ABSTRACT

ESTIMATION OF ABUNDANCE OF BLUE WHALE CALLS OFF CENTRAL CALIFORNIA USING A SEAFLOOR-MOUNTED HYDROPHONE

Blue whale vocalizations were monitored off central California during 1998-2000, using the Naval Postgraduate School's Ocean Acoustic Observatory, a former U.S. Navy SOSUS array. Long-term, continuous recordings from a single hydrophone were collected and used in this study. The abundance of blue whale "A" and "B" calls were estimated using a matched filter detector, of which 100,700 "A" calls and 176,585 "B" calls were found on 12,877 hours of recordings at a selected probability of false detection of 0.3%. The abundance of blue whale calls during 1998 was greater than subsequent years, with the greatest concentration between mid-August and late-October. Unexpected increases in abundance of "A" and "B" calls were observed from mid-December to mid-January in 1999. Historically, blue whales were sighted in Monterey Bay from approximately late July to October. These acoustic data indicated blue whales were abundant off central California during winter.

Anurag Kumar
December 2003

ESTIMATION OF ABUNDANCE OF BLUE WHALE CALLS OFF CENTRAL CALIFORNIA USING A SEAFLOOR-MOUNTED HYDROPHONE

by

Anurag Kumar

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INTRODUCTION

Estimating cetacean population density has relied upon aircraft, ship, and shore-based visual surveying techniques. Researchers using transect or point surveys count the number of animals in a given area and then make statistical inferences regarding the density of animals beyond the area surveyed (Buckland *et al.*, 1993; Garner *et al.*, 1999). Combined visual and acoustic surveys with a towed hydrophone array enhance the density estimate by detecting subsurface whales missed by the visual observers (Clark and Fristrup, 1997; Fristrup and Clark, 1997). All of these methods are useful for population density estimation but involve costly ship time or air time, cover limited areas, and without combined acoustic surveys, count only animals at the surface. Visual surveys require good weather and sea state to accurately observe the subjects; therefore, winter is commonly avoided, and observer biases can influence the results. In studying regional marine mammal abundance for prolonged time frames, other methods may prove more cost effective.

The ocean is largely transparent to low frequency sound, therefore, acoustical monitoring of baleen whales using shore-based hydrophone arrays provides a unique advantage over visual techniques. We can monitor the vocalizations throughout a greater geographic range from a single location (McDonald *et al.*, 1995; Fox and Stafford, 1996; Hager, 1997; Stafford *et al.*, 1998, 1999, 2001;

McDonald and Fox, 1999). Using the existing U.S. Navy Sound Surveillance System (SOSUS), it may be possible to monitor long-term changes in whale abundance using their vocalizations as an index of abundance (Nishimura and Conlon, 1993; Fox and Stafford, 1996; Moore *et al.*, 1998; McDonald and Fox, 1999; Watkins *et al.*, 2000). This could extend our range of detection of pelagic species, such as the blue whale *Balaenoptera musculus*, which vocalize regularly (Rivers, 1997) and often are not detected during near shore visual surveys (Calambokidis *et al.*, 1990, 1994; Barlow 1994, 1997; Mate *et al*., 1999; Benson *et al.*, 2002).

Blue whales produce loud, low-frequency sounds that propagate great distances in the deep ocean (Cummings and Thompson, 1971; McDonald *et al.*, 1995, 2001; Rivers, 1997; Stafford *et al.*, 1998; Watkins *et al.*, 2000). Males vocalize more frequently in productive regions, suggesting that the calls may be used for mating (McDonald *et al.*, 2001; Croll *et al.*, 2002). Their calls are well classified and stereotypic, making them suitable for automated detection methods (Chiu *et al.*, 1997; Chiu *et al.*, 1999; Moore, 1999). Blue whales have two alternating types of vocalizations that are frequently heard in our region: the “A” call, which is a pulsed, amplitude-modulated signal centered at 16.5 Hz, and a “B” call, which is a down-swept, frequency-modulated signal that sweeps from about 18 to 16.5 Hz (Rivers, 1997).

The blue whale population off California has been estimated using photo identification and visual surveys to be between 1,400 and 3,500 animals (Calambokidis *et al.*, 1990; Barlow, 1994; Forney *et al.*, 2000). Blue whales frequent the California coastal waters mostly during fall (Calambokidis *et al.*, 1990, 1994; Barlow, 1994, 1997; Mate *et al.*, 1999; Benson *et al.*, 2002), and forage in areas of dense aggregations of euphausiids (Schoenherr, 1991; Kieckhefer, 1992; Croll *et al.*, 1998; Fiedler *et al.*, 1998). Benson *et al.* (2002) found that blue whales were more abundant in Monterey Bay after the 1997/98 El Niño when productivity in the ocean was low (Chavez *et al.*, 2002). During the 1997/98 El Niño, euphausiids were abundant in Monterey Bay (Marinovic *et al.*, 2002). It was hypothesized by Benson *et al.* (2002) that during this low productivity, whales were forced to search for food in productive coastal upwelling regions.

At a similar time as these visual studies were conducted, blue whale vocalizations were frequently recorded by the Naval Postgraduate School's Ocean Acoustic Observatory (OAO) located off the central California coast. The OAO, located off Point Sur, California in the southern region of the Monterey Bay National Marine Sanctuary, is a former SOSUS array decommissioned by the U.S. Navy after the Cold War (Fig. 1). Though the multi-phone array still remains classified, the U.S. Navy declassified a single hydrophone on the array for research. Acoustic data were continuously archived from 1998 to early 2000. The

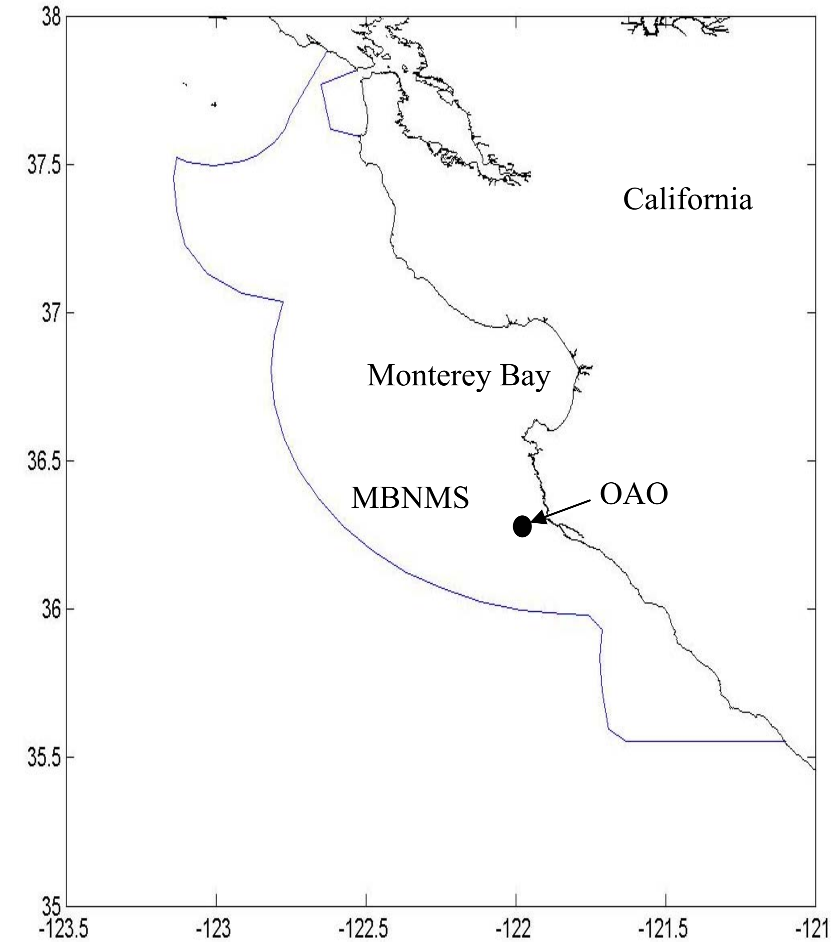

Figure 1. Map of the Ocean Acoustic Observatory (OAO) location within the Monterey Bay National Marine Sanctuary (MBNMS).

long-term archival of data, the location of the array, and the abundance of bioacoustic activity makes the OAO a valuable source for long-term acoustical monitoring with possibilities of assessing populations of roquals. The goal of this thesis was to devise a method for using long-term acoustical data as an index of blue whale abundance with a single hydrophone.

Objectives and Hypotheses

For this project there were three main objectives. The first objective was to evaluate detector performance of blue whale type “A” and “B” detectors and quantify the associated probabilities of detection and false detection rates. The second objective was to catalog the abundance and type of blue whale vocalizations in archived data. The daily vocalization rates were then tested for annual, seasonal, and diel variation. If blue whales were forced to search for food in coastal upwelling regions of Monterey Bay, California during the 1997/98 El Niño, as suggested by Benson *et al.* (2002), one would expect to find an increase in detection or daily call rates during that time. My hypothesis for annual variation, therefore, is that the blue whale calls were more abundant during late El Niño to early La Niña years. Seasonally, blue whales should be most abundant in this region during fall when upwelling provides nutrient rich water that stimulates primary productivity, hence euphausiids. For seasonal variation in call abundance, I hypothesized that there should be more calls in fall and winter, when primary productivity is high, than the spring and summer. On a daily basis, one would expect the blue whales to feed almost continuously to maintain their body mass (Brodie, 1975), represented by their dive rates and movements in feeding areas (Schoenherr, 1991; Fiedler *et al.*, 1998; Mate *et al.*, 1999; Langerquist *et al.*, 2000; Croll *et al.*, 2001; Acevedo-Gutierrez *et al.*, 2002) If male blue whales tend to vocalize in rich productive areas as suggested by McDonald *et al.* (2001) and Croll *et al.* (2002), no diel variation in their calls rates would be expected.

