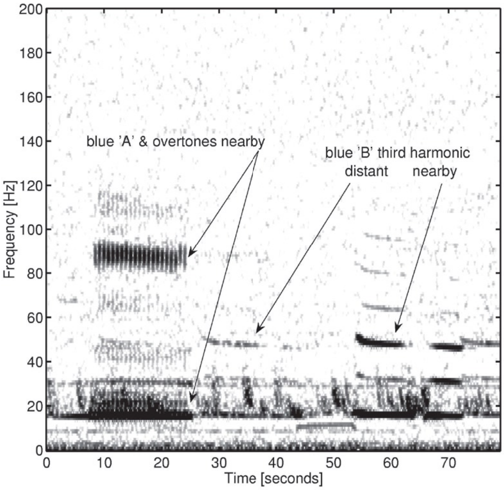

Figure 2. Spectrogram of ARP data showing blue whale A (pulsed) and B (tonal) calls, fin whale down-swept calls (~35 Hz to ~15 Hz), and ship noise (continuous tones). The B call has a series of harmonically related nearly tonal components. The B third harmonic is the detection call because of its high signal-to-noise ratio (SNR).

refurbish the instruments with new batteries and data disks, and conduct shipboard visual surveys.

An ARP consists of a frame that rests on the seafloor and a hydrophone tethered above the frame (Wiggins, 2003). The frame contains the pressure cases needed for batteries, release, and data logger electronics. The ARPs were configured to record continuously 16-bit samples (96-dB dynamic range) at a sample rate of 1 kHz onto hard disk drives. An ARP hydrophone consists of lead-zircon-titanate (PZT) ceramic cartridge (Benthos AQ-1); a 40-dB gain pre-amplifier; and a 6-pole, low-pass filter (-6 dB at 500 Hz).

Blue whale B calls were counted using an automatic detection algorithm. The B call third harmonic (Figure 2) was selected for detection since at 48 Hz and 20 s long, its SNR often is higher than the fundamental frequency at 16 Hz. The third harmonic is at a frequency well above the often present fin whale calls (~35 Hz to ~15 Hz down sweeps) and where ambient noise levels are typically less than at lower frequencies.

To detect B calls, we used the software program, *Ishmael* (Mellinger, 2002), a multi-functional program for analysis of bioacoustic data. *Ishmael* has three methods for automatic call detection: energy summation, matched filtering, and spectrogram correlation. We chose the spectrogram correlation method because it is well-suited for the FM characteristic of a blue whale B third harmonic call (Mellinger & Clark, 2000).

To calculate the spectrograms used with the detection algorithm, fast Fourier transforms (FFTs) of the time-series waveforms were performed with 2,048 samples, 50% overlap, and Hamming windows. These spectrograms were cross-correlated with a synthetic kernel or reference function representing the B call third harmonic. Our synthesized kernel was based on numerous recorded B calls and was constructed from sequential continuous, linear down-sweeps, starting at 52.0 Hz and ending 10 s later at 47.9 Hz. The kernel was based on only the first 10 s of the call because the received sound levels often varied past this time in the middle part of the call (Figure 2), making detections less reliable.

The output of the spectrogram cross-correlation was a recognizing score function. When this function was greater than a user-defined detection threshold for a given duration, a detection was noted by recording the time and a time-series data file of the detected call to a computer disk. Many "training" sessions with *Ishmael* were conducted to evaluate and modify the kernel and the detection threshold. One of the authors (EMO) manually detected calls by viewing spectrograms. These detections served as a basis for testing different detection thresholds and modifying the kernel. For example, if the detection threshold was set too low, then many false detections occurred. On the other hand, if the detection threshold was set too high, then many calls were missed. We chose to minimize the number of false detections at the expense of missing quiet/distant (low SNR) calls. Using our manually detected training data, we chose a detection threshold which produced < 4% false detections and < 10% missed calls.

