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14. ABSTRACT This report describes the research funded by the Office of Naval Research (grant # N00014-00-D-0043 D012) aimed at assessing marine mammal populations in prime areas of Naval interest: the Southern California Offshore Range (SCORE). Acoustic recordings and shipboard surveys were employed to study marine mammal behavior and populations. The ultimate goal of these studies is to determine the potential impacts on the marine mammals from Naval activities.
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University of California,  
San Diego

**Final Report for ONR # N00014-01-D-0043 D12  
"Marine Mammal acoustic monitoring and habitat  
investigation, Southern California Channel Island region"**

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Acoustic studies of marine mammals were the primary concern of the Scripps Institution of Oceanography, with John Hildebrand as the project principal investigator, and Sean Wiggins as the co-principal investigator. Erin Oleson conducted research on this project as the primary component of her dissertation in biological oceanography. Additional Scripps graduate student who contributed to this project were Jessica Burtenshaw, and Melissa Soldevilla. Scripps staff members that helped with this project were Allan Sauter, Chris Garsha, Graydon Armsworthy, Kevin Hardy, and Harry Lam.

Visual and tagging studies of marine mammals were the primary concern of the Cascadia Research Collective, with John Calambokidis as the principal investigator, and additional help provided by Kristin Rasmussen, Todd Chandler, Annie Douglas, Erin Falcone, and Randy Luper. Acoustic tag development was done in collaboration with Bill Burgess of Greeneridge Sciences Inc.

The Science Applications International Company, under principal investigator Michael Porter, provided acoustic data processing and modeling. Additional SAIC investigators were Chris Tiemann, Ahmad Abawi, Martin Siderius, and Paul Hursky.

The Naval Post-Graduate School collaborated in data collection within the SCORE range, and usage of range facilities. Principal investigator for this work was Curt Collins, along with co-principal investigator Chin-Sang Shiu, and Chris Miller.

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## Executive Summary

Acoustic techniques have the potential to assess marine mammal populations in areas of naval interest such as within the Southern California Offshore Range (SCORE). We report on a multi-year study of marine mammal presence within the SCORE range using both acoustic and visual techniques. The primary objective of this project was to develop methods for acoustic monitoring of marine mammals. We compared acoustic methods against conventional ship based and aerial visual methods for estimating marine mammal seasonality and relative abundance.

Environmental assessments are made to determine the potential impacts to marine mammals from Naval activities. The problem that the Navy confronts in preparing these assessments is a lack of scientific information on marine mammal population dynamics and behavioral ecology. To date, marine mammal assessments have relied on visual surveys. The difficulty and expense of visual surveys, and the low numbers of sightings that they generate has impeded their usefulness for Navy environmental assessment. The technology of passive acoustics has recently been advanced to allow these methods to make a contribution to studies of marine mammal seasonality and relative abundance.

We studied marine mammal populations within the SCORE range using four techniques: (1) aerial surveys, (2) ship-based transect surveys, (3) sonobuoy-based mobile acoustic surveys, and (4) continuous fixed-site acoustic surveys. By combining visual and acoustic methods, we have gained a more complete temporal and spatial coverage than is possible by use of a single approach.

Project milestones were: (1) conduct continuous acoustic recording with the SCORE range, (2) conduct quarterly shipboard visual and acoustic surveys within the SCORE range, (3) conduct quarterly aerial surveys within SCORE, (4) develop new technology and algorithms for the detection and classification of whale calls, (5) estimate whale calling statistics, and (6) conduct technology transfer to the Navy. Cascadia Research Collective was our collaborator for the marine mammal visual surveys, and the National Marine Fisheries Service was our collaborator for the aerial surveys.

Long-term acoustic recording and shipboard visual and acoustic surveys, were accomplished during quarterly shipboard expeditions to the SCORE region. During each of these expeditions visual surveys were conducted, sonobuoy acoustic data were collected, and autonomous acoustic recording packages were serviced. Aerial surveys were conducted quarterly in the SCORE region from spring 2001 to spring 2003. Following a comprehensive review, we discontinued the SCORE aerial surveys, owing to flight dangers, and low numbers of marine mammal sightings.

Two new technology developments from this project were high capacity (1.2 Tbyte) autonomous acoustic recording packages and acoustic recording whale-attached tags. The autonomous acoustic recording packages allowed long-term marine mammal monitoring. With these instruments we were able to select environmental settings appropriate for study of whales within SCORE. Through collaboration with Greeneridge Sciences Inc., we developed and applied a suction cup deployed acoustic recording tag for study of blue whale calling behavior. In

collaboration with SAIC (Michael Porter) we developed new algorithms for automatic detection and localization of calling whales.

We assessed the behavioral context of acoustic calls produced by Northeast Pacific blue whales using visual and acoustic observations along the California coast. We deployed acoustic recording tags, and employed photo-ID, tissue sampling, and acoustic monitoring with sonobuoys to evaluate the relationship between blue whale call occurrence and behavior. Only a small proportion of monitored blue whales produced calls, and these fell into three categories, 1) repeated low frequency pulsed A and tonal B calls or song, 2) irregularly patterned A and B calls, and 3) downswept D calls and highly variable amplitude or frequency modulated calls. A and B calls are produced only by male blue whales, while D calls are produced by both sexes. Song calls are heard from lone, traveling male blue whales, while D calls are heard during foraging, commonly within groups of animals. The precise function of each call type is not understood; however, information on the sex-bias in call production, and the non-acoustic behaviors associated with each call type help us to understand the context of call production and allow more effective use of certain call types to assess population status and habitat associations.

We developed algorithms for automated tracking of whales using arrays of sensors. Pair-wise time-differences in arrival of whale calls as measured by a phase-only correlation process were compared to time-lags predicted by an acoustic propagation model. Differences between measured and modeled time-lags defined an ambiguity surface that identifies the most probable whale location in a horizontal plane around an array. We applied this technique to tracking calling blue whales off the coast of California. The algorithm performed extremely well, providing the capability for real-time, automated monitoring.

Diel and seasonal calling patterns for blue whales were observed in coastal waters off southern California using seafloor-mounted autonomous acoustic recording packages. 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. Night time calling was greater than day time calling, but also showed a minimum between the dusk and dawn calling peaks. These peaks correlate with 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 preys 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 preys are dispersed near the sea surface and foraging is less efficient.

Blue and fin whale call patterns were monitored at Cortez and Tanner Banks in the Southern California Bight from August 2000 to February 2004. Seasonal and diel variation of calls may indicate changing environmental conditions and whale behavior. Three types of blue whale calls were monitored, 1) low frequency (type B) calls occurring in stereotyped sequences, or songs, 2) low frequency (type B) calls occurring in irregular temporal patterns, and 3) downswept (type D) calls. Fin whale downswept calls were also monitored. Blue whale calls were produced seasonally from April to January each year, with type D calls present predominantly early in the season, from April to November, and song and singular B calls predominantly present later in the

season from June to January. Fin whale calls were heard year-round, with a seasonal peak from August to December. Fin whale song character was variable among individuals and over the four year monitoring effort. The peak of acoustic detection for blue whale song calls and fin whale calls is delayed by one to two months from their peak presence observed during visual surveys in the Southern California Bight, suggesting a bias in the visual detection of vocal whales and/or an increase in individual calling late in the season, changes that may be related to reproductive activities. Blue whale D calls precede visual detections, though they have a common seasonal peak and both are thought to connote feeding whales.

Blue whale songs provide a measure for characterizing worldwide blue whale population structure. These songs are divided into nine regional types, which maintain a stable character. Five of the nine song types have been recorded over time spans greater than 30 years showing no significant change in character. The nine song types can be divided into those containing only simple tonal components (high latitude North Pacific, North Atlantic and Southern Ocean song types), those comprised of complex pulsed units in addition to the tonal components (Pacific Ocean margin song types from California, Chile and New Zealand), and those which have the greatest complexity of all and the longest cycling times (Indian Ocean song types from Sri Lanka, Fremantle and Diego Garcia). We suggest that temporally stable differences in song provide another characteristic for comparison with genetic and morphological data when defining blue whale populations. Furthermore, we recommend that when there is a lack of other data or lack of clarity in other data sets, evidence of distinct differences in songs between areas be used as a provisional hypothesis about population structure when making management decisions.

Using acoustic and satellite remote sensing, we have continuously monitored the acoustic activity and habitat of blue whales during 1994-2000. Calling blue whales primarily aggregate off the coast of southern and central California in the late summer, coinciding with the timing of the peak euphausiid biomass, their preferred prey. The northbound movements of the blue whales and primary production are apparent in the acoustic and satellite records, with the calling blue whales moving north along the Oregon and Washington coasts, to a secondary foraging area with high primary productivity off Vancouver Island in the late fall. El Nino conditions, indicated by higher sea surface temperature and lower chlorophyll-a concentrations, are apparent in the satellite record, particularly in the Southern California Bight. These conditions disrupt calling blue whale habitat and alter their presence in primary feeding locations. Remote sensing using acoustics is well suited to characterizing the seasonal movements and relative abundance of the northeast Pacific blue whale, and remote sensing using satellites allows for monitoring their habitat. These technologies are invaluable because of their ability to provide continuous large scale spatial and temporal coverage of the blue whale migration.

There are several ways that the data and results of our project are being transitioned to the Navy and to the SCORE range in particular. First, the raw visual and acoustic marine mammal data that were generated by this project are being included in a marine resources assessment that is being preparing for the Navy's Southern California Operating Area (SOCAL) (Julie Rivers, NAVFAC PAC, personal communication). Our dataset provides the most intensive and comprehensive set of marine mammal observations to date within the SCORE range and surrounding areas. Second, we have developed new technology and algorithms that are finding

application in other Naval ranges. For instance, we are now conducting long term acoustic monitoring, using the tools developed by this project, in the Navy's Quinault Range, located off the coast of Washington. As part of this project we collaborated with the Naval Post-Graduate School in collecting data from the SCORE underwater tracking range hydrophones, as a means for assessing how the installed hydrophones of the SOAR tracking range could be used for marine mammal monitoring. In addition, we helped to raise awareness of the potential for marine mammal tracking with Navy range hydrophones, so that consideration could be given to the potential for future hydrophone installations in the SCORE region, such as the future shallow water test range planned for the Tanner/Cortez Banks region, to be used for tracking marine mammals as part of Navy mitigation and/or monitoring efforts.

## **Objective**

The Southern California Off-Shore Range (SCORE) is a region where naval operations are frequently conducted and where marine mammals are seasonally abundant. Acoustic techniques have the potential to provide an efficient and accurate method for assessing marine mammal populations in areas of naval interest such as within SCORE. We report on a multi-year study of marine mammal presence within the SCORE range using both acoustic and visual techniques. The primary objective of this project was to develop methods for acoustic monitoring of marine mammals within the Southern California Off-Shore Range (SCORE). We compared acoustic methods against conventional ship based and aerial visual methods for estimating marine mammal seasonality and relative abundance. Simultaneous application of these techniques allows their comparison to determine the combination of methods most suitable for long term monitoring of marine mammals. We have created a database for marine mammal presence within SCORE as a planning tool for environmental compliance. We developed autonomous acoustic recording packages, and a low cost acoustic recording tag for monitoring marine mammal calls. Data from the acoustic recording packages allow long-term monitoring of marine mammals calls, and data from the acoustic tag aids in estimation of calling rates for marine mammals, and therefore estimation of abundance from calling statistics.

## **Background**

Environmental assessments are made to determine the potential impacts to marine mammals from Naval activities. The problem that the Navy confronts in preparing these assessments is a basic lack of scientific understanding of marine mammal population dynamics and behavioral ecology. The result is that the Navy must make judgments about the possible impact of at-sea operation on marine mammals, but lacks the scientific data to support these judgments.

Environmental assessments need to describe seasonal distributions and estimate the abundance of marine mammals expected in the region of potential impact. Key areas of Navy concern are regions of concentrated fleet training, such as in U. S. coastal waters and adjacent fleet operating areas. Except in rare cases, the abundance of marine mammals in areas of Navy interest are poorly known. The National Marine Fisheries Service (NMFS) collects data on marine mammal populations for the Economic Exclusion Zone (up to 300 nmi offshore), but these data do not have statistical power to predict marine mammal densities in smaller regions at the spatial and temporal scales of Naval interest.

To date, marine mammal assessment has relied on visual surveys from surface vessels and from the air. The difficulty and expense of these marine mammal visual surveys and the low numbers of sightings that they generate has impeded their usefulness for Navy environmental assessment. The technology of passive acoustics has recently been advanced to allow these methods to make a contribution to studies of marine mammal seasonality and abundance.