The final objective was to discuss the possibilities that long-term records of vocalizations could be used as an index of blue whale abundance. One can expect that an increase in the number of male blue whales in a given area would lead to an increased probability that more vocalizations were produced. Based on this, I hypothesized that within the range of detection, the abundance of vocalizations would correlate with abundance of whales.

Assumptions and Biases

Auto-detection methods detect signals based on how similar they are in comparison with a reference signal. The performance of the detector is highly dependent on signal-to-noise ratio (SNR) and how well the reference signal matches the data. Assuming blue whales vocalize at a constant source level, the further the vocalizing blue whale is from the hydrophone, the less likely the detector will find the signal because of the reduced SNR. In-band coherent noise, noise that resembles a signal, can contaminate the detector resulting in an increase in false detections. One known source for such types of noise are passing ships. Basing the detector's threshold on SNR helped avoid this bias.

Changes in ambient noise level could affect the range of detection in the sample range of the hydrophone. When the ocean's ambient noise increases, such as in winter because of increased wind, rain, and waves due to more frequent storms or when ships pass, the effective range of detection is diminished. This effect on the range of detection within the sample area was represented by classifying a probability of detection for each call found by the detectors.

The performance of the detector was measured by visually determining blue whale vocalizations and comparing these with the results from the detector. The evaluator must know the characteristics of the "A" and "B" calls to adequately assess the detector. In noisy data such as when a ship is approaching, the evaluator may not detect blue whale calls. This presents a bias that may produce a more conservative measure of the detectors' performances. If blue whale calls are present in noisy data and the evaluator does not find the calls but the detector does, this would result in an increase in false detections. This increase in false detections would reduce the performance measurement of the detector. For all measures of marine mammal abundance, conservative estimates are preferred when used for stock assessments which are often used for the mitigation of take and harassment. A conservative estimate would occur if the detector's abilities are underestimated. The "A" call is more difficult to visually identify than the “B” call in noisy data and could yield a more conservative estimate of detector performance than the “B” call detector.

If vocalizations are produced by male blue whales (McDonald *et al.*, 2001), then an acoustic survey would only sample half of the population. Therefore, no inference may be made about the female proportion of the population.

METHODS AND ANALYSIS

Automated Detector Design

An auto-detection routine was developed for the blue whale “A” and “B” calls, because it would be difficult and time consuming to visually inspect years of data. Both calls have similar fundamental frequencies so the detectors were designed based on unique features of each. In the OAO recordings, the strongest component of the “A” call was the fourth harmonic, which centered around 90 Hz (Fig. 2). For the “B” calls the strongest, most consistently apparent component was the second harmonic, centered around 51 Hz (Fig. 2). The detectors were designed to exploit these components of the calls, and the frequency band spacing allowed for the reduction in the probability of falsely classifying by type. The fundamental frequency was not selected due to overlapping energies (“A” = 18Hz, “B” = 17Hz) which would increase the risk of falsely classifying by type.

Developing an auto-detection routine involved two basic parts: a matched filter detector and a threshold detector (Fig. 3). First a matched filter detector was used to find the signals. A matched filter detector provides a measure of similarity between the data and a known reference signal of interest (Van Vleck and Middleton, 1946). Each detector used a unique matched filter, which was selective about certain features of the calls. The “A” call matched filter used a synthetically generated “A” call as a reference signal (Fig. 4). The reference

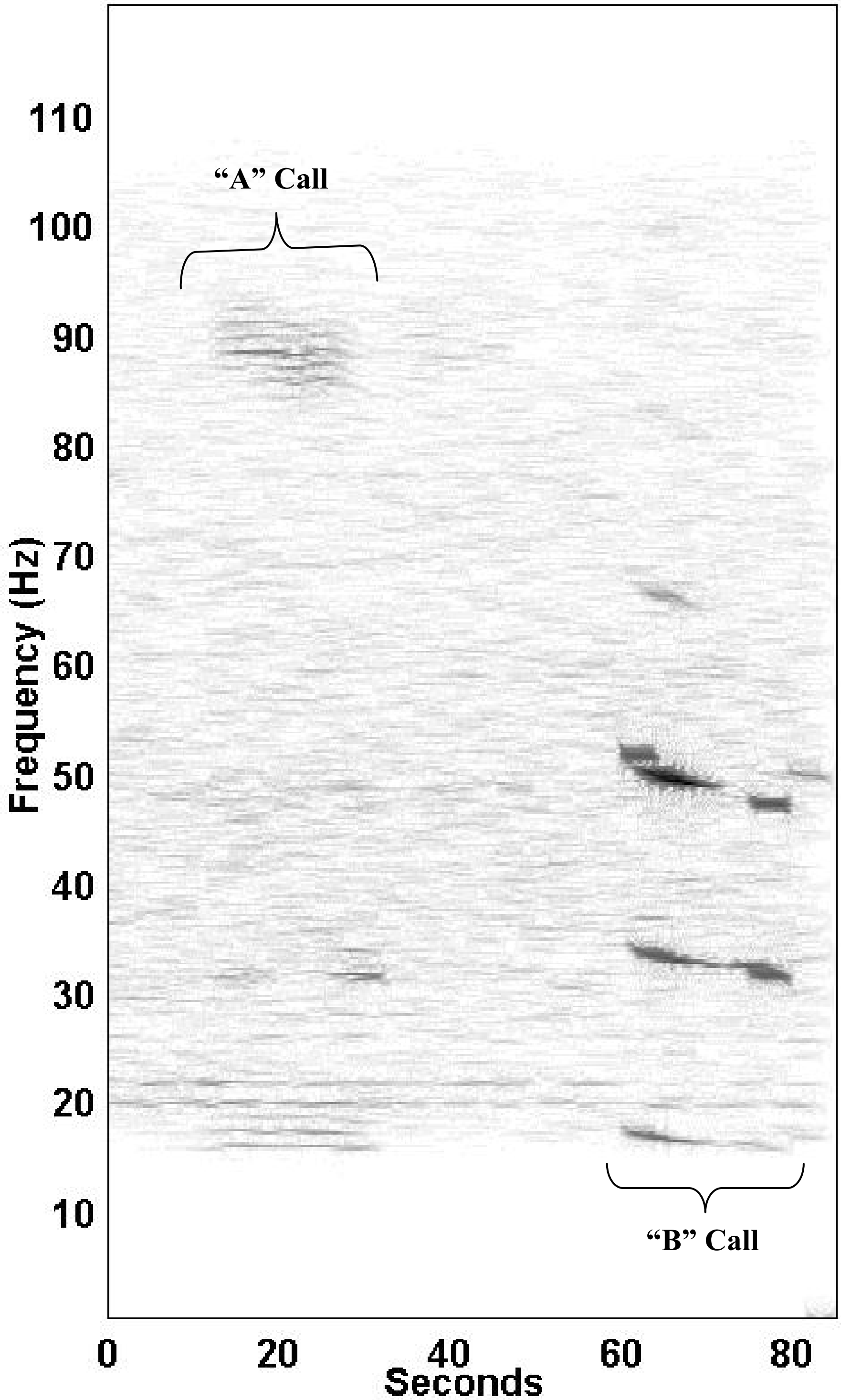

Figure 2. Spectrogram of a blue whale "A" and "B" call pair received at the OAO (FFT sample duration 0.5 – 1.0 seconds, Hanning shading window, 97.5% overlap).

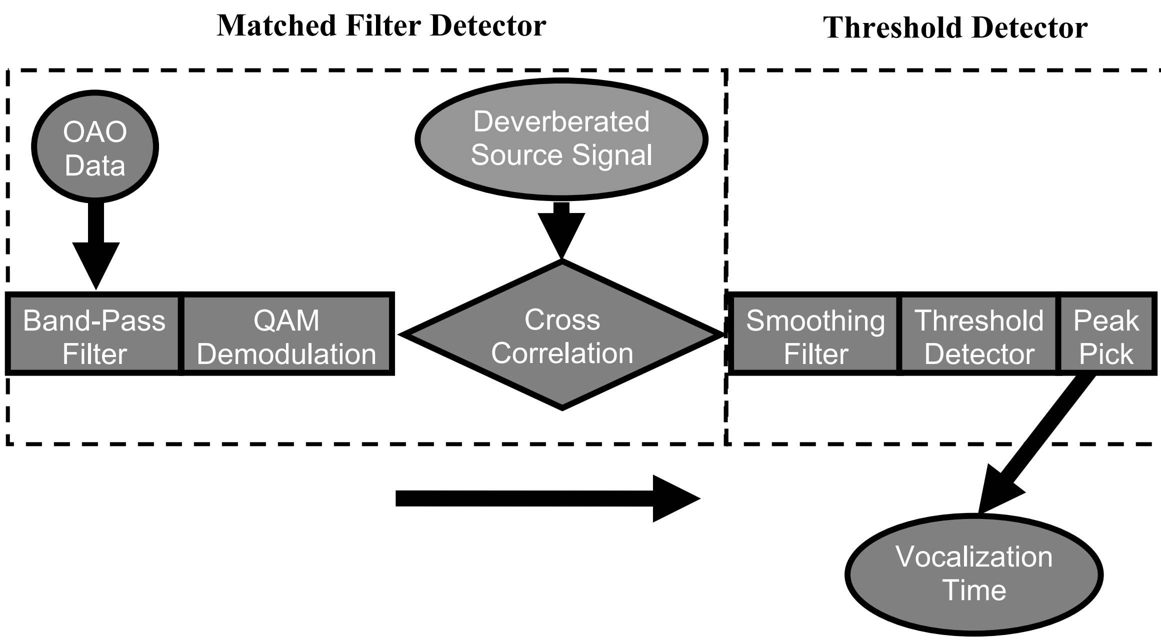

Figure 3. Flow diagram of detector design.