Blue whale B call detections were processed using the software programming language, *MATLAB*® (www.mathworks.com). The detection times were sorted into time periods for statistical analysis and pattern investigation. Detections in time periods from multiple instruments were divided by the number of instruments to provide an average count for that time period. The number of detections per hour (detections/h) were averaged over each week of the year and plotted to examine seasonal calling trends. Diel patterns were evaluated by sorting detections into time periods based on four light periods: dawn, day, dusk, and night. Dawn was defined as starting at nautical twilight (i.e., when the center of the sun was 12° below the horizon) and ending at sunrise; day consisted of the time between sunrise and sunset; dusk was defined similar to dawn, but starting at sunset, and ending at the other nautical twilight; and the time between the two twilights was night. Daily values for sunrise, sunset, and nautical twilight begin and end times were obtained for 2001 at 32° 36' N, 119° 08' W from the U.S. Naval Observatory's Astronomical Application Department (Anonymous, 2001). Hourly patterns used 24, 1-h time periods based on GMT time.

Only days with at least one detection were used for the diel and hourly pattern analysis. Because the diel time periods are different durations and vary over the course of one year, the number of detections in each diel time period was divided by the duration of the time period to provide normalized detection rates (detections/h) for each time period. The data were adjusted by subtracting each day's mean number of detections/h from the detection rate of each time period for that day to remove biasing effects caused by variations in the daily detection rates throughout the year.

We tested the null hypothesis that the number of detections/h is constant over a 24-h period by conducting a non-parametric analysis of variance (ANOVA) Kruskal-Wallis test because the mean adjusted data were not normally distributed (failed Lilliefors test). A multiple comparison test was performed on the mean adjusted averages for the four diel time periods to evaluate which time periods were significantly different.

Results

Analysis of the weekly average number of detections/h revealed a seasonal cycle of blue whale calling beginning in late spring and lasting until late fall (Figure 3). During midsummer, the average rate was about 15-20 detections/h, whereas during late summer/early fall, the rate increased to approximately 30-35 detections/h. Over 200,000 detected B calls from one to three instruments during six recording sessions were used for these weekly averages and diel pattern investigation (Table 2).

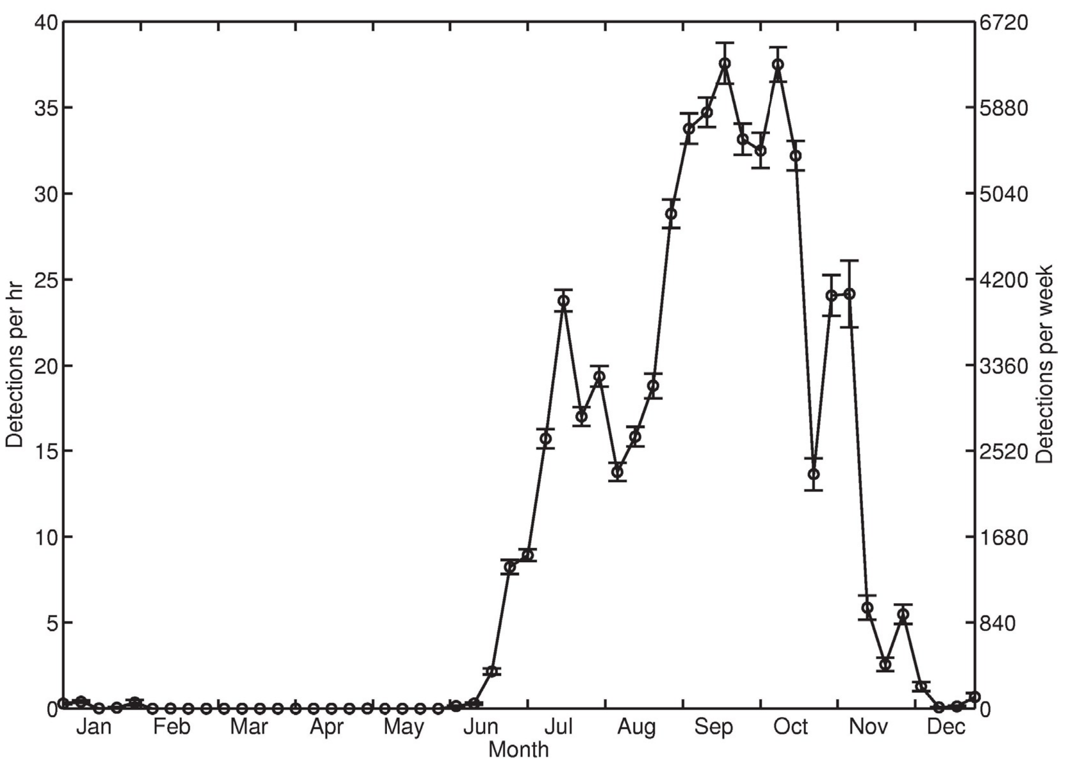

Figure 3. Number of detections/h averaged in one-week time periods and per instrument for 2001; error bars are ± SE. The right vertical axis shows the total number of detections in the one-week time periods per instrument.