## **Materials and Methods**

We are studying marine mammal populations within the SCORE range using four techniques: (1) aerial surveys, (2) ship-based transect surveys, (3) sonobuoy-based mobile acoustic surveys,

and (4) continuous fixed-site acoustic surveys. Simultaneous application of these techniques allows their comparison and correction. Are particular species of marine mammals more easily seen or heard during various seasons? Factors such as sea state affect visual detectability and seasonal calling patterns (e.g. more calls may be produced during the breeding season) affect the efficiency of acoustic detection.

The combination of visual and acoustic methods, allows a more complete temporal and spatial coverage than is possible by use of a single approach. Acoustic monitoring can be conducted relatively independent of daylight and weather, conditions that significantly effect visual surveys. Acoustic techniques have the ability to provide continuous temporal coverage and thus information on seasonal presence, providing data that are difficult to obtain with visual methods.

As part of this project we designed and deployed an autonomous acoustic recording package (ARP). This allowed us to record whale sounds within the southern California offshore area, and design experimental settings to compare visual and acoustic detections. Initially we focused on baleen whales and the recording package recorded with a 1 KHz sampling rate, and was capable of 76 Gbytes of data storage, sufficient for a one-year autonomous deployment. Later in the project we shifted our focus to toothed whales (odontocetes) and developed a recording package capable of 200 KHz sample rates and 1.2 Tbytes of data storage. These recording packages allow us to address questions related to a broader range of species, as the sounds of odontocetes are generally in the 1-100 kHz range..

One key issue for acoustic survey methods is species identification. In this area, much progress has been made on baleen whales. For baleen whale species (e.g. blue, fin, humpback, minke, right), call types are well known. Likewise, these animals have a consistent calling repertoire. For toothed whales there are species with distinctive calls (e.g. sperm, killer), but the variation of call types for others is a topic of current research. Another issue is calling rates; what is the probability of an animal calling during a given time period. Data on calling rates are needed to convert call counts into estimates of animal abundance and seasonality.

Ship based surveys, using both acoustic and visual techniques, were conducted at SCORE quarterly year as part of this project. Ship based visual surveys consist of teams of observers working daylight hours, individually recording sightings and group sizes. Biopsy, photo-identification, and detailed behavioral information, including acoustic tag data were collected at selected times during these surveys. These data provide gender and genetic relations between individual animals, as well as a time history for migrations and associations. Sonobouys were the primary acoustic tool used during the ship based surveys. We used DIFAR sonobuoy processing to provide bearing estimates to marine mammal calls and thereby differentiate calls from different individuals. Arrays of sonobouys were used for call localization.

Fixed acoustic recording systems provide a continuous year-round survey for marine mammal presence. We have deployed up to five seafloor autonomous acoustic recorders within the SCORE region. These continuous acoustic recordings provide data on marine mammal calls, their relative abundance, and their seasonality. Algorithms for automated call recognition and localization have been developed to aid in data processing. This report focuses on mysticete whale call detection and processing, but we have also amassed a database of odontocete calls which will form the basis for additional call detection algorithms for future projects in this area.

Estimating abundance from acoustic recordings requires consideration of the acoustic behavior of whales. We have found that behavioral settings and gender may bias call production. In blue and fin whales, the relative number of calls produced per animal increases in the fall. This may be a reflection of more time spent on developing pairings for breeding, instead of more time spend on feeding activities earlier in the summer. Gender determinations for blue whales suggest that certain call types are exclusively produced by males, implying that these calls play a role in breeding and/or competition for mates. Other call types are produced by both sexes, suggesting a more general function. By collecting data on gender and also the environmental settings in which calls are produced, we are beginning to clarify the contribution of these factors to call production and therefore population abundance estimation.

## **Results and Accomplishments**

Project milestones were: (1) conduct continuous acoustic recording within the SCORE range, (2) conduct quarterly shipboard visual and acoustic surveys within the SCORE range, (3) conduct quarterly aerial surveys within SCORE, (4) develop new technology and algorithms for the detection and classification of whale calls, (5) estimate whale calling statistics, and (6) conduct technology transfer to the Navy.

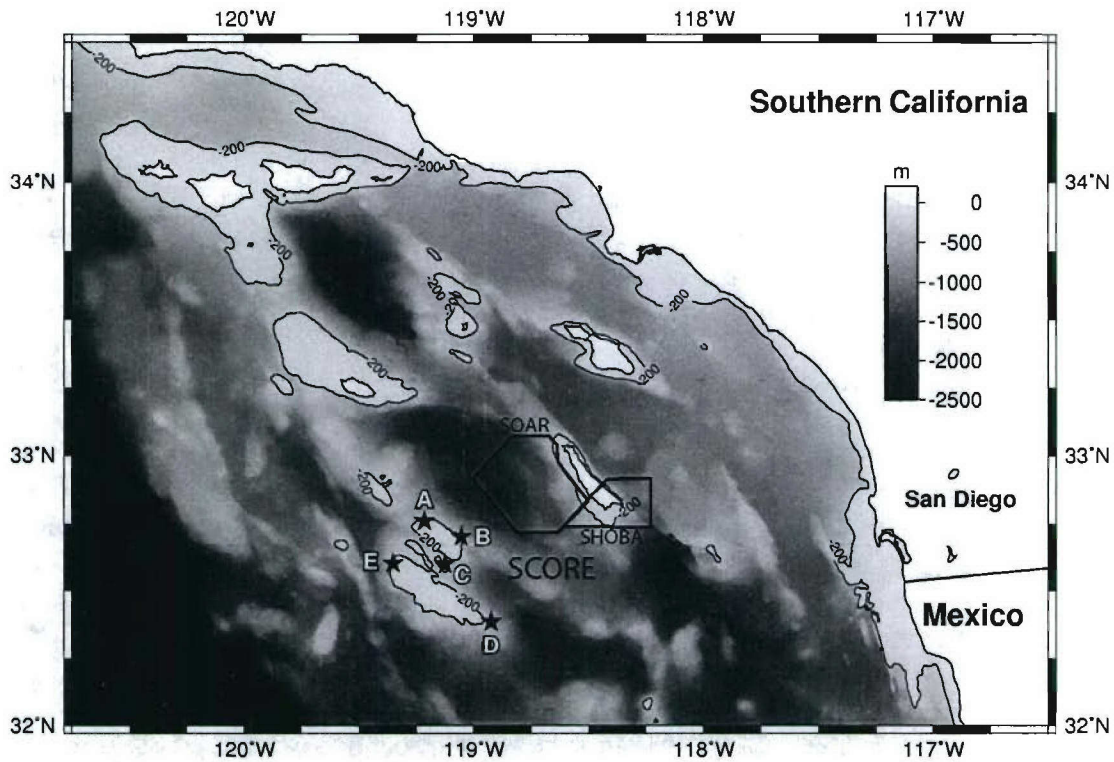
### **Acoustic Recordings and Shipboard Surveys**

Acoustic recording and shipboard surveys were accomplished during shipboard expeditions to the SCORE region which were conducted quarterly throughout the duration of the project. During each of these expeditions visual surveys were conducted, sonobuoy acoustic data were collected, and autonomous acoustic recording packages (ARPs) were serviced (batteries replaced and data downloaded from disc drives). All SCORE missions took place aboard Scripps Institution of Oceanography Research Vessel Robert Gordon Sproul. The detailed activities of SCORE cruises are described in individual cruise reports. The cruise names and dates of these shipboard surveys are given in Table 1.

Autonomous Recording Packages were deployed at up to five locations (Figure 1 and Table 1) around Cortez and Tanner Banks to continuously monitor the marine mammal calls and ambient noise levels in the region. The ARPs recorded with a sampling rate of 1000 Hz.

**Table 1: List of Shipboard Surveys**

SCORE 3	August 19 - 25, 2000;	SCORE 4	October 14 - 20, 2000;
SCORE 5	December 13 - 16, 2000;	SCORE 6	February 19 - 25, 2001
SCORE 7	April 28 - May 2, 2001;	SCORE 8	June 18 - 27, 2001
SCORE 9	August 21- 29, 2001;	SCORE 10	October 22 - 25, 2001
SCORE 11	April 14-18, 2002;	SCORE 12	June 23- July 1, 2002
SCORE 13	August 16-23, 2002;	SCORE 14	November 1-5, 2002
SCORE 15	January 10-14, 2003;	SCORE 16	April 4-7, 2003
SCORE 17	June 28 - July 3, 2003;	SCORE 18	August 15-19, 2003
SCORE 19	October 20-23, 2003;	SCORE 20	February 23-25, 2004
SCORE 21	April 6-8, 2004;	SCORE 22	July 15-23, 2004



**Figure 1 SCORE Study Area in the southern California Bight.** The SCORE Range includes the Southern California ASW Range (SOAR) where Anti-submarine warfare (ASW) training is accomplished using an underwater tracking hydrophone array, and the Shore Bombardment Area (SHOBA) which is used to conduct naval gunfire and special warfare operations. A shallow water test range is planned for the Tanner and Cortez Banks region, west of San Clemente Island, where we placed Acoustic Recording Package (stars) at five separate sites (designated by letters).

**Table 2: Sites for Acoustic Recording Package Deployments in the SCORE region**

Site	Latitude deg	Latitude min	Longitude deg	Longitude min	Depth
A	32	45	119	13	150
B	32	41	119	2	300
C	32	36	119	9	200
D	32	23	118	55	400
E	32	39	119	20	310

Type AN-SSQ 57B (Omni) and 53D (DIFAR) sonobuoys, were used to determine the location of

whales for assistance with visual efforts, as well as for comparison with recordings obtained from the APRs. These sonobuoys are autonomous instruments that transmit a continuous signal back to the ship via a VHF radio. If the same calling whale is detected on two or more DIFAR buoys, it is possible to precisely locate the calling whale by crossing bearings. Broadband omnidirectional 57B sonobuoys were used when odontocetes, with calling frequencies above 4 kHz, were observed.

Experienced marine mammal visual observers from Cascadia Research Collective maintained a watch schedule from sunrise to sunset each day. Three observers were on duty during each two-hour shift, searching the area with 7x50 handheld binoculars and with naked-eye. Observers maintained a watch from beam to bow of both sides of the ship from a height of 5.65 m above the water. When a marine mammal sighting was made, observations were conducted 360<sup>0</sup> around the ship to keep track of moving animals. Weather information, ship position, and the on-duty observers were recorded every 30 minutes. All sightings were noted with sighting number, species, group size, time, position, and bearing and distance of the animal from the ship. Appendix Table 3 lists all marine mammal shipboard sightings collected during this project.

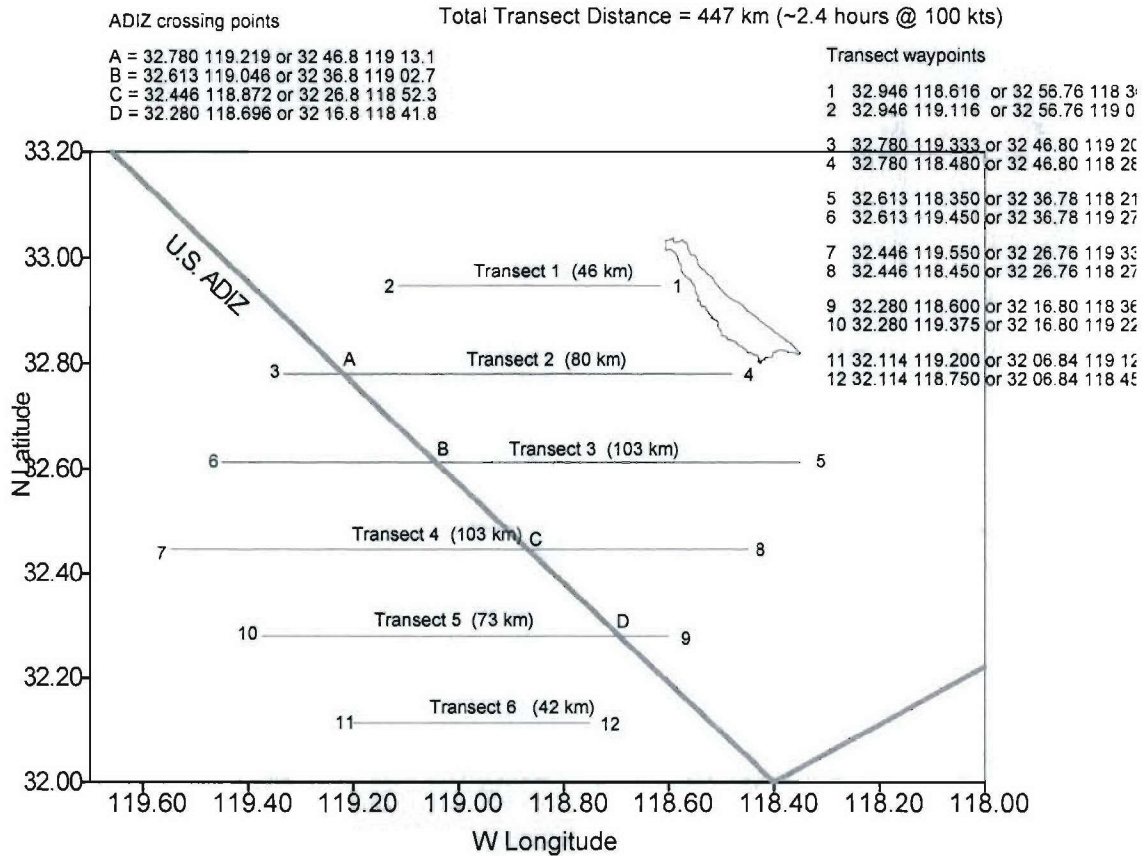
An 18' RHIB (Rigid Hull Inflatable Boat) is launched from the R/V Sproul to obtain biopsy samples from whales, and for a closer approach to animals for photo-identification efforts. Photos were taken for most approaches by the RHIB, and biopsies were obtained whenever possible. All photos are compared to known individual blue whales using the Cascadia Research photo-ID catalog. Biopsy samples were processed by the NOAA Southwest Fisheries Science Center to determine the gender of biopsied animals.