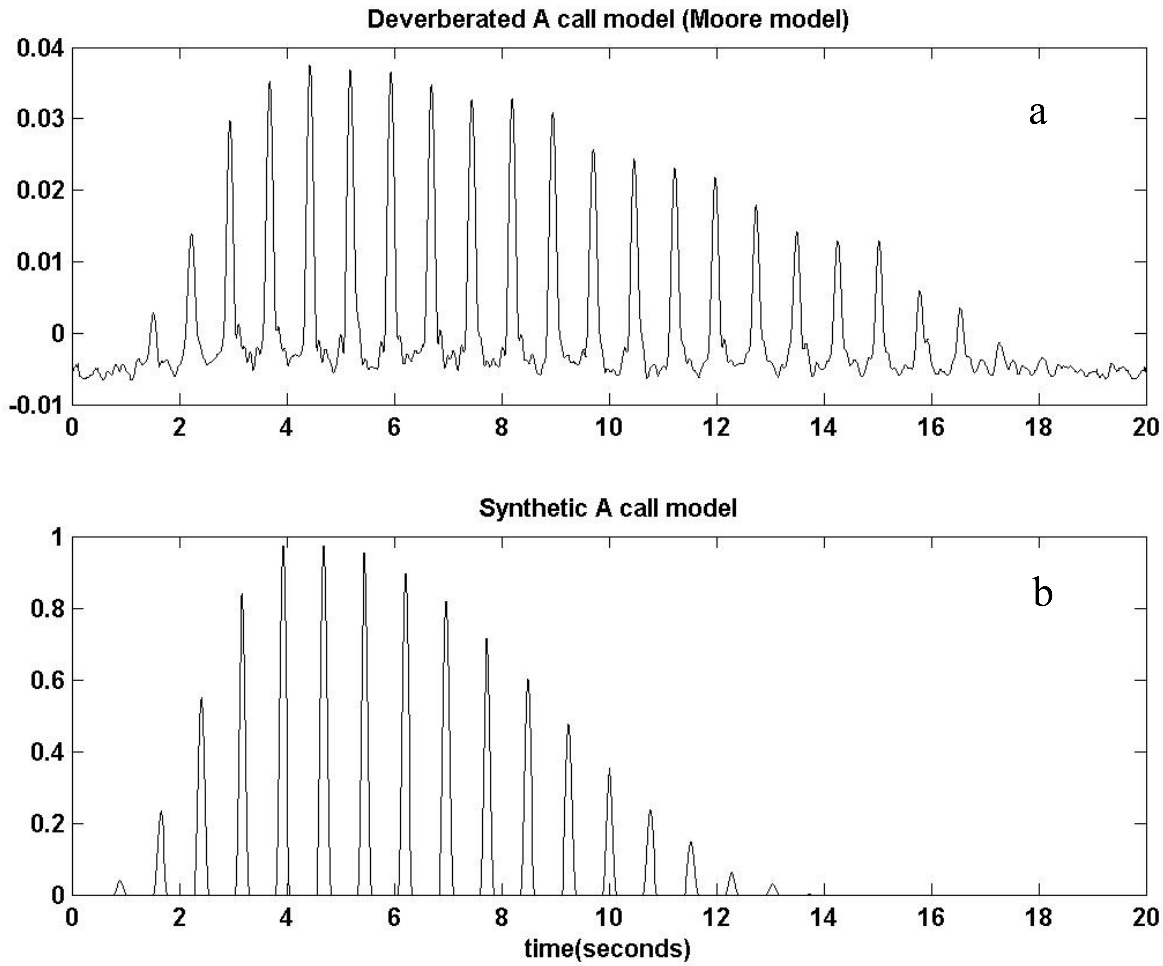

Figure 4. Plot of the deverberated model (a) and the synthetic reference "A" call matched filter (b). The noise in between the pulses of the deveberated model (a) resulted in poorer than expected correlations.

signal was generated based on the common signal parameters in the blue whale "A" calls found on the OAO recordings. The magnitude and pulse spacing of the "A" call provided a robust characteristic that was common among observed calls, whereas the waveform (phase) characteristic varied from call-to-call. The signal parameters that produced the optimal correlation values were 20 pulses with a pulse spacing of 0.76 sec., pulse width of 0.229 sec., and pulse train envelope weighting of 25%, which provided greater magnitudes for the beginning 25% of the pulses and gradually fading to lesser magnitudes. Because the "A" call is a pulse train, the matched filter output was smoothed with a filter so only a single peak was defined for each pulse train detected. For the "B" call, a matched filter detector designed by Moore (1999) was used. The "B" call waveform is very robust, in spite of wide amplitude variation. The waveform is unique, allowing for good detection using a matched-filter. The "B" call reference signal used the ensemble mean of a set of deverberated "B" calls recorded from a towed hydrophone array. Deverberation is the method of removing all of the environmental effects (i.e., multi-paths from bottom and surface interactions) resulting in a reconstructive model of a true source signal (Moore, 1999). It is beneficial to use an environmentally independent reference signal because it maximizes the correlation, regardless of where the blue whale is vocalizing in the ocean.

To locate the peaks of high correlation, a threshold was set and the maximum value above the threshold scored for each peak (Fig. 5). There are two probability density functions, one representing noise, and the other representing signal plus noise. Where a threshold is set defines the probabilities of detection, misses, and false detections, which are represented by the areas under the curves above and below the threshold (Fig. 6).

In noisy data, such as when ships pass the OAO, there is an increase in the noise probability density function (yielding a lower Signal to Noise Ratio, SNR). With a fixed threshold, this increase in noise would result in a larger area beyond the threshold and a greater probability of false detection (Fig. 6). Therefore, a fixed probability of false detection rate was used instead of a constant threshold. This fixed false detection rate is based on the number of calls that could be falsely detected over all available data. For example, if a detector, looking for a 3-second signal, yields one false detection in a data set 60 seconds long (20 possible signals occur), the false detection rate is 1/20 or 5%. The false detection rate for this study was set low, 0.3%, to minimize error in call counts (i.e., 5% would not be good for this long-term scale of measurement). When estimating marine mammal abundance, it is desired to maintain and minimize error and provide a good conservative estimate. The selected probability of false detection rate defined how changes in noise affect the probability of detection.

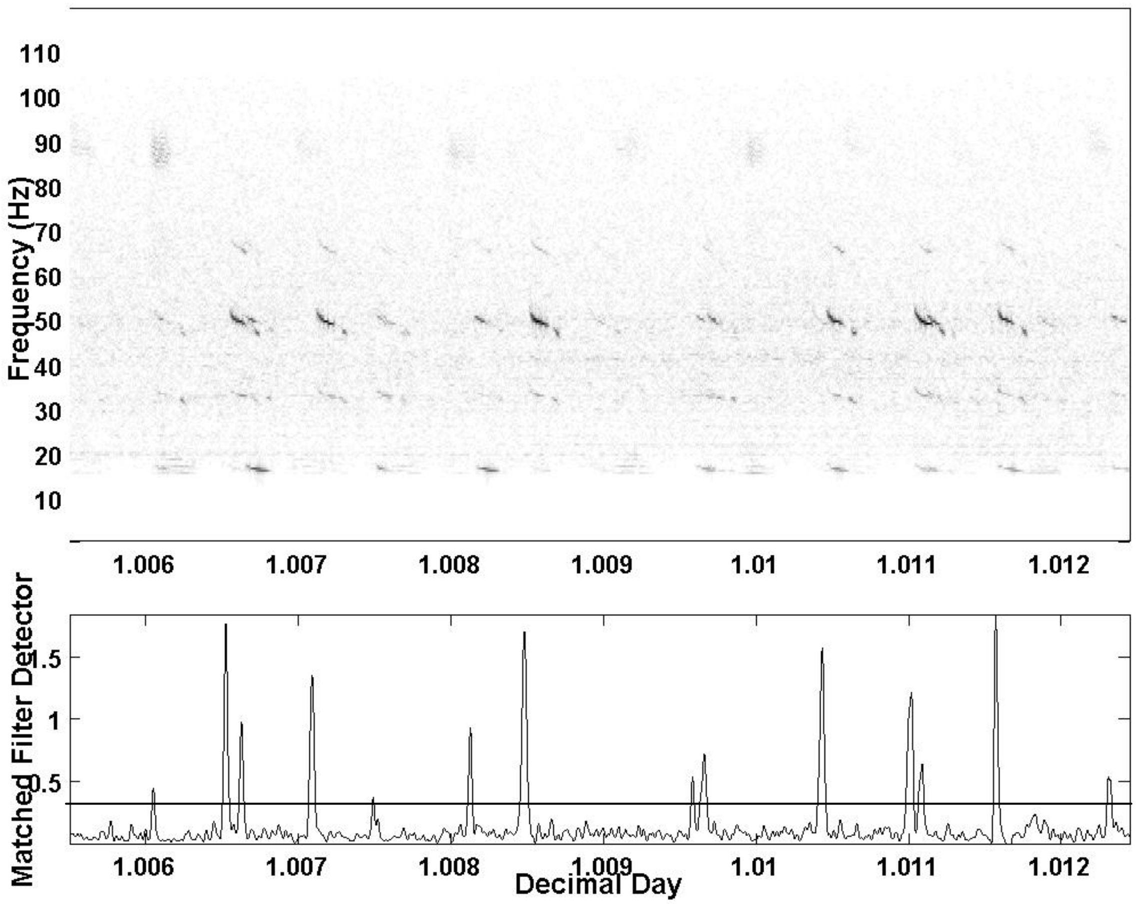

Figure 5. An example of the matched filter detector output for the “B” call detector.