Table 2. Number of blue whale B detections for each recording period and site during 2001

Site	Jan.-Feb. (52 days)	Feb.-April (68 days)	April-June (51 days)	June-Aug. (63 days)	Aug.-Oct. (63 days)	Oct.-Dec. (68 days)	Total
A	-	0	-	-	-	-	0
B	254	-	-	15,347	61,277	-	76,878
C	311	0	129	29,685	33,734	-	63,859
D	603	-	-	-	-	13,460	14,063
E	-	-	-	24,562	44,574	-	69,136
Total	1,168	0	129	69,594	139,585	13,460	223,936

The null hypothesis that the call detection rate was the same for the four diel time periods was rejected (Kruskal-Wallis ANOVA = 75.68, n = 207, $p < 0.001$). The adjusted average number of detections/h for the four diel time periods and their SE for n = 207 days were 2.24 ± 0.66 (dusk), 1.45 ± 0.27 (night), 3.48 ± 0.59 (dawn), and -1.43 ± 0.24 (day) (Figure 4). The multiple comparison test showed that the dusk, night, and dawn periods were not significantly different from each other, but all three were significantly different from the day-time period.

Adjusted average detection rates for 24, 1-h time periods showed more detail in the daily calling pattern than the diel time period averages (Figure 5), but a similar pattern for the two time scales was observed with detection rates lowest during the day and highest during twilight periods. The additional detail showed rapid increases and decreases in calling rate near the dusk/dawn periods, with a nighttime minimum between the two peaks.

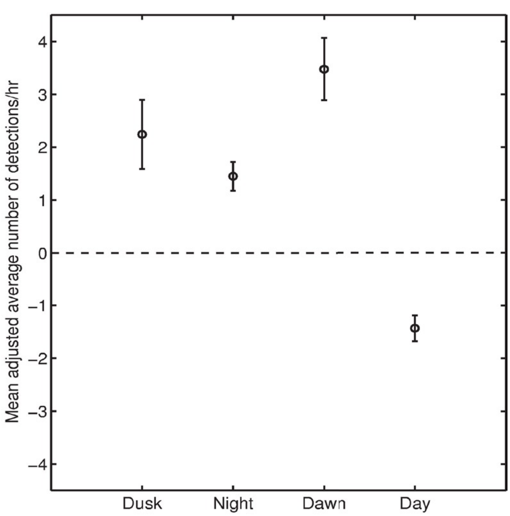

Figure 4. Adjusted average number of detections/h in four diel periods for n = 207 days; daily diel periods were obtained for 2001 at 32° 36' N, 119° 08' W from the U.S. Naval Observatory's Astronomical Application Department (Anonymous, 2001). Error bars are ± SE values.

Discussion

Our seasonality results are consistent with Burtenshaw et al. (2004), who used spectral sound pressure levels from military hydrophone data to monitor blue whale calls along the west coast of North America, including two stations near San Nicolas Island, close to our current study area. These data suggest that blue whale A and B calling begins off southern California in the early summer, peaks in the late summer/early fall, and ends in late fall. This calling pattern has been previously related to their seasonal migratory cycle (Stafford et al., 2001)

There was a diel pattern for blue whale calling, with most calls detected during the summer and fall for our study area. The transitions from low-to-high and high-to-low calling rates were correlated with sunset and sunrise, respectively. The peak calling rates occurred just after sunset and just prior to sunrise. This pattern is similar to what Thompson (1965) reported 40 years ago for 20 Hz long pulses