### **Aerial Surveys**

Aerial surveys were conducted at SCORE over a series of transect lines, ranging in length from 25 to 200 km with a total survey area of approximately 12,600 km<sup>2</sup> (Figure 2). In the air, a team of three observers and one data recorder searched for marine mammals at an air speed of 185 km/hr (100 kts). Aerial surveys were conducted on the following dates:

May 14, 2001; June 11, 2001; July 13 & 20, 2001; October 29, 2001; December 18 & 19, 2001; February 10, 2002; April 9, 2002; May 9 & 31, 2002; July 2, 2002; August 15, 2002; December 6 & 23, 2002; March 3, 2003.

Following a fatal accident during a marine mammal aerial survey on the East Coast, NOAA undertook a comprehensive review of all its marine mammal aerial survey activities. As a result of this review, in the spring of 2003, we decided to discontinue the SCORE aerial survey, owing to the distance of our survey lines from the mainland air facilities, and from dangers due to airspace conflicts with military aircraft in the San Clemente Island region. We additionally felt that the low numbers of marine mammal sightings were not yielding sufficient scientific data to justify the flight risks.



**Figure 2. Marine mammal aerial survey transects.**

All aerial survey sightings for our project, including those outside the survey area, can be found in Appendix Table 2. A total of 230 sightings were reported over 16 days of effort. The most commonly sighted animals were California sea lions (*Zalophus californianus*) with a total of 132 sightings.

### Technology and Algorithm Development

A key milestone for our project was the development of new technology and algorithms for the application of acoustic techniques to the study of marine mammals. We have developed new technology for long-term marine mammal monitoring using acoustic techniques by the development of acoustic recording packages (described in the Methods Section above), and through collaboration with Greeneridge Sciences Inc. (Bill Burgess) we developed and applied a suction cup deployed acoustic recording tag for study of blue whale calling behavior. In collaboration with Science Applications International (Michael Porter) we developed a new approach for automatic detection and localization of calling whales. These technological and algorithm developments are described below.

#### Behavioral Context of Blue Whale Calls: Insights from Acoustic Recording Tags

Passive acoustic monitoring of baleen whale calls is a powerful tool for studying their presence and movements (Thompson and Friedl 1982). Blue whales, in particular, produce low

frequency and high intensity calls allowing regional monitoring by single instruments. Northeast Pacific blue whales (*Balaenoptera musculus*) maintain a seasonal annual migration, primarily feeding in the waters off California in summer and fall (Croll et al. 1998), before migrating to waters off Mexico and near the Costa Rica Dome in the winter and spring (Calambokidis et al. 1990, Mate et al. 1999). Blue whale calls can be heard along the entire migration route and at all times of year (Stafford et al. 1999, 2001, Burtenshaw et al. 2004). While calling varies in rate and intensity along the migration route and in feeding areas, we do not yet understand what drives spatial and temporal differences in calling. We do not understand the ecological role of calling for blue whales. By understanding the behavioral context of blue whale calling, we may be able to better understand habitat preferences, social structure, the effects of anthropogenic sound, and the distribution and abundance of populations.

Four blue whale call types have been identified from the northeastern Pacific (Thompson 1965, Thompson et al. 1996). The best described vocalizations consist of a combination of two low frequency long duration calls: A and B. Repeated A and B blue whale call sequences have been classified as song (McDonald et al. in press). It has been suggested that song is produced only by males (McDonald et al. 2001) similar to song production in humpback and fin whales. Blue whales also produce downswept calls, known as D calls (Thompson et al. 1996, McDonald et al. 2001). A fourth class of highly variable frequency modulated (FM) calls, have also been reported (Thode et al 2000). Behavioral observations do not exist for D and highly variable FM calls, though it has been suggested that D calls may occur in call-counter-call sequences between individuals (McDonald et al. 2001).

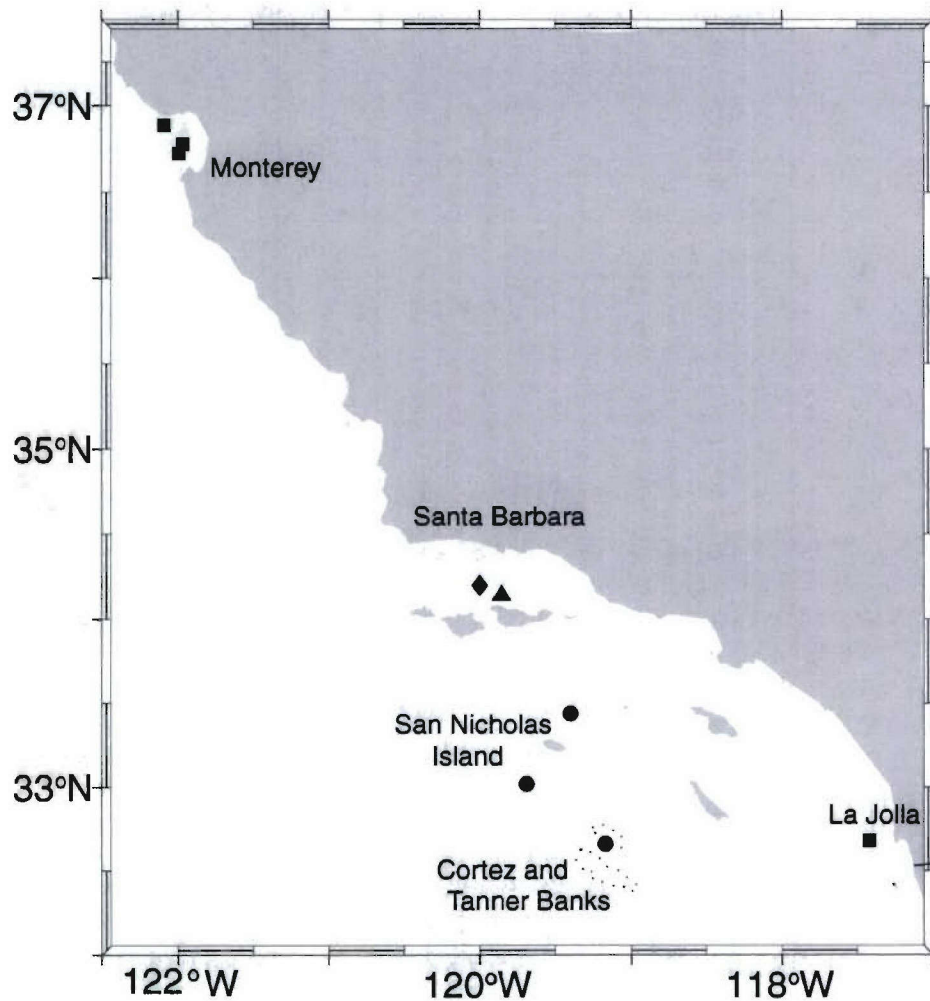
Few behavioral observations have been reported in association with blue whale call production. We have been studying blue whales along the California coast with the goal of understanding how sex and behavior of individual whales varies with call type production. We have made measurements of blue whale acoustic and diving behavior using acoustic recording tags, and have evaluated the associated sex and behavioral relationships using biopsy, photo-identification, surface behavioral observations, and real-time acoustic monitoring with sonobuoys. Our observations suggest that only male blue whales produce A and B calls, while D calls are produced by both sexes. Further, song calls are heard only from lone, traveling animals, while D calls are heard from foraging, and often paired blue whales. Finally, we have determined that A and B calls, traditionally observed only in song sequences, also occur individually, and have a different behavioral context than song. Our evaluation of blue whale calling includes the rate and intensity of calling in relation to dive depth, feeding or traveling behavior, sex, and the association with other whales. Our observations provide context for calls which have been widely heard and documented, yet not understood in their biological and ecological context.

## **Methods**

### *Locating and sampling calling blue whales*

Ship-based observations for blue whales were conducted in the summer and fall of 2000 through 2003, aboard the 38m R/V Robert Gordon Sproul in the waters of the Southern California Bight. We periodically deployed DIFAR (direction-finding) sonobuoys to acoustically monitor for vocally active blue whales in real time. Acoustic signals were monitored as scrolling spectrograms using the software Ishmael (Mellinger 2002) (FFT length 1.5 s, 50% overlap, Hanning window). When calls were detected visually in the spectrographic display, the bearing to the sound source was estimated. When bearing estimates could be calculated from more than one sonobuoy position, a track of the vocalizing whale was generated and used to help visually

locate the calling whale. The sonobuoy recording and direction-finding system are described in detail elsewhere (McDonald et al. 2001, Swartz et al. 2003, McDonald 2004). When a calling whale was located, the ship was directed to its position. Visual observers aboard the Sproul searched for the calling blue whale using 7x50 power binoculars and naked eye. A 5.3m Rigid-Hulled Inflatable Boat (RHIB), deployed from the Sproul, was used to approach the calling whale to obtain a skin biopsy and for photographic identification. The location of skin samples from calling whales is shown in Figure 3. Photo-ID and biopsy procedures are described in more detail elsewhere (McDonald et al. 2001, Calambokidis and Barlow 2004). In addition, a sonobuoy was usually deployed by the RHIB at the location of a whale surfacing to verify the identification as the calling whale. Sex was determined from genetic analysis of the skin sample through amplification of the ZFX/ ZFY gene, using the characteristic cetacean TaqI Restriction Fragment Length Polymorphism (RFLP) (Berube and Palsboll 1996, Rosenberg and Mesnick 2001). When ample genetic material was recovered from the biopsy, the sample was split, making half of the sample available for a pregnancy test based on hormone levels in the blubber (Mansour et al. 2002, Kellar and Dizon 2003).



**Figure 3. Blue whale study area in central and southern California.** Symbols indicate the position of a tag deployment which recorded calls (■ = BProbe, ◆ = Crittercam, and ▲ = DTag), or the location of a skin sample of a calling whale.

*Application of acoustic recording tag*

We deployed three types of acoustic recording tags on blue whales. We focus here on the results of deployments during which blue whale vocalizations were detected. These records provided detailed information on the vocal behavior of individual whales. Tagging of blue whales using our RHIB was conducted both during surveys with the Sproul, as well as during several additional periods without ship support. These additional operations have been conducted in the Santa Barbara Channel (2002, 2004), in Monterey Bay (2002-04), and near Point Reyes (2004). All of our tag deployments on blue whales are summarized in Table 3, with the position of calling whales shown in Figure 3.

**Table 3. Tag deployments on blue whales in 2002-2004.** Regional designations are defined as Southern California (SC) from Point Conception and the United States/ Mexico border, Central California (CC) from Bodega Bay to Monterey Bay, and Mexico (MX) near Isla San Jose, Mexico. Tag deployments shown in bold italics included calls.