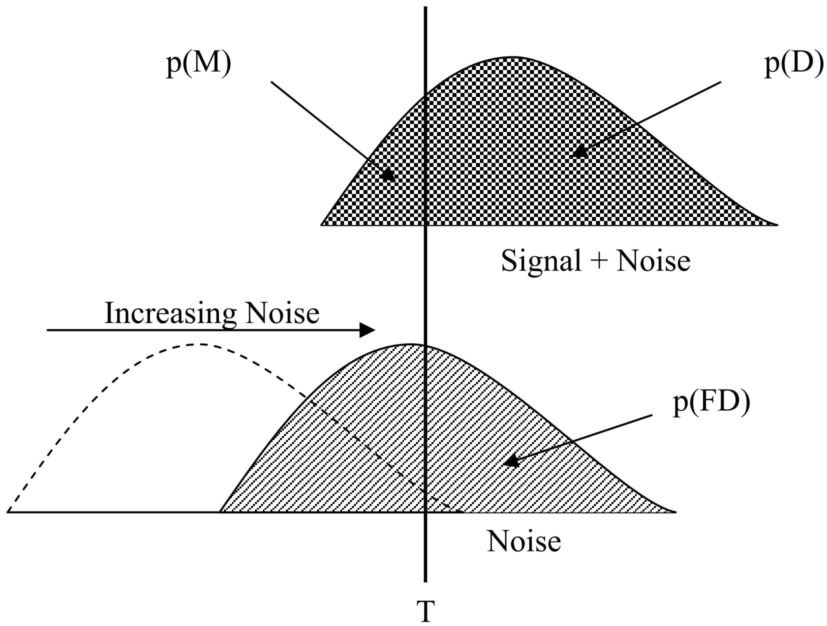

Figure 6. Probability density function example of signal + noise and noise. The areas under the curve represent p(D), the probability of detection, P(FD), the probability of false detection, P(M), the probability of misses, and T, the detection threshold. For the noise probability density function, the dashed curve represents a high SNR case and the solid represents a low SNR case.

In this experiment, acoustic recordings were processed in 10-minute segments for computational efficiency. OAO recordings were conditioned before running the matched filter detector by band-passed filtering to remove out-of-band noise, base-banded, normalized, de-meaned, then down-sampled. SNR was measured at the matched filter detector's output by measuring ratio, in each 10-minute window, between the mean of the peak correlation values for each call to the mean noise in between each call. To build the noise probability density function, noise was estimated by taking the average of the noise between the signal peaks in the correlation output. The signal peaks were preliminary located with a constant optimal threshold. The threshold settings were then defined by the fixed false detection rate. The threshold was then used to locate the peaks of high correlation, which were the detections, and the peaks were used to build the signal-plus-noise probability density function.

The threshold, probability of detection, and the probability of false detection were used to create a Receiver Operator Characteristic, or ROC, for each detector. The ROC curve defines the relationship between the probabilities of detection and the probability of false detection and is a measure of performance for a detector. The optimal detector has a ROC curve that has a higher probability of detection with a low probability of false detection. Because the detector's performance is SNR dependent, a ROC curve was generated for each level of SNR.

Detector Performance Verification

To assess the performance of each auto-detection routine, the probability of detection was evaluated during all possible noise conditions. The effectiveness of detecting blue whale “A” and “B” calls using the matched filter detectors was assessed by visually reviewing 48 hours of data for “A” calls and 120 hours for “B” calls, each containing various levels of ambient noise commonly found. Spectrograms (Fast Fourier Transform (FFT) with a sample duration of 0.5 – 1.0 seconds, a 96% overlap, and a Hanning shading window) of the data were visually scanned for the signals. The visual survey provided a ground truth to evaluate detector performance. The detectors were scored on the number of correct, missed, and false detections.

Data Analysis

Daily rates of blue whale vocalizations were tested for annual and seasonal variation. Rates were compared using a two factor analysis of variance (ANOVA) to test for any difference between the mean call rates among years and seasons. To maximize the usage of the available data, seasons were divided into two subcategories, summer, from the beginning of May to the end of August, and winter, from the beginning of November to the February. Annual categories were defined as a summer/winter pair.

Any presence of diel variation was tested between the categories dawn, noon, night, and dusk. The categories were defined as follows: dawn from 30 minutes before sunrise to 2.5 hours after, dusk from 2.5 hours before sunset to 30 minutes after, noon was the daylight time between dawn and dusk, and night was the time between dusk and dawn. The United States Naval Observatory (USNO) published sunrise and sunset times for Point Sur, California were used to define the categories for each day. A one-factor ANOVA was used to test the difference among the mean call rates for the categories.

The time interval between a call and next-occurring call were investigated for any patterns present in a blue whales calling sequence. The frequencies of occurrence of call-to-call intervals were compared to examine any relation between the "A" and "B" call patterns. By measuring the frequency of occurrence of time intervals less than an average call length, these histograms also revealed the detector's ability to resolve overlapping calls.

Given that much of the information about the specification of the SOSUS array remain classified, estimating range of vocalizing blue whales could not be performed by conventional calculations based on received level and transmission loss. However, one method may be useful in estimating trends in the proximity of blue whale signals without the knowledge of the hydrophone's specifications. Because the "B" call waveform is robust, the major factor governing the peak level of the cross-correlation output from the detector is the source level of the call. The greater the received SNR, the greater the cross-correlate peak. If we assume that blue whales produce signals at a constant source level, then we can get an index of the proximity of the signals based on the transmission loss model for a blue whale call (Hager 1997). Greater peak correlation values signify a vocalizing whale that was closer to the hydrophone. The mean peak correlation value was calculated and used to assess the trends in proximity of vocalizing whales to the hydrophone. A Kolmogorov-Smirnov test was used to test for significant variation between the means and distributions of the seasonal categories.

RESULTS

The effectiveness of the matched filter detector was evaluated, and ROC curves were created for "A" and "B" calls. Each ROC was divided into 15 SNR categories of 0.5 bins (for instance 1-1.5, 1.5-2, etc.) for the "A" call and 12 categories with 1-unit bins (1-12 SNR) for the "B" call (Fig. 7). The "A" call had less frequent occurrences of high SNR and more instances of SNR values less than 2; therefore, ROC curves were divided into SNR category increments of 0.5 to generate more data points to evaluate the probability of detection. The "B" call had more frequent occurrences of all SNR categories from 0 to 12, therefore SNR category increments of 1 adequately defined the probability of detection for a p(FD) of 0.3%. With the ROC curves (Fig. 7), the probability of detection was plotted against the probability of false detection. The greater the SNR, the better the detection performance was for both calls.

Due to various system outages, 12,877 hours of data were recorded from the beginning of 1998 to June, 2000. The "A" and "B" call detectors were used to find all calls present in the entire available data set. For each call counted, the probability of detection was measured based on the ROC, at a fixed p(FD) of 0.3%. The numbers of calls per day were simultaneously plotted with the weighted mean average probability of detection for that day (Fig. 8). Blue whale "A" and "B" calls were detected year-round. Overall 100,700 "A" calls and

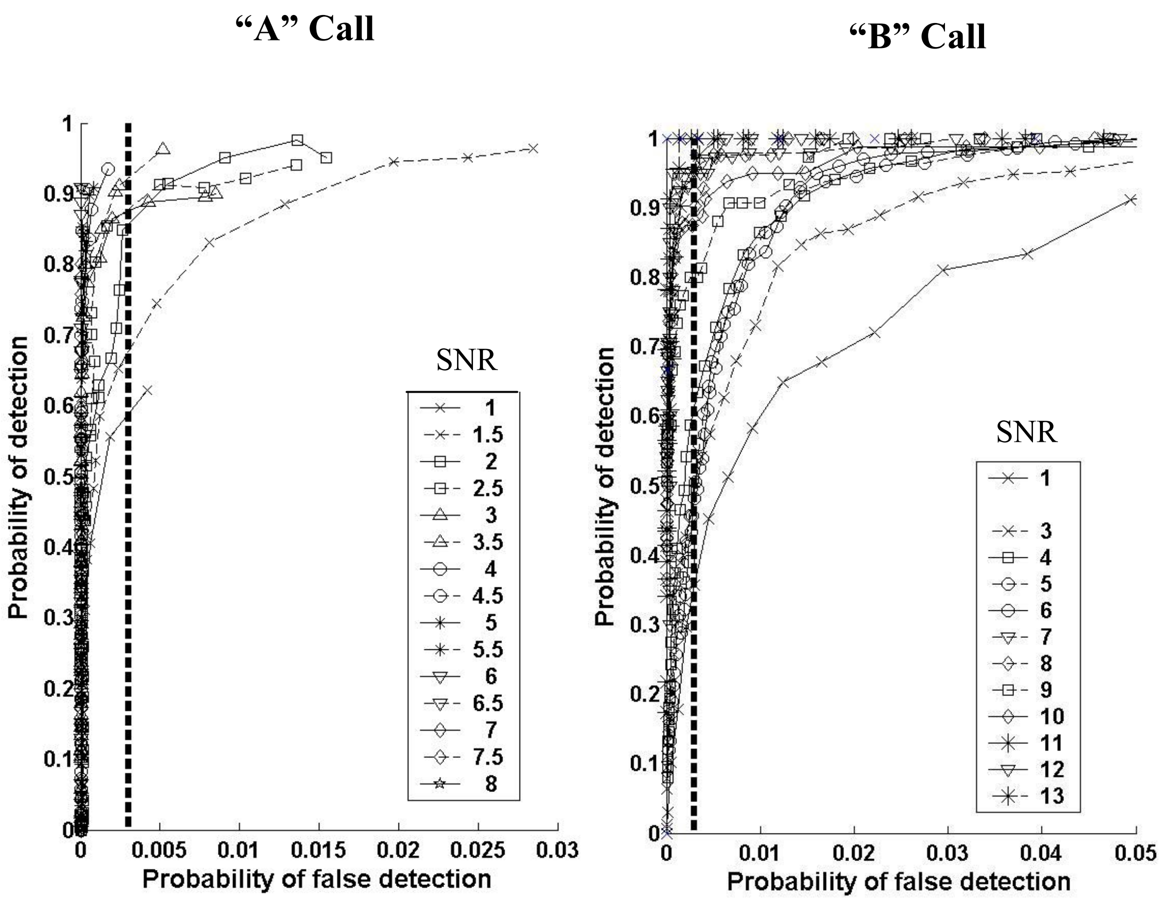

Figure 7. The Receiver Operator Characteristics (ROC) for both the "A" and "B" call detectors. As SNR (Signal to Noise Ratio) increased so did the probability of detection. A fixed false detection rate, p(FD), of 0.3% was selected as the constant, therefore, the probability of detection determined by SNR.