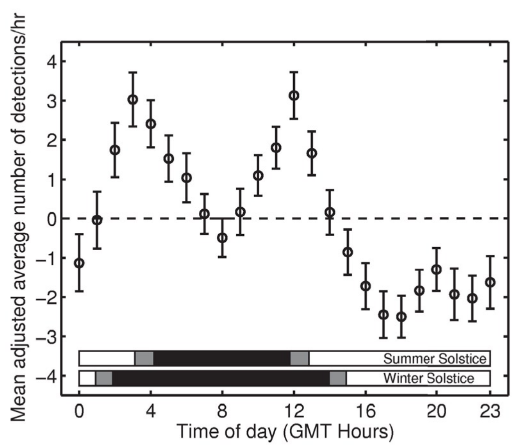

Figure 5. Adjusted average number of detections/h in GMT-based 1-h periods during 2001 (n = 207; error bars are ± SE values); horizontal bars at bottom of plot show day (white), dawn and dusk twilight (gray), and night (black) periods for the two extreme light regimes during the summer and winter solstices.

(now known to be blue whale calls), using two hydrophones west of San Clemente Island in the San Nicolas Basin, approximately 30 miles east of our study area. Peaks after sunset and before sunrise, and lows at midnight and during daylight hours were shown for eight days of data recorded during July 1963. Stafford (2001) also showed the number of blue whale B calls in the eastern tropical Pacific (8° N 95° W) was greater at night than during the day, with peaks at sunset and sunrise for 28 days of data during May-June 1996.

Several hypotheses have been put forward to explain blue whale call behavior. Blue whale call production may be related to mating, serving to attract, stimulate, or guard a potential mate. Alternatively, calls may serve a different social function, such as territory defense. Calling may be nonsocial, enabling the blue whale to sense its environment for navigation purposes (Clark & Ellison, 2004) as do odontocete whales (i.e., echolocation). Or, perhaps calling is used for a combination of the above.

Whether blue whales call to attract mates, display fitness, or aid navigation, the diel pattern of calling may be related to foraging. The blue whale calling peaks appear to correlate with the daily vertical water-column migration of their primary food source, the euphausiid species, *Euphausia pacifica* and *Thysanoëssa spinnifera* (Fiedler et al., 1998). The vertical daily migration of krill, aggregating at depth during daylight, presumably is to avoid the threat of visual hunting predators such as pinnipeds, birds, and fish (Brinton, 1967, Genin et al., 1988). Croll et al. (1998) showed that blue whales forage offshore of southern California during the day at depths corresponding to these dense euphausiid swarms, making repeated foraging lunges during a dive cycle.

Blue whales may call more at dawn and dusk because foraging is less efficient at these times when krill are dispersed, migrating to or from the surface; presumably, they call less when occupied with foraging during the day when the krill are aggregated at depth. Croll et al. (2002) proposed, however, that in the closely related fin whale, males call to attract females to regions of high-prey concentrations, which would suggest that calling should peak during the day, contrary to our results. The nighttime lull in calling in our data may be an indication of increased surface skim feeding (Fielder et al., 1998) or perhaps a period of rest (Lockyer, 1981).

Physiologically, blue whales cannot produce their high-intensity, low-frequency calls at feeding depths. The hydrostatic pressure limits calling depth since air volume decreases with increasing pressure. The maximum depth where there is sufficient air for calling may be about 40 m (Aroyan et al., 2000). Also, field data reveal that blue whales produce their calls when they are between 10 m and 40 m deep (Oleson et al., 2004; Thode et al., 2000), which suggests that feeding blue whales are less likely to call since foraging places them at depths greater than where they are known to call.

Conclusions

Long-term acoustic monitoring of blue whales has provided insight to their seasonal and daily calling patterns. The diel calling pattern of the blue whale B call is correlated with daylight, showing the greatest change in calling activity near sunrise and sunset, and more calls at night than during the day. While we do not have a complete understanding as to why blue whales call, it seems likely that the diel pattern is related to feeding activity. The diel vertical migrations of the blue whales' main food source suggest an inverse relationship between number of whale calls and level of feeding activity.

Understanding temporal, seasonal, and spatial characteristics of calling in blue whales will improve the estimation of relative abundance and seasonal occurrence from acoustic monitoring, as well as contribute to understanding why blue whales call.

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