Date	Time	Tag Type	Latitude	Longitude	Region	Attach duration
<b>6/23/02</b>	<b>11:19</b>	<b>dTag</b>	<b>34 08.01</b>	<b>119 53.21</b>	<b>SC</b>	<b>1.16</b>
6/24/02	12:34	dTag	34 08.34	119 56.11	SC	7.28
6/26/02	9:03	Bprobe	34 06.85	120 04.25	SC	2.85
6/27/02	7:27	Bprobe	34 06.64	120 05.53	SC	0.20
6/27/02	10:49	<i>Bprobe</i>	<i>34 06.92</i>	<i>120 03.17</i>	SC	1.48
<b>6/30/02</b>	<b>15:49</b>	<b><i>Bprobe</i></b>	<b><i>32 47.10</i></b>	<b><i>117 22.63</i></b>	<b>SC</b>	<b>0.50</b>
9/16/02	12:14	Crittercam	36 46.59	121 57.02	CC	1.10
9/19/02	9:50	Crittercam	36 46.58	121 55.58	CC	0.18
<b>9/21/02</b>	<b>11:00</b>	<b><i>Crittercam</i></b>	<b><i>34 08.27</i></b>	<b><i>119 51.50</i></b>	<b>SC</b>	<b>0.25</b>
9/24/02	12:01	Crittercam	34 07.81	119 46.37	SC	0.28
7/24/03	15:45	Bprobe	33 29.81	119 35.80	SC	0.88
8/22/03	12:59	Bprobe	32 48.86	119 22.53	SC	0.38
8/22/03	15:48	Bprobe	32 48.68	119 22.50	SC	0.78
9/24/03	9:55	Bprobe	36 43.65	121 59.10	CC	1.20
9/26/03	11:06	Bprobe	36 46.59	121 57.00	CC	0.23
<b>9/26/03</b>	<b>11:35</b>	<b><i>Bprobe</i></b>	<b><i>36 46.80</i></b>	<b><i>121 58.10</i></b>	<b>CC</b>	<b>3.35</b>
9/26/03	15:14	Bprobe	36 41.52	122 01.69	CC	1.52
<b>9/28/03</b>	<b>13:43</b>	<b><i>Bprobe</i></b>	<b><i>36 44.52</i></b>	<b><i>121 58.70</i></b>	<b>CC</b>	<b>3.62</b>
9/30/03	15:45	Bprobe	36 33.54	121 58.65	CC	0.77
3/4/04	9:57	Bprobe	25 08.43	118 41.37	MX	1.47
3/4/04	4:09	Bprobe	25 07.89	118 41.94	MX	1.18
3/5/04	10:11	Bprobe	25 08.51	118 41.46	MX	0.85
7/20/04	14:17	Bprobe	34 07.31	120 03.25	SC	0.70
7/21/04	13:09	Bprobe	34 06.74	120 04.01	SC	0.90
7/26/04	12:46	Bprobe	36 43.23	121 59.18	CC	0.30
7/26/04	16:54	Bprobe	36 51.52	122 09.23	CC	2.80
<b>7/28/04</b>	<b>9:45</b>	<b><i>Bprobe</i></b>	<b><i>36 49.10</i></b>	<b><i>121 58.5</i></b>	<b>CC</b>	<b>3.30</b>
9/28/04	18:27	Bprobe	38 04.41	123 21.54	CC	1.12

The primary tag we deployed and report on was a commercially available acoustic recording tag, developed by one of the authors (WCB), known as the Bioacoustic Probe (BProbe). This tag records pressure, temperature, and sound up to a maximum sample rate of 20 kHz. The 2003

and later version of the BProbe included a 2-axis accelerometer, enabling the monitoring of tilt and roll. Whales were approached from behind in the RHIB to a range of ~1-5m, and a tagger, harnessed to the front of the RHIB, used a 2.6m metal or 5m fiberglass pole with a specially designed PVC bracket to hold the tag in place, yet allow it to detach from the pole when it became attached to the whale. The tag was held on the animal with suction cups. Skin was collected from tagged animals, either from the inner surface of the suction cup or tagging apparatus, or by biopsy. When possible, the position of the whale was noted by collecting GPS data at each surfacing while the tag was attached. Whales were tagged based on our ability to locate and track them visually, and therefore were not selected to be acoustically active.

Upon tag retrieval, data were downloaded from the tag to a computer for analysis. Acoustic data were initially viewed in spectrogram form (FFT length 1s, 80% overlap, Hanning window) to determine the presence of calls. When calls were found, the time was noted for comparison to the pressure and accelerometer records, and the call was extracted into a separate sound file for later analysis.

Two additional styles of suction-cup-attached acoustic tags were deployed less often: the National Geographic Crittercam (Marshall 1998), and the Woods Hole Oceanographic Institution dTag (Johnson and Tyack 2003). In addition to video, the Crittercam also records depth and sound, and all data are stored to a Hi8 tape. The dTag was used in June, 2002 in the Santa Barbara Channel for two separate deployments. The acoustic data from both tag types were viewed as described above.

#### *Estimating call source level from tag records*

The BProbe provides calibrated acoustic data from which received levels, and subsequently source levels, can be calculated. Power spectral density (PSD) estimates were obtained over the duration of the call in 1Hz bins from the calibrated acoustic data using a Hanning window of length equal to the sample rate and no overlap. The PSD estimates for each 1Hz bin were then summed from 10 to 110 Hz and converted to decibels (dB) referenced to 1  $\mu$ Pa. The received levels, along with the known position of the tag on the back of the whale, were then used to estimate the source level of sounds produced by the tagged animal.

We recorded and, when possible, photographed the position of the tag on the whales. In a few cases we noted a change in position of the tag on the whale following successive dives. Based on the analysis of anatomical measurements of blue whales, sound is thought to be generated at the arytenoids, at the junction of the laryngeal sac and the lungs of the whale (Aroyan et al, 2000). Given the arytenoid source location and tag position on the whale's back, the distance over which the sound has traveled between source and receiver can be estimated. Assuming a small, arytenoid source, the placement of the tag on the whale's back puts it within the far-field of acoustic propagation and therefore spherical spreading transmission loss can be assumed. This transmission loss was added to the calibrated received level to determine source level. We have not adjusted calling levels for potential changes in acoustic propagation through whale tissues (see discussion).

Since calls were produced at shallow depths, close to the surface (a reflective boundary), there may be some addition to the received level based on the reflection of sound from the surface-air

interface (Urick 1983, Charif et al. 2002), known as the Lloyd Mirror Effect. The total received pressure ( $p_R$ ), including the Lloyd Mirror interference, can be calculated given the distance between the source and receiver via direct path ( $L_1$ ) and reflected path ( $L_2$ ), the source pressure ( $p_0$ ), swell height ( $H$ ), grazing angle ( $\theta = \tan^{-1} L_1/\text{source depth}$ ), the travel time between source and receiver via the reflected path ( $T$ ), and the angular frequency ( $\omega$ ), wave length ( $\lambda$ ), and duration ( $t$ ) characteristics of the signal using the following equation (Urick 1983):

$$p_R^2 = p_0^2 \left[ \frac{1}{L_1} \sin \omega t + \frac{e^{-\frac{2\pi}{\lambda} H \sin \theta}}{L_2} \sin \omega(t + T) \right]^2$$

With the tag on the back of the whale, at very close range to the source (defined as  $L_2^2/L_1^2 < 2$ ), the second term is insignificant. Rearranging to solve for source pressure and subsequent source level:

$$SL = 20 * \log \left( \frac{P_R}{(1/L_1) \sin \omega t} \right)$$

## Results

### *Visual and acoustic tracking of singing whales*

We have visually and acoustically tracked four singing blue whales in the Southern California Bight (Figure 3; Table 4). We collected skin samples from two of the four singers, and surface behavioral observations for all four. The photograph of one calling whale, for which we were unable to obtain a skin sample, was matched to a photo from the Costa Rica Dome which had an accompanying skin sample. All three whales for which skin samples were available were male, and all four tracked whales were traveling at moderate speed and on a predictable course. We were unable, or did not attempt, to attach acoustic recording tags to these whales. In all cases, calling whales were visually identified based on their location relative to sonobuoy bearings, the relative amplitude and timing of calls compared to other calling whales, and the coincidence of surfacing and breathing gaps in the song evident from the acoustic records. While we have obtained concurrent visual and acoustic identification of other calling whales, it has proven difficult to get close enough to many calling whales to obtain a photograph, skin sample, or detailed surface behavioral observations. The position and monitoring time for each of the whales discussed here, in addition to the whale reported in McDonald et al. (2001), are shown in Table 4, along with behavior, average swimming speed and direction of travel. Table 6 summarizes the call characteristics of each tracked whale.

### *A and B calls with irregular temporal patterns*

Based on data from acoustic recording tags deployed on three occasions (June 24 and 30, and September 21, 2002), we found that blue whales may produce A and/or B calls in irregular temporal patterns, or non-song sequences (Table 5). These calls will be referred to as singular A and/or B calls. The characteristics of the calls are similar to A and B song calls, except for the irregular timing between calls or call pairs (Table 6). A variety of surface and diving behaviors were observed in association with these recordings, including feeding, milling, and traveling.

**Table 4. Tracking information for singing blue whales described in this study.** Behavior was determined through the evaluation of surface behavior. All whales in this table were operating as a group size of one, that is, they were not directly associated with any other whales. All singing whales were tracked within the Southern California Bight between Point Conception and the U.S./ Mexico border.

Date	Latitude (N)	Longitude (W)	Time (PST)	Monitoring Time (hrs)	Sex	Behavior	Speed (km/h)	Direction
10/15/97 <sup>†</sup>	33 07.2'	119 54.0'	16:52	4.2	M	Traveling	5	W
10/18/00*	32 01.2'	119 41.4'	11:12	8.0	M	Traveling	7.4	N
8/24/01	33 26.4'	119 24.0'	12:50	2.0	M	Traveling	3.7	N
8/28/01 <sup>‡</sup>	32 37.8'	119 08.5'	13:05	0.8	-	Traveling	9.3	NW
11/3/02	32 39.6'	119 10.2'	13:35	3.0	M	Traveling	7.5	SW

<sup>†</sup> From McDonald et al (2001). \* Photo of tracked whale matched to a whale photographed in the Costa Rica Dome, with coincident sloughed skin sample used for the identification of sex as described in Gendron and Mesnick (2001). <sup>‡</sup> A skin sample was not obtained from this animal. It is included here for comparison of behavior with other singing whales.

**Table 5. Tagged singular A and/or B calling and D calling whales described in this study.** Region “SCB” is Southern California Bight; “MB” is Monterey Bay. Group size is defined as the number of whales acting in a coordinated fashion, such that they are directly associated. Behavior was determined through the evaluation of surface behavior, and feeding was only ascribed when vertical lungs were evident in the dive profile from the tag. Calling depth, tilt and roll angles were measured from the BProbe auxiliary sensors over the duration of the call and are averaged between calls and presented with one standard deviation. Body position is defined by tilt (0° = horizontal) and roll (0° = upright).

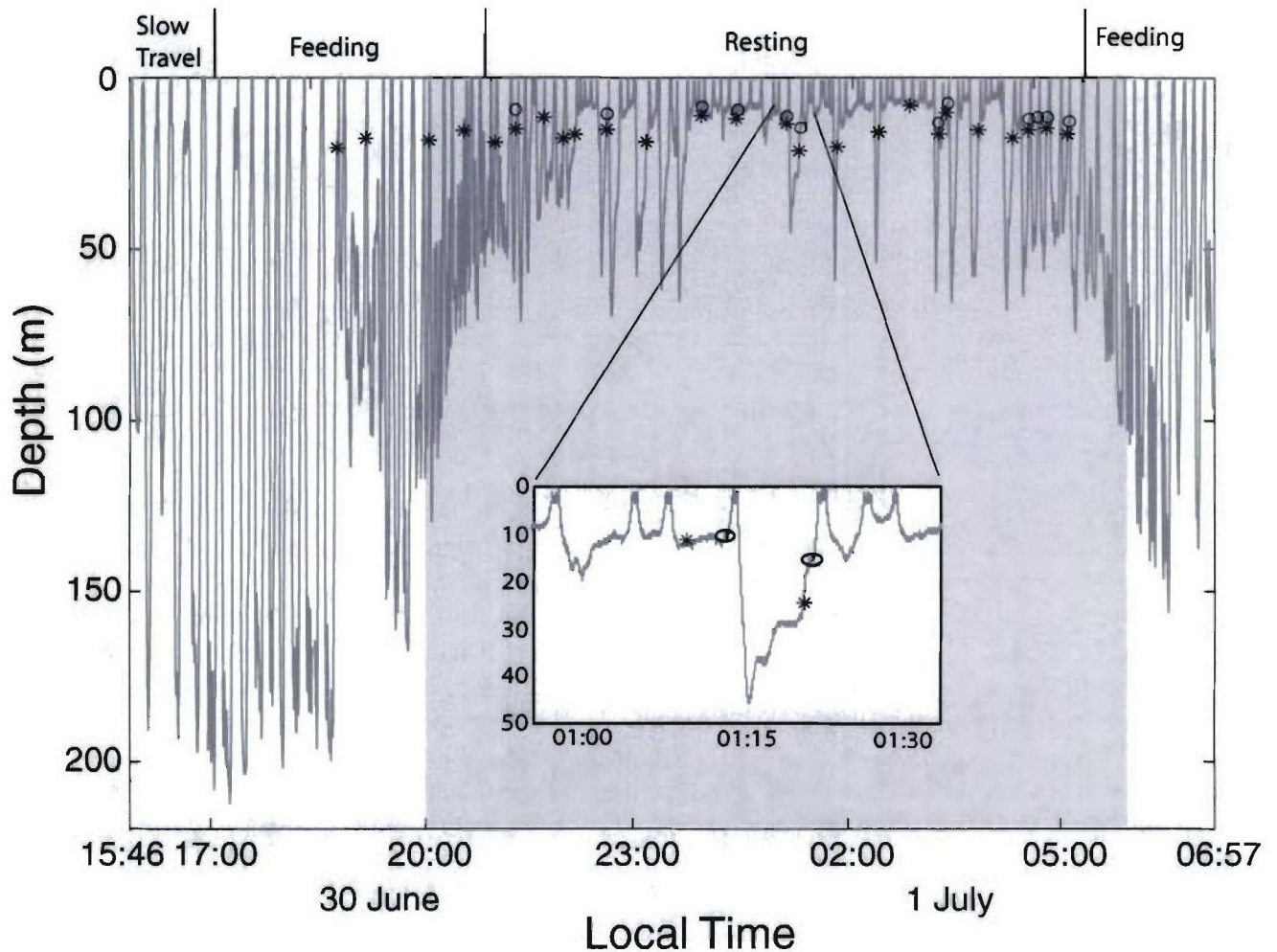
Type of Calling	Date	Region	Sex	Group Size	Behavior	Call (m)	Depth	Tilt (deg)	Roll (deg)
<i>Singular AB</i>	6/23/02	SCB	M	2	<i>Traveling</i>	20.4 +/- 2.0	-	-	-
Singular AB	6/30/02	SCB	M	2	Feeding, milling	18.3 +/- 3.3	-	-	-
<i>Singular A</i>	9/21/02	SCB	M	3	<i>Milling</i>		-	-	-
D AM/FM variants	9/26/03	MB	M	1	Feeding	20.9 +/- 5.0	1.5 +/- 5.9	0.9 +/- 2.2	
D	9/28/03	MB	F	2	Feeding	12.2 +/- 3.8	-1.3 +/- 12.6	-3.6 +/- 10.3	
D*	7/28/04	MB	-	2	Feeding, milling	7.8 +/- 8.7	2.0 +/- 8.3	-1.9 +/- 3.9	