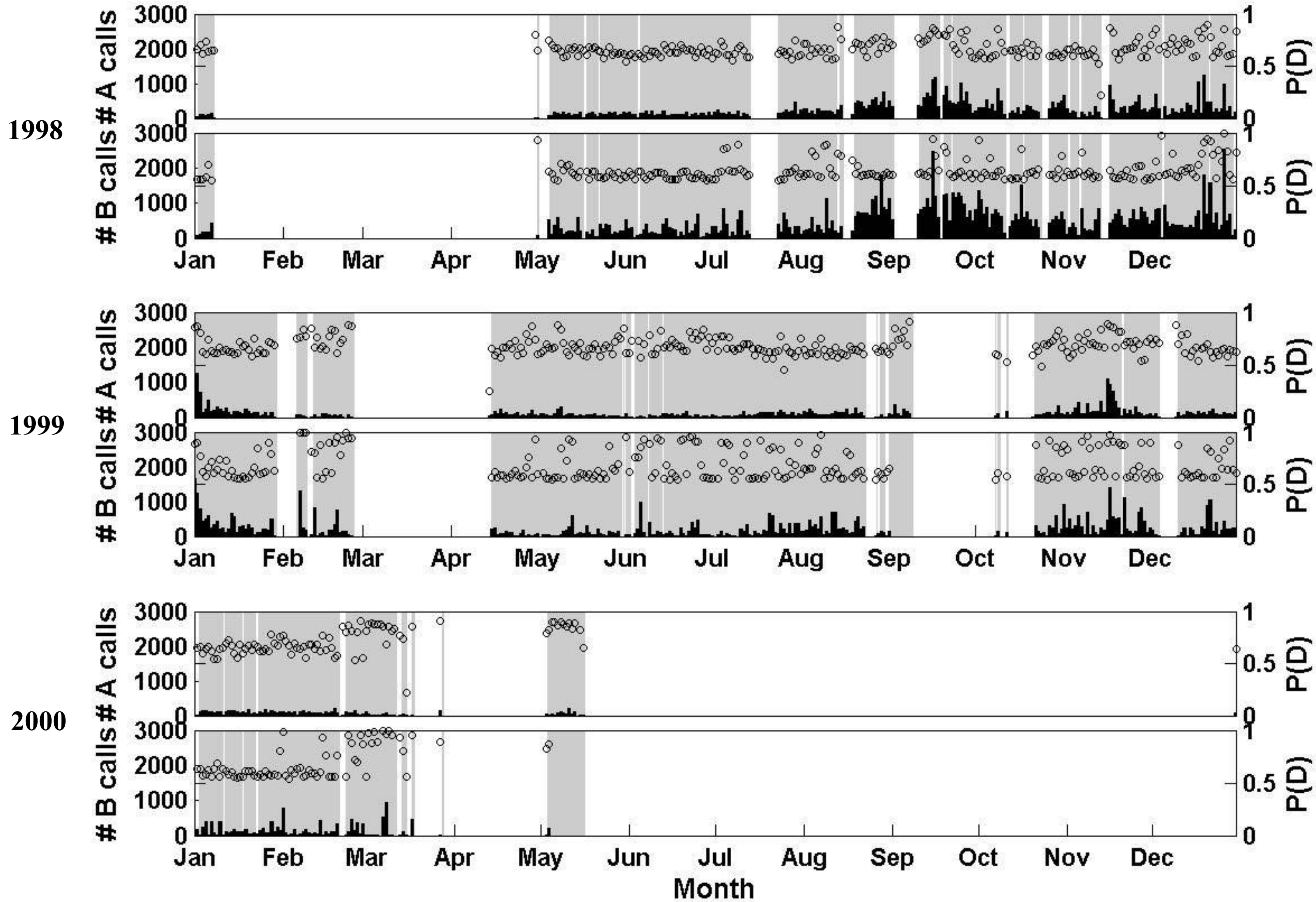

Figure 8. Number of “A” and “B” blue whale calls per day detected (black bars) from 1998 to 2000. Shaded regions represent when data were collected. Circles represent the weighted mean average of p(D) at a fixed p(FD) of 0.3%.

176,585 “B” calls were found. For each day, anywhere from 0 to 1,300 “A” calls and 0 to 2,500 “B” calls were detected. The mean probability of detection was 0.708 ± 0.195 for the “A” calls and 0.697 ± 0.172 for the “B” calls at a p(FD) of 0.3%. The variability in the probability of detection is a result of the variability in the SNR, where an increase in SNR resulted in an increase p(D). A large number of calls were detected during mid-August through early October 1998 (21,244 “A” and 39,269 “B” calls with a peak of 1,770 “A” and 2,477 “B” calls on September 16) and around late November 1998 through January 1999 (10,351 “A” and 16,760 “B” calls with a peak of 985 “A” and 2,530 “B” calls on December 27). Another increase in the number of calls detected occurred during late November through early December 1999 (5,282 “A” and 7,890 “B” calls with a peak of 949 “A” and 1,400 “B” calls on December 17). During April through July the number of calls per day ranged from 0 to 463 “A” and 0 to 1,141 “B” calls.

A significant difference was observed in mean call rates between seasons and years with no significant interaction between the two categories (Tables 1 and 2). More calls were detected during winter than summer, with more calls detected during 98/99 than 99/00 (Fig. 9). Blue whale calls were detected less often during the summer months of May to mid-August in 1998 and 1999. Annual and seasonal variation in “A” and “B” call rates followed similar trends. Call rates of “A” and “B” calls were correlated for seasons and years (Table 3).

Table 1. “A” call two factor ANOVA for seasonal (summer/winter) and annual variation (1998/1999 or 1999/2000).

Source	df	F	P
Year	1	28.17	<0.001
Season	1	20.67	<0.001
Year X Season	1	0.82	0.364
Error	490		

Table 2. “B” call two factor ANOVA for seasonal (summer/winter) and annual variation (1998/1999 or 1999/2000).

Source	df	F	P
Year	1	47.33	<0.001
Season	1	15.35	<0.001
Year X Season	1	1.76	0.185
Error	438		

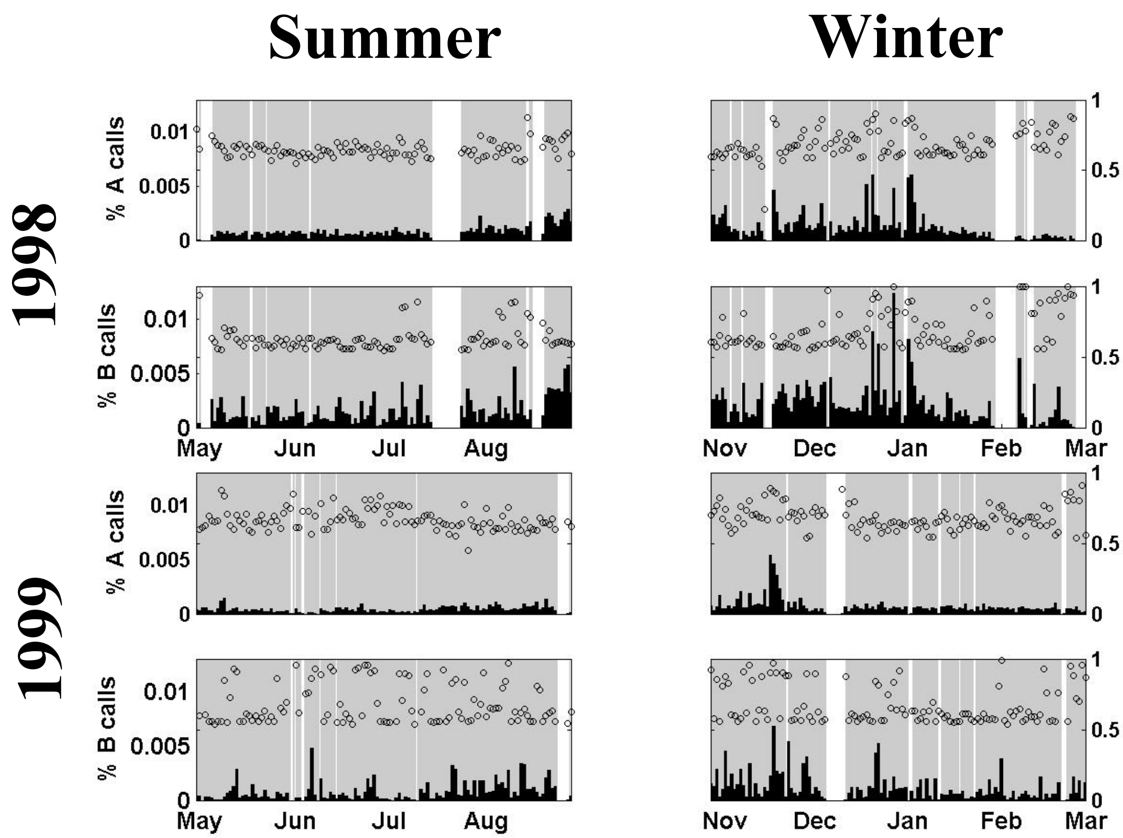

Figure 9. Annual and seasonal call rates (percent occurrence normalized among seasonal categories and among call types) for “A” and “B” calls of blue whales off central California (black bars). Circles represent the weighted mean average of p(D) at a fixed p(FD) of 0.3%.

Table 3. Cross correlation results of the comparison with the “A” and “B” call rates.

Summer 98	Winter 98-99
0.85	0.85

Summer 99	Winter 99-00
0.68	0.70

When looking at all of the data, no apparent pattern appeared among the four categories, dawn, noon, dusk, and night (Fig. 10). For each time category, the mean call rate per hour with one standard deviation was plotted simultaneously with the weighted mean probability of detection (Fig. 11). No significant difference in mean call rate among the diel periods was found (Tables 4 and 5). However, each of the categories had a large standard deviation. The “A” and “B” calls exhibited similar trends in diel variation.

To investigate any pattern in call-to-call interval variability, the frequency of occurrence of time intervals between a call and the next call were tallied in 1-second bins (Fig. 12). For the “A” call, two major peaks were found. One occurred at 18 seconds and the other occurred at 126 seconds. The “B” call had three major peaks. They occurred at 3 seconds, 45 seconds, and 126 seconds. These occurrence peaks suggest that there is a pattern present in call-to-call interval and that a relationship between “A” and “B” call patterns may exist at 126

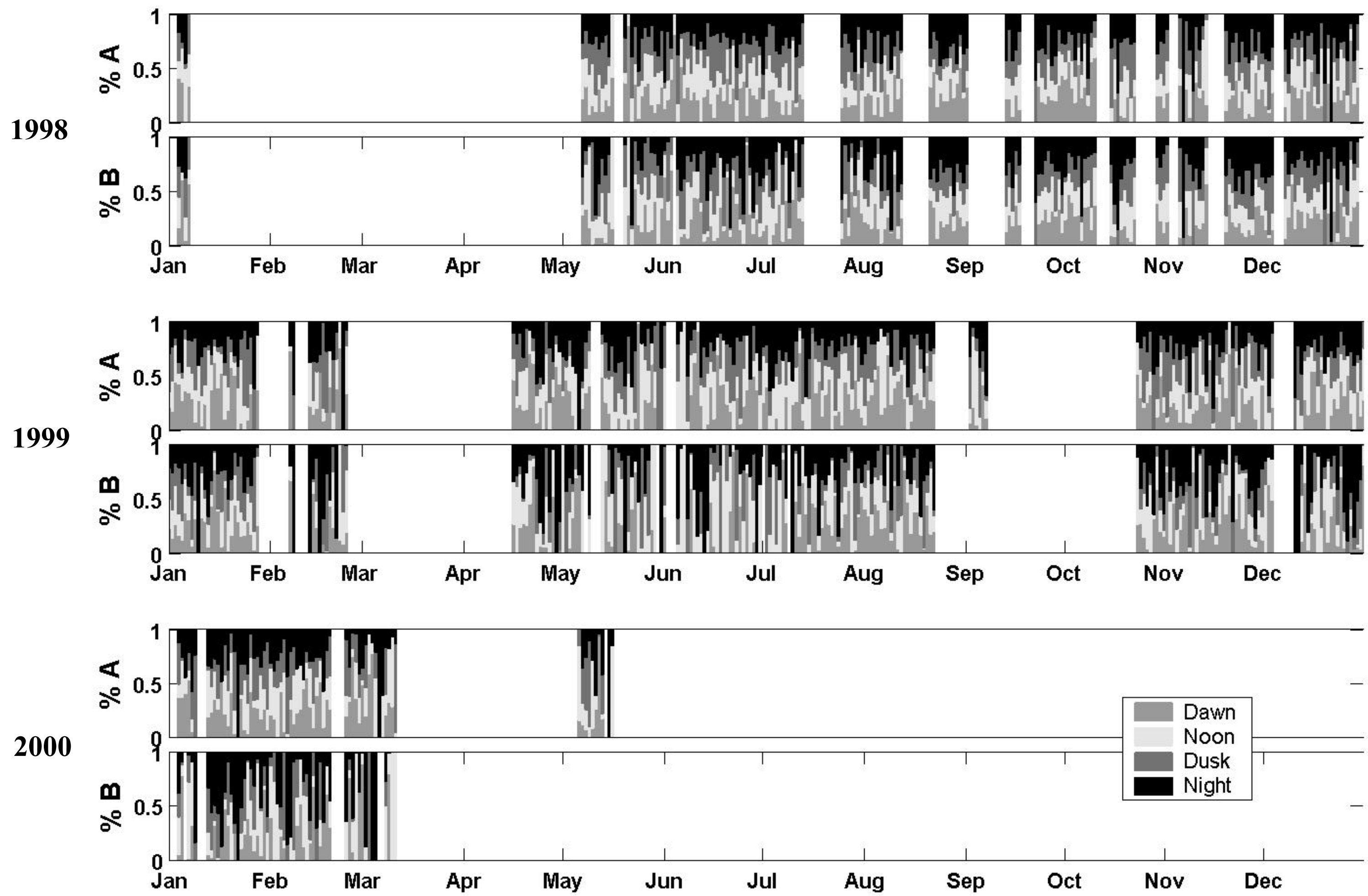

Figure 10. Diel variation in daily “A” and “B” call rates (percent occurrence of calls within each diel category).

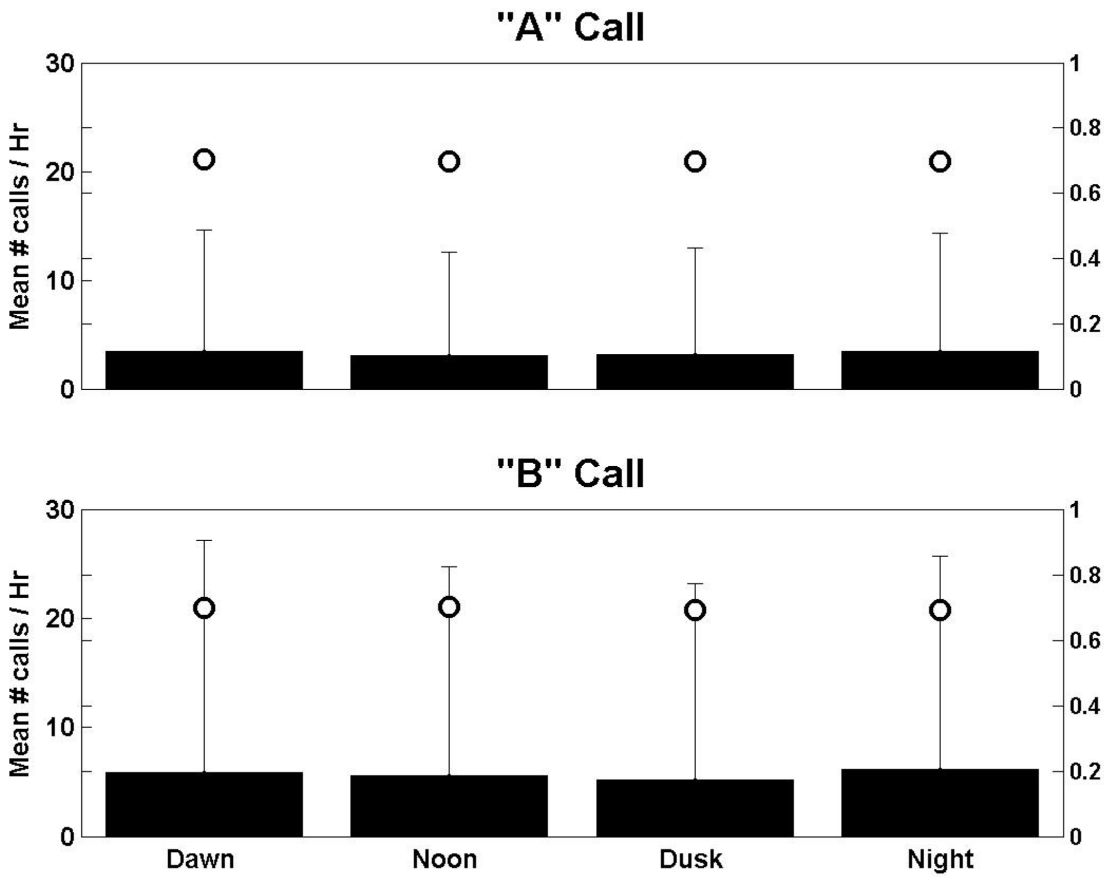

Figure 11. Mean number of calls per hour during dawn, noon, dusk, and night. Error bars represent one standard deviation. The circles represent the mean probability of detection [p(D)] at a fixed p(FD) of 0.3%.

Table 4. “A” call one factor ANOVA results for diel variation (dawn from 30 min. before sunrise to 2.5 hours after, dusk from 2.5 hours before sunset to 30 min. after, noon was the daylight time between dawn and dusk, and night was the time between dusk and dawn).

Source	df	F	P
Diel Category	3	1.22	0.3
Error	1948		

Table 5. “B”call one factor ANOVA results for diel variation (dawn from 30 min before sunrise to 2.5 hours after, dusk from 2.5 hours before sunset to 30 min. after, noon was the daylight time between dawn and dusk, and night was the time between dusk and dawn).