Listings in italics indicate whales observed by the DTag and Crittercam where the identity of the calling whale can not be conclusively assigned to the tagged whale due to lack of hydrophone calibration. \* A skin sample was not obtained from this animal.

**Table 6. Call characteristics of blue whales tracked in this study.** Call frequencies were measured from spectrogram displays (1 s FFT, 80% overlap, Hanning window) and inter-call interval is measured from the onset of one call to the onset of the next. D and highly variable call intervals were measured between successive calls, with no regard to their assignment as D or variable. Received levels were measured from calibrated BProbe recordings between 10 and 110Hz, and source level estimated assuming spherical spreading from the arytenoids to the hydrophone position, including the correction for the additive water surface reflection as described in the text. See discussion on estimating source levels from tags for cautionary points in interpreting these values. We do present received or source level for song calls because of the large variation in received level between sonobuoys. Source level was not estimated for whale tagged on 9/28/03 and 7/28/04 because it is likely both whales in the pair were calling, therefore making the distinction between the tagged whale's calls and that of its pair difficult.

Type	Date	Call	N	Frequency		End (Hz)	Call Duration (s)	Intercall Interval (s)		Number Pulses (A) Harmonics (B)	Received Level (dB)	Source Level (dB re: uPa-m)
				Start (Hz)	+			A-B	B-A			
Song AB	8/24/01*	B	16	52.8 +/- 0.9	46.8 +/- 0.8	17.7 +/- 1.5	6.3	(B-B) 45.1 +/- 6.3	3-6			
		A	9	89.5 +/- 3.9	86.0 +/- 3.1	14.2 +/- 3.1	48.5 +/- 3.9	112.4 +/- 46.3	16-21			
	11/3/02	B	14	52.7 +/- 0.9	45.3 +/- 0.4	16.0 +/- 0.5			4			
		A	15	90.9 +/- 1.5	86.5 +/- 1.2	16.3 +/- 1.4	49.1 +/- 4.7	111.5 +/- 48.1	19-23			
	6/23/02	B	16	52.8 +/- 0.5	47.2 +/- 0.6	16.4 +/- 0.4			5-11			
		A	1	89.5 +/- 0.3	85.3 +/- 0.1	15.1	45.7	(B-B) 1294.8 +/- 911.7	3			
Singular AB	6/30/02	A only	14	87.3 +/- 1.2	85.0 +/- 1.2	15.2 +/- 2.2			17-23		159.4 +/- 2.9	172.6 +/- 2.9
		A pair	11	87.7 +/- 1.4	85.1 +/- 0.7	17.8 +/- 2.0	48.5 +/- 0.0	1261 +/- 690	20-26		158.7 +/- 4.1	171.8 +/- 4.1
	9/28/03	B pair	13	50.8 +/- 0.9	45.9 +/- 0.3	16.0 +/- 0.8			3-9		163.4 +/- 3.2	177.0 +/- 3.3
		AM/FM	10	45.4 +/- 7.6	45.0 +/- 9.1	2.2 +/- 0.8	14 +/- 11		1-6		171.1 +/- 2.6	180.2 +/- 5.3
D	9/28/03	D	12	70.6 +/- 15.7	34.8 +/- 10.7	2.7 +/- 0.9			2-5		172.8 +/- 2.6	188.6 +/- 9.5
		D	5	77.2 +/- 17.7	43.7 +/- 12.8	0.9 +/- 0.5	1656 +/- 379		1-2		168.7 +/- 7.3	NA
D	7/28/04	D	39	79.3 +/- 14.4	39.5 +/- 9.3	1.5 +/- 0.5			1-2		167.8 +/- 3.5	NA

\* A-B call intervals could not be accurately measured because of the presence of A calls from other whales that were at similar amplitude, preventing identification of A calls from the focal animals.



**Figure 4. Dive profile of calling whale on June 30, 2002 tagged near La Jolla, CA.** The depth and time at which A (\*) and B (o) calls were received at the tag are indicated. The tagged whale's general behavior is annotated along the upper axis. Periods of feeding track the vertical migration of the whale's euphausiid prey are evidenced by vertical lunges at depth (Croll et al. 1998). The period between sunset and sunrise is highlighted with grey shading. The inset shows detail of two dives including A and B calls. The tagged whale was male and paired with a pregnant female.

The occurrence of singular A and/or B calls shared several features among the three deployments. All calls occurred at shallow (< 25m) depth (Table 5), and only a single call or A-B call pair occurred per dive (Figure 4). Calls were always produced as the whale was ascending from a deeper dive or at the end of a flat dive profile. On all three tag deployments the tagged whale was in close association (ie. paired or grouped) with at least one additional blue whale, and when paired (two occasions) was with a female whale, with other blue whales within 1 km. Additionally, while the identity of the whale producing the calls is unknown for two of the three deployments, all three whales carrying tags while singular A and/or B calls were heard were male. In both cases where the tagged animal was paired, the tagged whale was male and the other whale was female.

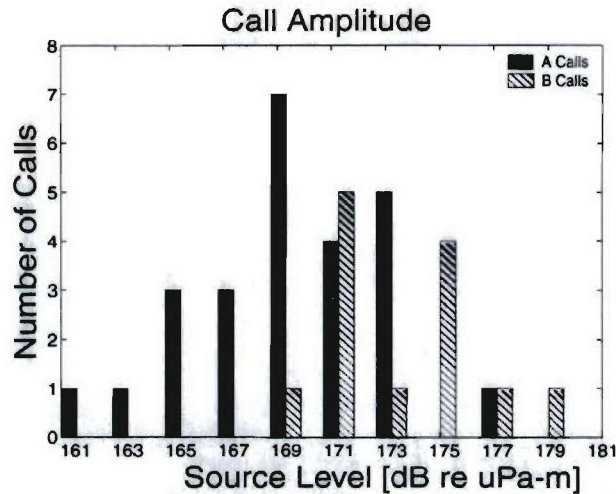
While our records of singular A and/or B calls share several commonalities, there are also differences among the deployments. We show in detail the dive profile with time and depth of calling and surface behavioral observations for the tagged whale near La Jolla, CA on June 30, 2002 in Figure 4. This animal was feeding during the day, evidenced by the lunging profile. While the record shows most calls occurring during the night time period, acoustic monitoring of this animal with sonobuoys prior to tag attachment indicates that it may have been calling during the day as well. All calls in the tag record had lower source levels than those previously reported for type A and B calls (Figure 5; Table 6). In addition, surface observations indicate the other animal in the pair, a pregnant female, commonly surfaced a few minutes before the tagged male. Some of the calls were produced during periods when the tagged male was underwater and the paired female was surfacing confirming the tagged whale produced the calls, not the leading female.

The two remaining records (June 24 and September 21, 2002) occur in slightly different contexts. It is not possible to attribute the calls to the tagged whale with certainty for either record because of the close association between whales during surfacing, and due to the lack of calibration for the hydrophone in the tag (dTag and Crittercam). The dive profile for the whale tagged in the Santa Barbara Channel on June 24, 2002 is shown in Figure 6. All calls in this record have similar (uncalibrated) received levels and all occur at a constant, shallow depth (~20m: Table 5). The tag record from September 21, 2002, occurred in a group of three whales. The video track of the Crittercam record shows the tagged whale next to another blue whale during the time that the single A call occurred. The primary difference between these records and that of June 30, 2002 are deeper excursions immediately following calls without a surface interval.

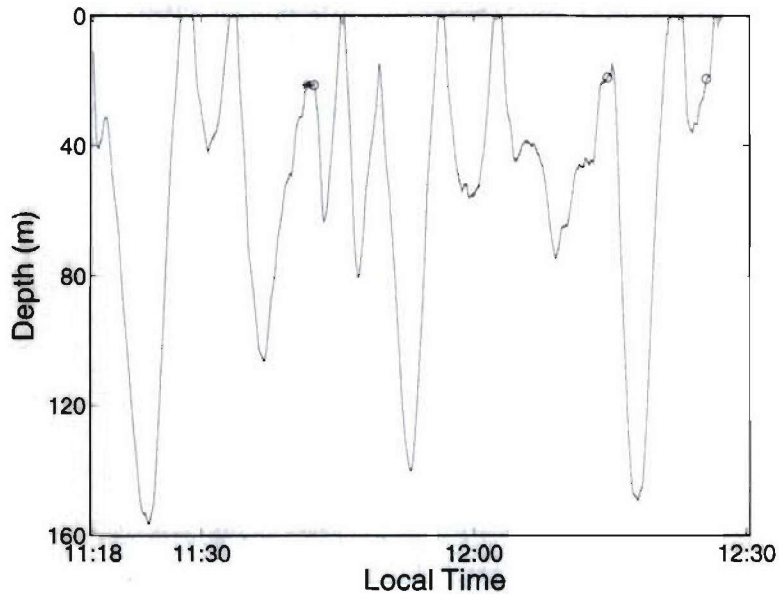
#### *D and highly modulated tonal calls*

We have observed type D calls on three BProbe attachments to blue whales (September 26 and 28, 2003 and July 28, 2004), all within Monterey Bay. Two of the three attachments were on animals in loosely associated pairs, while the third was on a single whale. Skin samples from all tagged and paired animals indicate that both male and female blue whales produce D type calls. The observed D calls are highly variable in both frequency content and sweep rate (Table 5), even those produced by a single animal. In all three cases, additional blue whales were within 1 km of the tagged whale, though there did not appear to be any coordinated behavior between the tagged whale and these more distant animals.

During attachments to paired whales, we observed large variability in the signal-to-noise ratio (SNR) of received calls, occasionally due to variation in the received level, such that both whales in the pair may have been calling, and other times due to increases in background noise. Figure 8b illustrates one dive in which a D call with high SNR was received on the tag, followed by two much lower amplitude calls, probably produced by the other whale in the pair (Figure 8c). Additionally, there were variations in the dive behavior of the tagged whale during call reception. For example, the July 28 record shows calls occurring at the surface and at depths of up to 33m (Figure 9).



**Figure 5. June 30, 2002 source level estimates** for each call type estimated from received levels recorded on the tag including spherical spreading losses and Lloyd mirror interference.



**Figure 6. Dive profile for calling whale tagged on June 24, 2002**, in the Santa Barbara Channel. The depth and time at which A (\*) and B (o) calls were produced are marked. The tagged whale was male, and paired with a female.