Source	df	F	P
Diel Category	3	1.22	0.3
Error	1852		

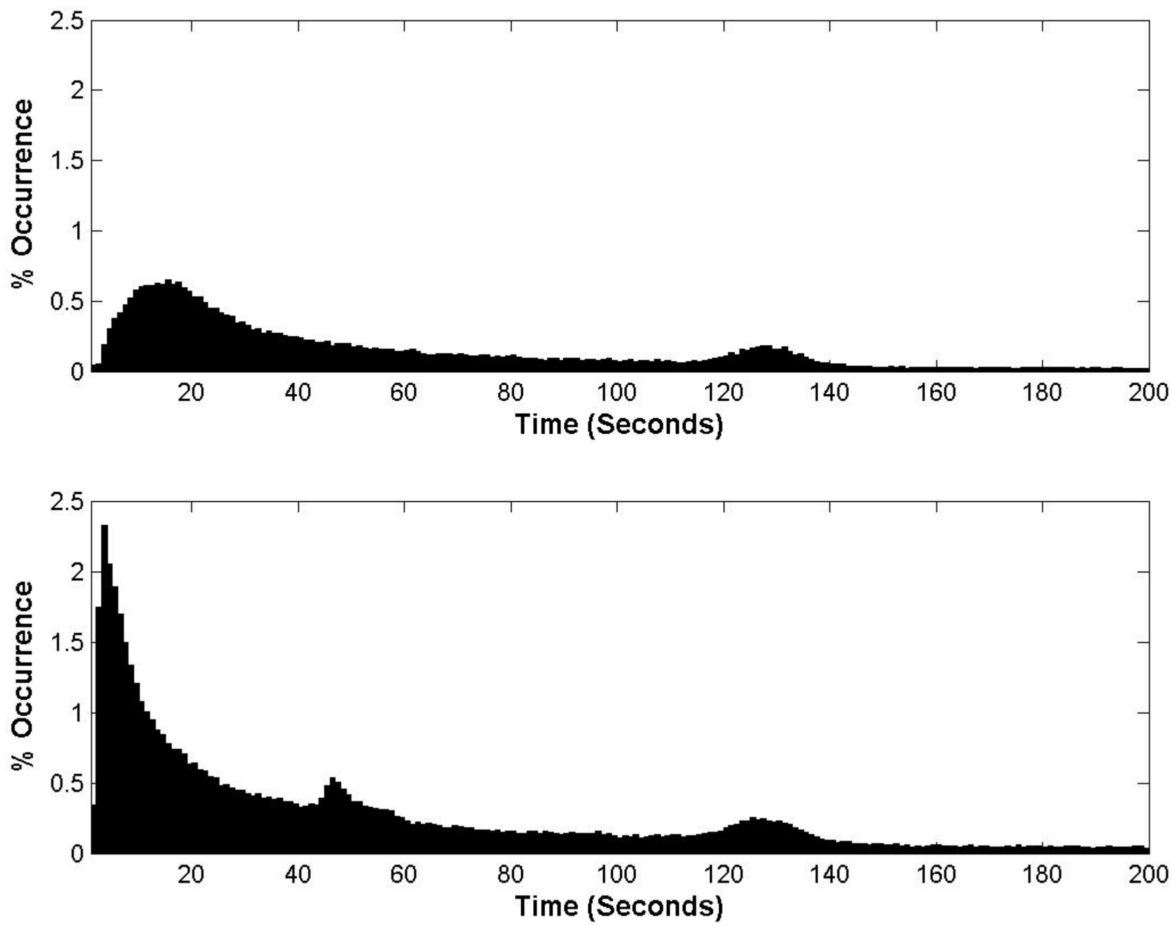

Figure 12. A frequency histogram of the interval between calls for "A" and "B" call of blue whales. The peaks of the "A" call (upper) at 18 and 126 seconds, and the "B" call (lower) at 3, 45, 126 seconds suggest there is a pattern present in the vocalization.

seconds. The region less than the average call length represents overlapping calls. The average call length for a sample of 336 "A" calls was 18.6 seconds (SD = 2.9 seconds). The average "B" call length from a sample of 218 calls was 10.3 seconds (SD = 1.5 seconds). The "B" call detector was able to detect overlapping calls up to a minimum of 3 seconds, which was represented by a distinct drop in frequency of occurrence below that value. The "A" call detector did not perform as well, which was signified by the lack of a distinct cutoff.

A frequency histogram of the peak correlation value and the mean for each seasonal category from summer 98 to winter 99/00 shows the proximity distribution of the blue whale calls detected (Fig. 13). Lesser peak correlation values were more frequent, indicating that most calls were distant. The winter 98/99 mean peak correlation value was significantly greater than the other seasons. Significant differences were found between all periods except between summer 99 and winter 99/00 (Table 6). Assuming a constant source level, blue whale "B" calls were heard in closer proximity to the hydrophone during winter 98/99.

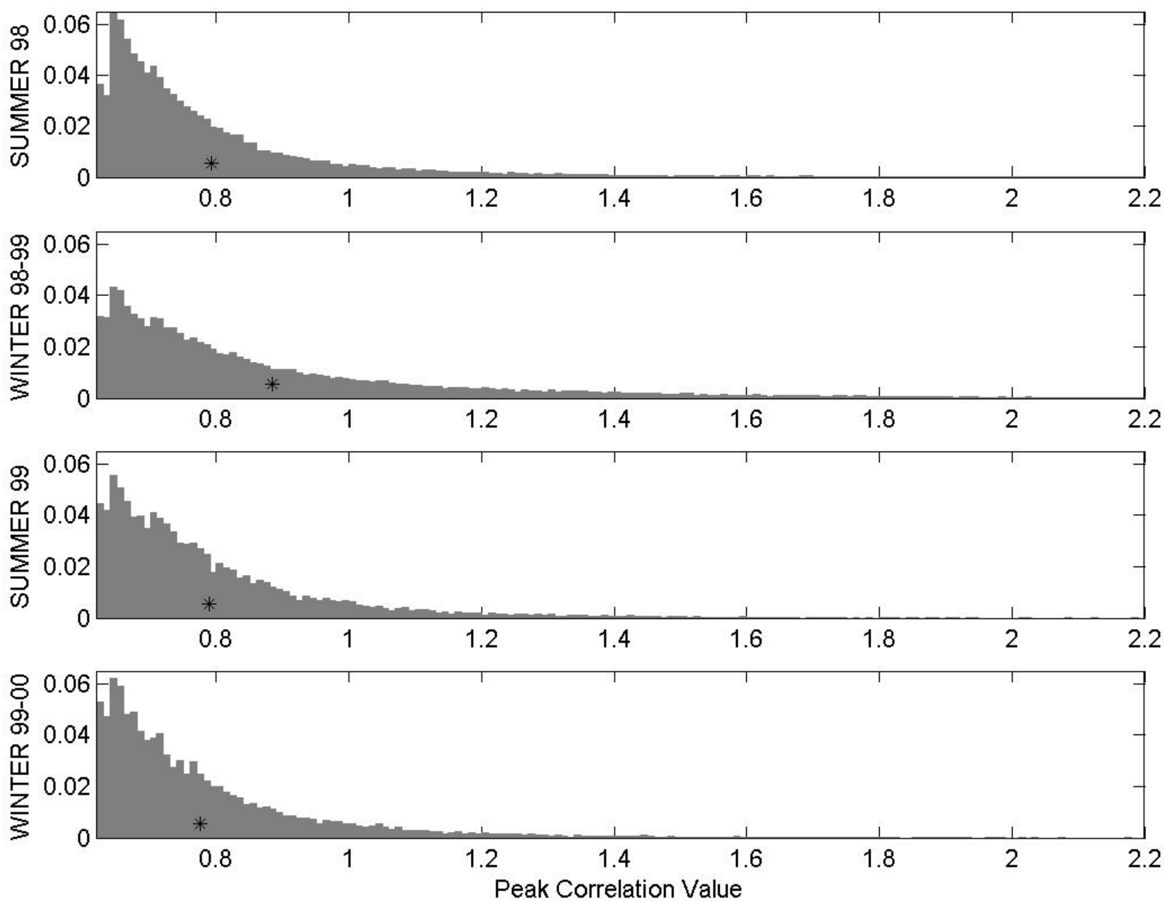

Figure 13. A histogram of the frequency of occurrence of peak correlation values. Assuming a constant blue whale source level, the greater peak correlation values represent vocalizations in closer proximity to the hydrophone.

Table 6. Kolmogorov – Smirnov test of range variation among seasonal categories.

	Summer 98	Winter 98-99	Summer 99	Winter 99-00
Summer 98	**1**	**0.0005**	**0.0001**	**0.0001**
Winter 98-99	**0.0005**	**1**	**<0.0001**	**<0.0001**
Summer 99	**0.0001**	**<0.0001**	**1**	**0.6579**
Winter 99-00	**0.0001**	**<0.0001**	**0.6579**	**1**

DISCUSSION

Evaluation of Automated Detector Performance

The "B" call matched filter detector, with a probability of detection average of 70%, performed well. The waveform contains unique information (magnitude and phase) that is easily exploitable by the matched filter. In this case the optimal detector used an ensemble mean of a set of deverberated calls as a matched filter. The performance of the "A" call detector using a deverberated call as a matched filter did not perform as well. This is not unexpected because the "A" call waveform has less information (magnitude only). To determine what factors contributed to the poor detection, a synthetically generated "A" call as the matched filter was evaluated on a subset of data. With the synthetic filter, I was able to adjust features of the signal and evaluate its performance. Pulse width, pulse spacing, number of pulses, and weighting were all examined to find the values that produced the greatest correlation peak value. Pulse spacing was the most important feature that affected detection performance. The deverberated signal had the optimal pulse spacing; however, it also had significant noise in between the pulses. Additional ensembles of deverberated calls would reduce this noise to zero. This inherent noise in the deverberated matched filter weakened the correlation. Therefore, using a synthetic matched filter with zero noise was a better choice for a matched filter. The matched filter synthetic “A” call, performed just as well as the “B” call matched filter (average of 70% probability of detection).