Estimating source levels for all calls in the record (including Lloyd mirror interference) indicates a bimodal distribution, with the calls occurring deep (>10m) being significantly louder (183.5 +/- 7.7 dB re  $\mu$ Pa-m) than shallow (<4m) calls (166.4 +/- 7.9 dB re  $\mu$ Pa-m) (Student's T-test, unequal variance:  $t_2 = 5.799$ ,  $P \ll 0.001$ ). This may indicate that calls occurring deep were produced by the tagged whale, while those heard while the tagged whale was at shallow depth were produced by the other animal in the pair. Alternatively, the other whale in the pair could have produced all calls, with the difference in received level attributed to greater distance between the whales. Surface behavioral observations are not available for examination of the

surfacing activity of the other animal in the pair. Because we cannot be certain which calls were produced by the tagged whale, source levels are not presented for records including paired whales. While feeding dives were evident in all three records, calls were only heard during relatively shallow dives (<35m, Table 3), with several calls per dive. There were no significant deviations from 0° tilt (horizontal) or 0° roll (upright) during call production (Table 5).

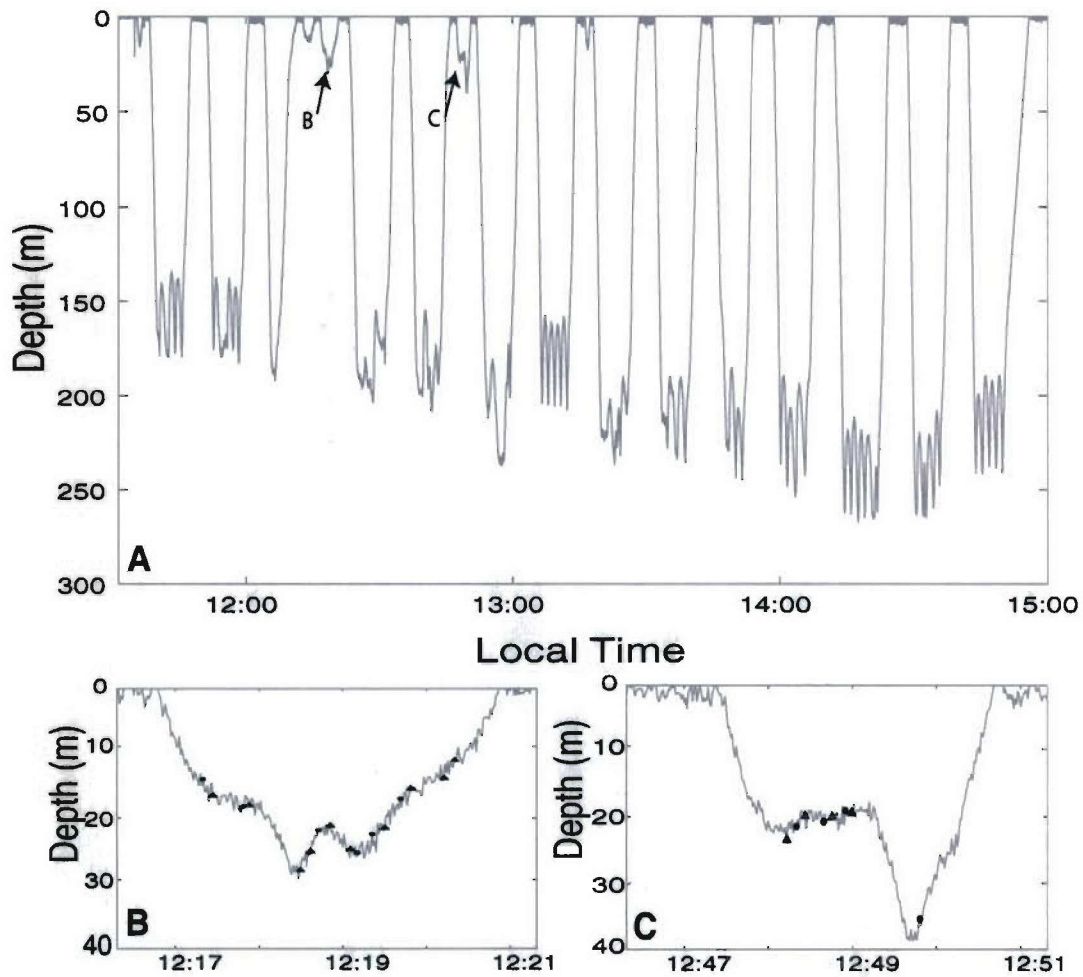
The tagged single animal (September 26, Table 5) producing D calls also produced several highly variable frequency and amplitude modulated (AM) calls. An example of a sequence of calls is shown in Figure 10a, illustrating the highly variable nature of both D and FM calls produced. Some of the calls appear to be similar to type B calls because of their frequency content; however, these calls were highly frequency- modulated and significantly shorter in duration than typical B calls. Figures 10b and 10c show some of the AM variants heard from this whale. The frequency, duration, and source level characteristics of D calls, and AM and FM variants can be found in Table 6.

## Discussion

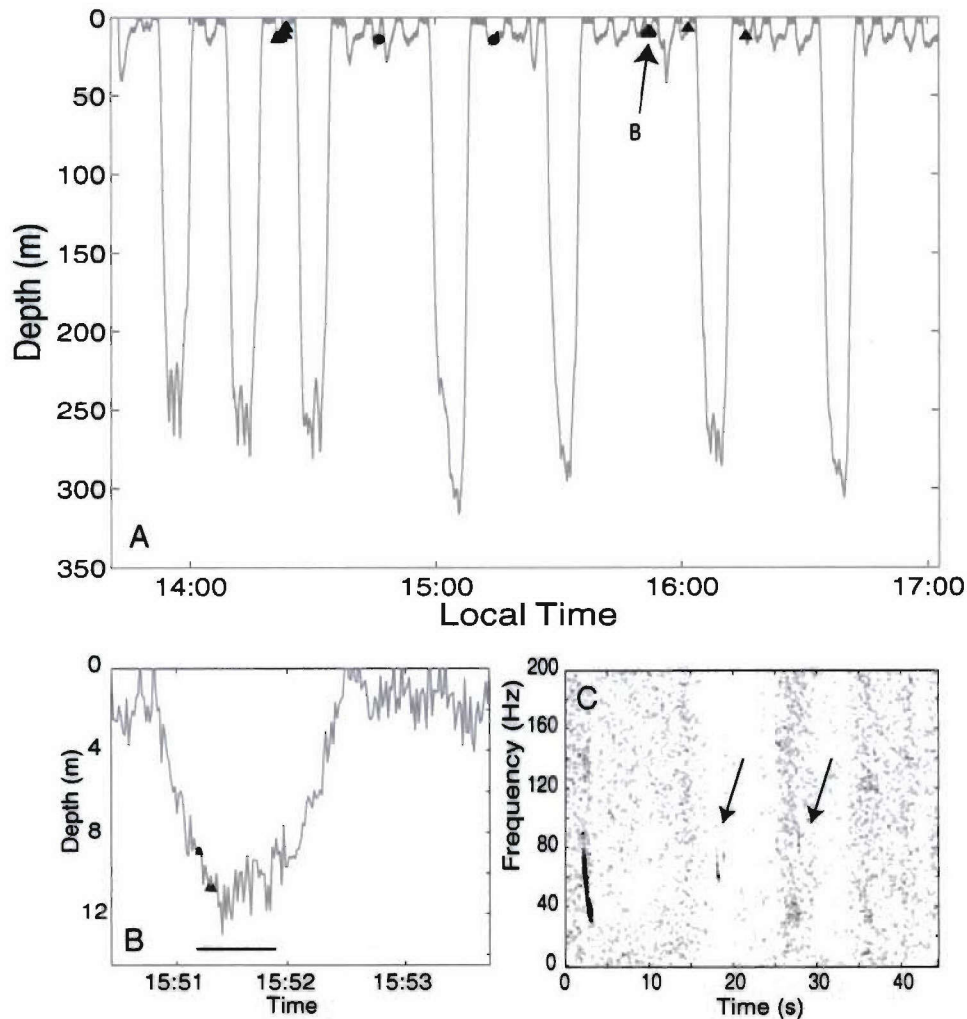
### *Song and Singular AB Calls*

Our observations of singing blue whales suggest a unique context for the production of this call type. Based on four unambiguous samples presented here (three singers, one singular AB), and one additional report from McDonald et al (2001), there is mounting evidence that blue whale A and B calls are produced by males only. Given our current sample size, the probability that we sampled only males by chance is 3.13% ( $0.5^5$ ). The singing blue whales we have observed were not displaying any sort of coordinated behavior, either acoustically or visually, with the other whales in the area, and were traveling (Table 7), similar to previous behavioral observations of this call type (Stafford et al. 1998, Tyack 1998, McDonald et al. 2001). In addition, these singing whales were not feeding, evidenced by the markedly different surfacing and movement patterns of singing whales and known feeding whales. Singers are often difficult to approach because of the distance covered between surfacings, their speed of travel, and their short surface sequences.

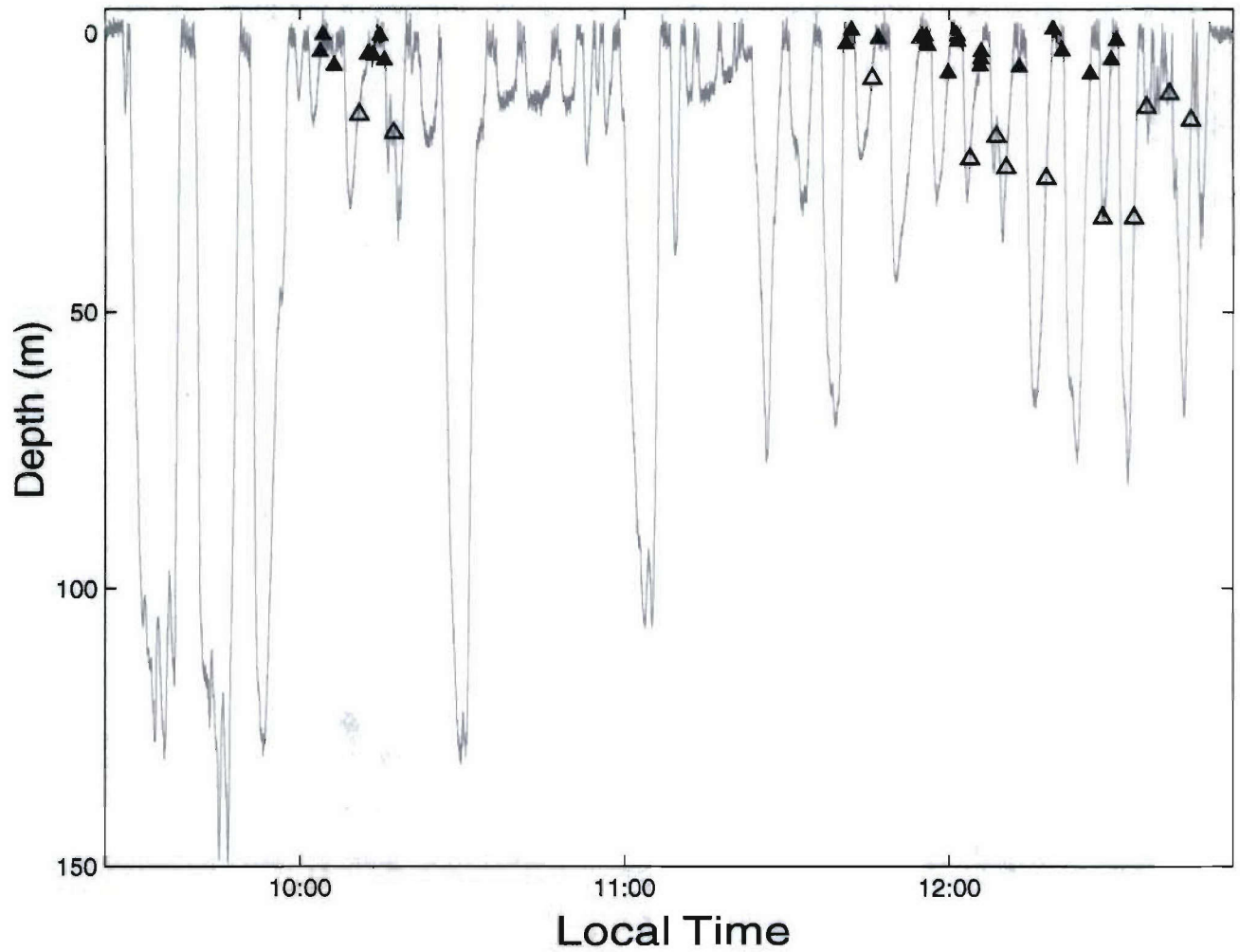
Song has been documented in other baleen whale species as being produced primarily by males, supporting the common conclusion that songs may function in reproduction. The most extensively studied of these species is the humpback whale (*Megaptera novaeangliae*). In contrast to blue whales, humpback whales produce complex songs (Payne and McVay 1971). Singing is heard primarily on low-latitude breeding grounds, with most singers producing the same song (Payne and McVay 1971, Cerchio et al. 2001); however, like blue whale song, it has also been heard along migration routes (Norris et al. 1999) and on feeding grounds (Clark and Clapham 2004). The precise function of humpback song is still unknown (Payne and McVay 1971, Tyack 1981, Clapham 1996); however, it has been suggested that song may function to mediate interactions between males (Tyack 1981, Darling 1983, Frankel et al. 1995) or to advertise species, sex, location, and condition to females (Payne and McVay 1971, Winn and Winn 1978, Tyack 1981). If breeding is confined seasonally, the detection of humpback song along migration routes and on feeding grounds complicates the interpretation of song as a reproductive display only. Clark and Clapham (2004) do, however, point out evidence for out-of-season breeding in humpback whales.