When evaluating the performance of the “A” call detector, it was noted that some ships with broad band noise near 90 Hz caused false detections. Other ships produced a signal in the 52 Hz band which appeared similar in structure to the “B” call. Basing the detector on a fixed false detection rate maximized the probability of detection during increases in noise such as when ships passed. With multiple ships passing the OAO each day, it was very important to reduce these false detections and determine the extent of the reduction in the probability of detection.

To keep the detector error at a fixed rate, the p(FD) was held constant. A p(FD) of 0.3% was selected for both detectors to keep the probability of false detections as low as possible due to the large amount of data. The probability of false detections was based on the total number of possible detections over the time scale of all the data; therefore, it becomes more important to keep this rate low with larger amounts of data. It was determined that holding the p(FD) at a fixed low rate was important in marine mammal population density estimation. In general, it would be better to underestimate population size rather than overestimate it, when regarding threatened species.

Annual, Seasonal, Diel, and Call Rate Variation

The “A” and “B” call detectors were evaluated and used to find all possible blue whale calls in all available data off Point Sur, CA from 1998 to 2000. At a fixed false detection rate, daily weighted mean probability of detection varied due to changes in SNR. When the ocean was noisy, such as when ships passed by the array or when a storm was in the area, the detector performance decreased. Whales vocalizing at a distance would not be detected due to the lower SNR. At a fixed false detection rate, an SNR dependent threshold accounts for this decrease in the probability of detection. This can be useful in determining optimal and poor recording conditions for blue whale detection, or merely the distance of the whale to the hydrophone if detected.

The hypothesis that increased number of calls detected indicates increased numbers of vocalizing blue whales was evaluated by comparing the variation in call rates detected to published visual surveys of local rorqual density. Seasonal trends have been found in blue whale population abundance off central and southern California (Calambokidis *et al.*, 1990; Barlow, 1994, 1997; Calambokidis and Steiger, 1994; Benson *et al.*, 2002). From visual surveys, blue whales were most abundant off central California during fall (Calambokidis *et al.*, 1990; Barlow, 1994, 1997; Calambokidis and Steiger, 1994; Benson *et al.*, 2002). During spring and summer, blue whales were more abundant in southern California (Mate *et al.*, 1999; McDonald *et al.*, 2001). Blue whale calls were detected almost year round at the OAO, with the greatest number of calls heard during fall and winter. The reduced number of calls heard during spring and summer indicate that blues whales were not as abundant as in fall and winter. Similar seasonal trends in blue whale call abundance were found during a separate study of the SOSUS stations in the Pacific (Watkins *et al.*, 2000) and by Stafford *et al.* (2001) in the North Pacific. Compared with 1999 there was an increase in rorqual density in Monterey Bay during the end of 1998 (Benson *et al.*, 2002). It was hypothesized that during the end of the 97/98 El Niño, whales were forced to search for food in upwelling regions along the coast (Benson *et al*., 2002). It also has been hypothesized that male blue whales tend to vocalize in food rich regions (McDonald *et al.*, 2001). If blue whales vocalize more often in productive areas and the only productive areas are near shore during the 97/98 El Niño (Chavez *et al.*, 2002), then I would expect more vocalizations in fall 1998. I found more blue whale calls were detected off central California during the end of the 97/98 El Niño than the following year. Based on these similarities in trends between visual surveys and the call rate variations found, it is suggested that over a long-term study, blue whale call abundance is a good index of population abundance. If only male blue whales vocalize, this method of measuring population abundance does not measure the female population.

Using the blue whale calls as an index of population abundance, the recordings from the OAO indicate there were more blue whales off California during 1998 than 1999, and blue whales were more commonly found during fall and winter than spring and summer. Blue whales were not thought to be present off central California during winter. However, a large number of calls were detected, at high probability of detection, during December and January 1998 and November 1999. This indicated that blue whales were still present off central California during the winter, perhaps moving further off shore out of visual survey range. Visual surveys do not occur often during the winter because of the inclement weather. Acoustic surveys from the OAO could provide insight into blue whale abundance during this time.

When considering the entire dataset, no evidence of consistent diel variation was found. Blue whale calls were found during all periods of the day. The large standard deviation indicates that there is a large amount of variability in the number of calls per hour in each diel category. Stafford *et al.* (1999) found that vocalizing blue whales in the eastern tropical Pacific exhibited diel variation with more calls heard during dawn. Some evidence of this diel variation can be seen when examining a limited amount of the OAO data. It may be possible that the diel variation found is non-stationary, sometimes suggesting diel variation is present and sometimes not. It also may be possible that diel variation is always present, but changes equally in both directions and was inadvertently averaged out. Long-term acoustic data can be important in examining such periodic trends.

Though similar trends in call rate variation were found in “A” and “B” calls, about half as many “A” calls as “B” calls were found. One possible explanation for this may be that blue whales produce more “B” calls than “A” calls. The blue whales’ call-to-call interval variability exhibited a definite pattern. There was a unifying pattern interval at 135 seconds between the “A” and “B” call indicating that they were related at this interval. This possibly represents the “A-B-A” or “B-A-B” pattern sequence commonly seen in the data. The increased frequency of occurrence at the 45-second interval in the “B” call may be the “B-B” pattern interval also commonly observed. All of the call-to-call intervals less than the length of “A” and “B” calls represent overlapping vocalizations from multiple whales. The “B” call detector was able to resolve and identify individual calls up to 3-second interval apart. This ability to resolve closely overlapping calls was not present for the “A” call. It was not surprising that it was difficult for the matched filter to resolve between overlapping pulsed sequences.

Using basic common knowledge of the physics of sound propagation one can get a sense of the proximity of a vocalizing whale from a single hydrophone. The evaluation of the peak correlation values for each detection can be a good means of estimating the proximity of the blue whale vocalizations to the OAO if one assumes that blue whales vocalize at a constant source level, and the signal type has little variation. At an assumed source level, the further away a vocalizing blue whale was, the lesser its received signal strength and corresponding peak correlation value. In this study this was the only viable means of estimating the range without knowledge of the hydrophone sensitivity, which would allow calculation of received pressure levels and extrapolation distances. Using the “B” call’s peak correlation values and assuming a constant source level, winter 98-99 had more vocalizations detected in closer approximation to the hydrophone than any other season. This is consistent with the hypothesis by Benson *et al.* (2002) that whales were forced to search for food in nearshore upwelling regions at the end of the 98-99 El Niño.

Although the distribution of blue whales nearshore along California is fairly well documented (Calambokidis *et al.*, 1990; Barlow, 1994, 1997; Calambokidis and Steiger, 1994; Benson *et al.*, 2002), our perception of the distribution is based on limited survey efforts. Not much is known about blue whales further offshore and in the region between Monterey and Santa Barbara, especially during winter when weather conditions are too poor for visual surveys. Long-term passive acoustic detection may be useful in augmenting these survey gaps. Utilizing pre-existing SOSUS arrays to acoustically survey blue whales is a cost effective means of continuously surveying a large area. In future research the addition of more hydrophones can extend the survey range. Visual surveys have historically been conducted for many years. The results from these visual surveys provides a baseline reference for interpolating acoustical survey data; therefore, the integration of visual and acoustic surveys must be continued in order to continuously monitor blue whale abundance.

SUMMARY

Long-term passive acoustic detection of blue whale vocalizations presents a promising means of studying regional abundance of whales. One can monitor populations from a single location over a vast survey area (Chiu *et al.*, 2002). Former SOSUS bottom-mounted arrays are a useful and economic means of recording and spatially tracking blue whale vocalizations. From long-term recordings we are able to observe annual, seasonal, and diel variations in vocal activity. These trends may be useful in determining local male blue whale abundance.

The matched filter detector was an effective means of detecting blue whale calls. Using an ensemble mean of a set of deverberated signals as a reference for detection was not as effective at detecting "A" calls as it was at detecting "B" calls. The "A" calls' detection performance may be improved upon by using a greater number of calls in the "deverberated" model of the "A" call. A synthetic reference signal performed better as an "A" call detector. Using an automated detector instead of visually inspecting the data reduced the processing time from years to 3 months on a fast CPU.

Blue whale vocalizations were detected more often during 1998 than the subsequent years with most vocalizations heard during late summer to early winter. During late summer/early winter of 1998, more vocalizations were heard

closer to the hydrophone than any other season. These trends were similar to those found by Benson *et al*. (2002) conducting visual surveys in Monterey Bay. This indicates a correlation between the abundance of blue whales and the abundance of vocalizations detected. With passive acoustics, weather is less a limitation than using visual surveys. At the end of Benson's survey period in November 1998, I detected vocalizing whales well into January 1999. Based on the correlation of whales to vocalizations, I suggest that blue whales were still present off the central California coast.

In future implementations, the detection methods chosen could be implemented in real-time as the data is being collected and made publicly available. This could be useful in recognizing trends in the data as they occur. This could aid in mitigation of the Marine Mammal Protection Act and be used in the Monterey Bay National Marine Sanctuary, limiting potential harm during seasonal increases in local whale population density. Though this study is with blue whales, this method also may be easily applied for fin whales. Fin whale population density estimation based on their vocalizations has already been investigated on former SOSUS arrays off Hawaii (McDonald and Fox, 1999).

Future work in correlating visual survey with acoustic survey will enhance our understanding of the relationship between these two survey methods. The vocal behavior of individual blue whales needs more study. An expansion of visual surveys in the OAO's detection range could help validate the correlation between vocalizations detected and the presence of an animal. Future declassification of additional SOSUS arrays would allow for and provide a better spatial representation of the vocalizations heard. This would provide information on the locations and movements of blue whales along the coast. With the location of the calls heard, we would be able to track individual animals, measuring the average duty cycle of a vocalizing whale, which would allow for estimation of the number of vocalizing blue whales. Studies on what proportion of the blue whale population vocalizes would provide a factor that could be used to estimate population from acoustical surveys at SOSUS stations.

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