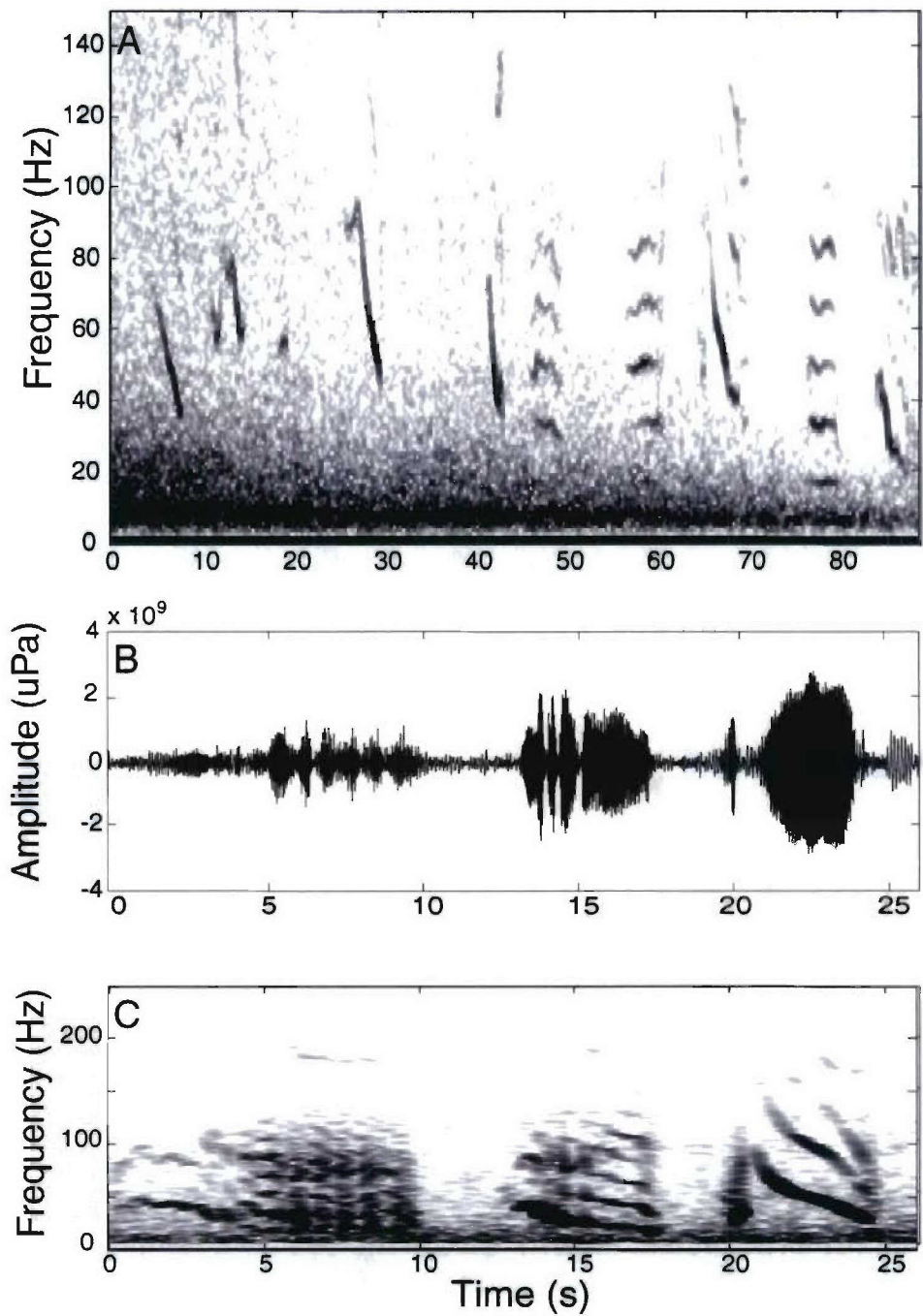
**Figure 7. Dive profile for tagged D and variable calling whale on September 26, 2003 in Monterey Bay. A) Overall dive profile indicating vertical lunging feeding behavior, punctuated by two anomalously shorter, shallower dives containing calls (labeled B and C corresponding to panels below). B) and C) provide depth and timing of D calls (▲) and highly variable AM and FM calls (●).**



**Figure 8. Dive profile for tagged whale September 28, 2003** in Monterey Bay. A) Overall dive profile of tagged female with times of medium and high SNR D calls noted by ▲. One calling dive is shown in greater detail (B) in which there are likely counter-calls between the whales in the pair. High and medium SNR calls are noted as ▲, and the horizontal line indicates the time period shown in panel C. C) Spectrogram showing counter-calls heard during B), with high SNR call likely produced by tagged female, and low SNR calls (indicated by arrows) likely produced by the untagged male in the pair.



**Figure 9. Dive profile for tagged whale on July 28, 2004** in Monterey Bay. It is likely that calls were produced by both whales in the pair, with those occurring shallow (▲ <6m) produced by the non-tagged whale, and those deep (△ >10m) by the tagged animal because of the difference in received level and estimated source level.



**Figure 10. D and variable tonal calls on September 26, 2003 in Monterey Bay. A) Spectrogram, B) Time series, and C) spectrogram of three sequential AM and FM calls from the same tag deployment.**

Fin (*B. physalus*) and minke (*B. acutorostrata*) whales also produce songs. Both species are pelagic, unlike coastal humpback whales, and may use song in a similar manner to blue whales. Male fin whales produce short, low frequency downsweeps in song sequences (Watkins 1981, Thompson et al. 1992), and it has been proposed that these songs, are produced to attract females to patchily distributed prey, a notion which is supported by the high intensity of the call, in addition to the absence of a specific breeding area for this species (Croll et al, 2002). Observations of Watkins et al. (1987) indicate that singing fin whales remain stationary over a singing bout, suggesting advertisement of location, similar to the findings of Croll et al. (2002), but in contrast to the traveling behavior of singing blue whales. While it has not been shown that singing minke whales are exclusively male, it is thought that their complex song also functions as a reproductive display (Gedamke et al. 2001) as it occurs primarily during the presumed breeding season (Rankin and Barlow in press). Recently, it has been shown that the songs of dwarf minke whales on the Great Barrier Reef function to maintain space between singers, and that some whales may display dominance through their songs (Gedamke et al. 2003).

**Table 7. Summary of behavioral correlates with each calling type.** “Other calls” refers to the presence of additional calls heard from the focal animal. Coordination “within” refers to observed organization within the group, while “between” is observed coordination between the focal animal and others who do not appear to be directly associated with the focal animal. The number in parentheses in N is the number of known sex individuals producing that call type. Function has been assessed based on our observation presented in this paper and the concordance with observations presented in other published reports of calling whale behavior.

Call Type	Song AB	Singular A/B	D	AM/FM
N	5 (4)	3 (1)	3	1
Sex	Male	Male	Male & Female	Male
Behavior	Traveling	Feeding, Traveling, Milli	Feeding	Feeding
Group Size	1	2-3	1+	1
Other Calls?	No	No	AM/FM	D
Coordination Within	No/No	Yes/?	Yes/?	No/?
Function	Reproduction	Reproduction/ Territory defense?	Social/Contact (food associated)	Social/ Aggression?

Classifying the song as serving a reproductive purpose does not necessarily limit possible uses for the call type, as reproduction encompasses many behaviors including mate attraction, guarding, and stimulation, as well as territory defense, and male-male dominance. To assign the function of song to one particular reproductive context is not yet possible; however we may be able to eliminate some of the possibilities given the observations presented here. Signals designed for mate attraction in other animals are generally of the lowest possible frequency, have a high repetition rate, long signal duration, and are produced by a single sex when receptive to mating, and in a stationary position (Bradbury and Vehrencamp 1998). Blue whale songs are annually decreasing in call frequency (J. Hildebrand, pers. comm..) which may be encouraged by sexual selection toward lower frequency signals. While blue whale songs have many of these characteristics (low frequency, high repetition rate, long signal duration, produced by a single sex), they are heard all along the migration route, at all times of year, and the whales are

traveling rather than stationary. Mate guarding and male-male aggression do not appear to be a plausible functions of song as singing blue whales are commonly observed traveling alone, and uncoordinated with other whales in the region. Territory defense signals are generally designed to transmit over the entire territory, can be localized by listening whales, and have a sufficient duration and repetition rate that species and individual identity can be discerned by possible intruders (Bradbury and Vehrencamp 1998). Dwarf minke (Gedamke et al. 2003) and fin whale (Watkins 1981, Croll et al. 2002) songs have been shown to play some role in territory defense, and blue whale songs are loud and localizable; however, there is no evidence that blue whales maintain stationary territories. Unlike fin whales (Croll et al. 2002), blue whale song does not appear to be consistently and most frequently heard in regions of high food concentration. We cannot discount that larger, mobile territories may exist for this species; however it is unclear how the territory would be defined.

The long duration of the individual blue whale song components, and the repetitive nature of the song along with high source levels (McDonald et al. 2001), optimize this call type for communication over long distances (Payne and Webb 1971, Clark and Ellison 2004), a potential benefit to migrating blue whales which are often widely dispersed. While it seems likely given these design features and by comparison to humpback, fin, and minke whale songs, that the blue whale song is involved in reproduction. It also has been proposed that a secondary function of song may be for long-range navigation using reflections from distant bathymetric features (Clark and Ellison 2004), as has been suggested for bowhead (*Balaena mysticetus*) calls (George et al. 1989). Both sexes and all age groups of whales must navigate over large distances, suggesting that song calls are not solely for navigation, because females would be at a disadvantage. In addition, we have not observed changes in call duration or intercall interval, which would be expected if the calls were used for navigation as the whale approached features upon which it was echolocating.

We have discovered that blue whales also produce A and B calls in irregular patterns. In this mode A calls are not necessarily followed by Bs, nor are there predictable intervals between successive calls. The behavioral context for producing singular A and B calls appears to be more complex than that associated with singing. All three whales observed producing this call type have been engaged in different behaviors; however there is one unifying theme: this call has only been heard by a whale or whales that are part of a pair or group of animals (Tables 5 and 7). This observation is in marked contrast to the social context of singing. Singular callers occur in groups and are of lower source level than song calls, suggesting the function of singular calls is likely different than that of song. The record from June 30, 2002 of a male whale paired with a female whale stands out in the use of the call type. On at least four occasions, the female in this pair surfaced before the male. The times of these asynchronous surfacings are coincident with the times that calls were detected on the tag. Her surface position isolates her from the call, suggesting the call may be intended for another whale as a guarding action.

Singular A and B calls share the frequency and duration characteristics of song A and B calls (Table 5), but it is the amplitude and timing of these calls that clearly distinguish them from song. The consistent depth of singular A and B call production along with their lower amplitude may be related to their function. All three instances of this call type were heard from a whale in a group, and with other blue whales in the immediate vicinity, the low source level (compared to

song calls) suggest that the intended receivers are nearby. The social context further suggests coordination or aggression within the group, in that the grouped whales are often seen surfacing in a coordinated fashion, and are interacting underwater, as seen on the Crittercam video, where the vocalizing blue whale was nose-to-nose with another blue whale during the production of a single A call.

#### *D and highly variable calls*

D calls appear to be produced by both sexes. Two whales heard producing D calls were genetically sampled: one male and one female. We have heard this call type in association with feeding and from single and loosely associated pairs, suggesting this call may be used to maintain contact with conspecifics. Previous reports of whales producing D calls have also shown that this call type is quite variable and is observed from lone blue whales, as well as whales that are part of aggregations. Thode et al. (2000) also notes that D calls are quite variable and associated with other “highly modulated” variants. Similar to our observations of D callers from tags, Thode et al (2000) observed multiple calls per dive, with calls produced throughout the dive profile, and at depths between 15m and 35m. In contrast, McDonald et al. (2001) observe D calls from two or more whales in an alternating pattern, and suggest that these are contact calls.

The function of type D and variable calls is likely to be social interaction or contact, rather than reproductive. These calls are made by both sexes on feeding grounds, and often come as sets of call-counter calls. Social sounds, as described by Edds-Walton (1997), are produced by two or more animals in close proximity whose activity appears to be coordinated. In balaenopterids, this type of vocalization generally includes frequency sweeps and is repeated (Edds-Walton, 1997). Our observations of type D calling whales are consistent with both types of sounds (Table 7). Similar vocalizations have been recorded from several rorqual species; however, fin whales may provide the best comparison in terms of the behavioral context of this type of call. Fin whales have been observed using their 20Hz pulse calls while traveling at distances of up to 3km from each other (McDonald et al. 1995), and are believed to be using the call to maintain contact between the individuals in the group.

The presence of highly variable tonal and amplitude-modulated calls indicates that calling behavior is more complex than has been previously recognized. The occasional association of these highly variable calls with D calls may indicate that their combined function serves a purpose different than that of D calls which occur alone. Greater complexity may be an indicator of aggression (Edds-Walton 1997), as may be the case with the AM and FM combination calls observed on the tags, as other blue whales were present in the area. In contrast, contact vocalizations are produced by only a single whale, physically separated from a conspecific (like the record from July 28, 2004), which result in interaction between the caller and the conspecific (Edds-Walton, 1987). Fin whales have been observed producing 20Hz calls in conjunction with other growl like calls on feeding grounds in the North Atlantic (Edds 1980, Watkins et al. 1987), perhaps analogous to our observations of type D and highly variable AM and FM calls of blue whales.

#### *Using calls to study blue whale populations*

Acoustic monitoring is becoming an increasingly important method for delineating species boundaries, migration routes, and relative abundance, and offers promise in aiding in abundance

estimation, and the prediction of critical habitat (Mellinger and Barlow 2003). However, before acoustic detection can be a robust survey method for blue whales, we must understand how the whales use sound so that we can adequately account for changes in acoustic behavior over time and space.

Previous acoustic monitoring of blue whales has focused on the detection of song calls. While this is useful for outlining seasonality and distribution of singers, monitoring song calls does not necessarily yield the best estimate of the distribution of the entire population. Our observations of blue whales producing singular A and/or B calls suggest that interpretation of these long-term records is more complex. While there are no previous reports of blue whales producing song calls in irregular patterns, this is probably not because the calls were absent. The nature of the call type, with the same frequency and duration as song calls, might prevent the unique identification of these calls, particularly in the presence of singing whales. However, singularly calling whales may make up a larger percentage of the total number of vocalizing whales than do singers, a distinction important for researchers interested in using the detection of blue whale sounds for abundance estimation.

Additionally, monitoring the presence of D and singular A and/or B call types may provide a more direct means for delineating whale habitat, as these calls have been heard from feeding whales in known productive areas. The presence of these call types, together with environmental data (eg. Moore et al. 2002) may allow for the calculation of predictive habitat models.

#### *Estimating source level from tag recordings*

To calculate source level from a moderate distance (100m - 1km) you minimally need only the received level and the distance to the source assuming spherical spreading and little or no directionality to the source. However, at close range we need more information including the size, dimensions, and detailed position of the source within the whale. If the sound is originating at the arytenoids, at the junction of the passageway to the lungs and the laryngeal sac, approximately 1m posterior to the blow hole and 1m to the interior of the whale (Aroyan et al. 2000), and the tag is placed 5m posterior to the blow hole, it is recording sound at a range of 4m, equivalent to a spherical spreading loss of 12dB. The tag is then well within the far-field, and the received level is not complicated by the constructive and destructive interferences of the source from near-field propagation (Medwin and Clay 1998). If we assume that sound is simply spreading spherically from the arytenoids, the mean source level estimates for the singularly produced A and B calls would then be 172dB re:  $\mu\text{P-m}$  and 176dB re:  $\mu\text{P-m}$ , respectively (Figure 5a), lower than previously reported source levels for the corresponding song call types.

The placement of an acoustic recording tag on the back of a calling whale may not be the best way to estimate the source level of vocalizations, as we do not know the precise location or dimensions of the sound source or the impact of bony and air filled structures. While we have assumed the sound source location to be the arytenoids, the propagation of sound through the whale is likely complex as it encounters and reflects off air spaces (lungs, laryngeal sac) and bones (skull, vertebrae), each influencing the received level with its own acoustic transmission properties. If in fact the source is not at a specific point (the arytenoids), but is dispersed (the entire lung acting as a resonator), then the source dimensions would be large and we would be measuring sound within the near-field. Blue whale vocalizations are thought to be omni-

directional, however, (Aroyan et al. 2000, Bass and Clark 2003), such that the choice of tag location on the whale should not be affected by the whale's transmission of sound in a particular direction. Without an independent measure of source level of calls recorded on acoustic tags, we cannot be sure what effect such close placement to the source might have been on our received levels. For this reason we have presented received levels at the tag and the inferred source level assuming spherical spreading from an arytenoids source, including the removal of the additive surface reflection (Lloyd Mirror Effect), with the belief that the actual level will be between these values.

#### *Review of call production mechanism*

A theoretical model of blue whale sound production is presented in Aroyan et al. (2000). The model suggests that the frequency, intensity, and duration for B call production require such a large air volume that the whale may be using changes in depth to move the required air volume over the arytenoids. In their example, a whale producing a B call with a fundamental frequency of 17Hz, 19 sec duration, and an intensity of 187 dB re  $\mu\text{Pa}\cdot\text{m}$ , would require a flow volume of 800L to 1100L without resonance. They suggest that it is not reasonable for a blue whale to move or store such large quantities of air without the aid of a compression system and a change in pressure to facilitate the production of a continuous tone. The maximum volume of air that a blue whale can move during a dive from the surface to lung collapse depth at 90m is 650L to 700L, therefore, resonance must be an additional factor in the production of such a loud, long duration signal. The model presented in Aroyan et al. (2000) suggests that singing whales would maintain an undulating dive profile as they move from deep to shallow depth (or vice versa) to move the air required for each B call.

While this model was developed with only the knowledge of blue whale song call characters, our data on the dive characteristics during production of singular B calls, as well the song call depths presented by Thode et al. (2001), refute the theory of an undulating dive profile. Long duration, low frequency, high intensity B calls, even produced singularly, should be subject to the same physical limitations; however, significant changes in depth have not been observed during call production (less than 1m upward for A calls, and 1.5m downward for B calls). Our observations of singularly produced B calls are several dB less intense (176 dB re  $\mu\text{P}\cdot\text{m}$ ) than the most intense song calls reported in the literature (186 dB re  $\mu\text{P}\cdot\text{m}$ ). They require only half of the total air volume, and therefore eliminate the theoretical need to create a pressure differential to aid in the movement of air. An air volume of 380L (the estimated volume necessary to produce the singular B calls observed on June 30, 2002) is potentially moved across the arytenoids at depths of 20m from air stored in the lungs, without changing depth. It is instructive to note that it is possible for a blue whale to produce this type of long-duration, high-intensity sound while maintaining a nearly constant depth. While it is possible for two separate mechanisms to exist for the production of the song and singular B call, this begs the question: Why would blue whales have different mechanism for producing the same call depending on the intensity and behavioral context of the signal? If the signal carries some information of the mechanism of sound production, then two mechanisms may exist to transmit different types of information. The other possibility is that the mechanism is in fact the same for both types of B calls. Additional information on the source level of both forms of B call, as well as detailed dive descriptions for singing whales, will be necessary before we can determine if more than one call production mechanism exists.

## Conclusions

Understanding and interpreting blue whale calling requires finding patterns in the occurrence of different call types, with their variable frequency, duration, and amplitude characteristics, as well as their associated non-acoustic behaviors. Acoustic recording tags and genetic sampling, paired with acoustic monitoring with sonobuoys and surface behavioral observations, have provided the opportunity to increase our knowledge of the behavioral patterns exhibited within categories of calling whales. It appears likely that singing and singular A and/or B callers are male. These calls, particularly song, may be involved in reproduction, as for singing humpback and fin whales. Both sexes produce the more variable type D calls and this call type appears to be associated with feeding and social interactions. Knowledge of non-acoustic behaviors associated with particular blue whale call types should aid in the interpretation of long-term acoustic data sets. Further studies on the behavior of calling whales in different environmental contexts, in addition to comparisons of the relative seasonality and geographic distribution of these various call types will also help to define how acoustics can be most appropriately applied to monitoring blue whale populations.

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## **Automated Model-Based Localization of Blue Whales in SCORE**

A common technique for passive acoustic localization of marine mammals is hyperbolic fixing (Stafford et al. 1998; Janik et al. 2000). This is a simple approach; however, its accuracy is limited in environments where refractive and multipath effects are important. To compensate for these effects, we developed a new algorithm for localizing calling whales using acoustic propagation modeling. The new technique uses comparisons between predicted and measured time differences of arrival (time-lag) between widely spaced receivers to build an ambiguity surface showing the most likely whale position in a horizontal plan view around an array. During acoustic travel time prediction, the acoustic model can account for variations in bathymetry and sound speed in the waters under observation. The output ambiguity surface also has the feature that it inherently provides confidence metrics in the location estimate. The model-based algorithm is fast and does not require user interaction, making it suitable for automated, real-time monitoring applications.

### **Experiment**

The Southern California Offshore Range (SCORE) is a naval training area near San Clemente Island. Four bottom-mounted seismometers were deployed in a 3-km square as shown in Figure 11. The water is relatively shallow at 230 m depth, and average historical sound speed profiles for the area are known as well. The seismometers measure velocities on three axes as well as pressure, and eleven days of continuous seismometer data from August 28 to September 7, 2001, sampled at 128 Hz, were analyzed. Whale calls were recorded on every instrument and at all times of day. While viewing spectrograms of the data, spectral patterns associated with blue whales were frequently observed (McDonald et al. 2001). A typical blue whale call lasts about 20 seconds and has much of its energy at frequencies less than 60 Hz. As an example, Figure 12 shows a spectrogram from seismometer #1 for a 3-minute segment of data from August 28, 2001; the spectrograms were made using 512-point FFT's with 90% overlap. Alternating type 'A' and type 'B' calls are evident.

When spectrograms from all seismometers for the same time segment were viewed concurrently, similar spectral patterns could be recognized in two or more spectrograms, but offset in time. In such cases, the same whale call is being recorded on multiple receivers, but the time of arrival at the receiver varies according to range from the caller. It is this difference in arrival times for the same call, called the time-lag, which will be used in the localization process.

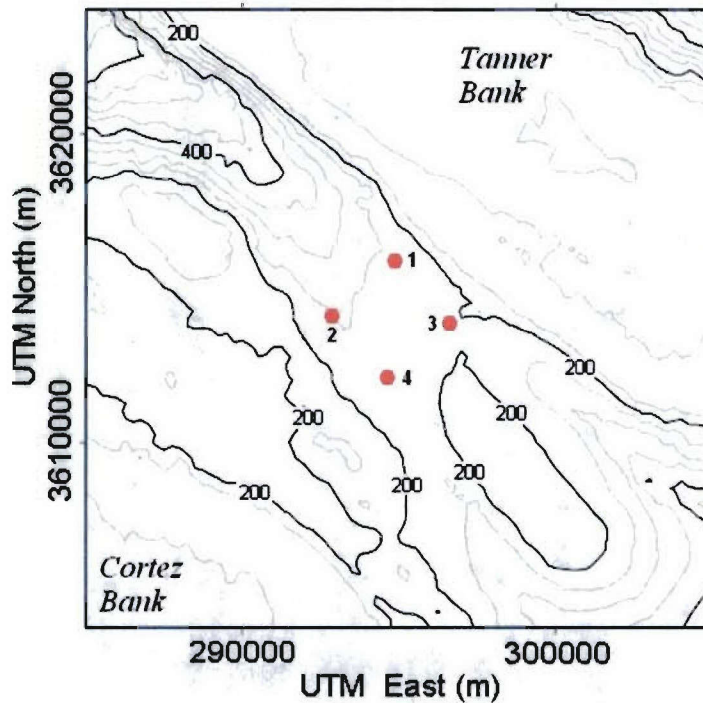
### **Localization Algorithm**

A calling whale is localized through the construction of an ambiguity surface, or probabilistic indicator of the source location made through the comparison of measured time-lags ('data') to predicted time-lags ('replicas'). There are three main components of the localization algorithm: 1) cross correlation to calculate time-lags, 2) replica generation, and 3) ambiguity surface construction, which takes input from the other two modules. Because each of these modules is distinct, alternative methods of performing each can be tested to find the best processing solution. This was the case when measuring time-lags through a correlation process.

#### *Phase-only Correlation*

Measuring time-offsets between whale call arrivals at different receivers is a critical step in the localization algorithm. The standard method for determining time-lags between two whale calls

is through cross correlation, but whether the correlation should be performed in the time domain or frequency domain is open to debate (Clark and Ellison 2000; Janik et al. 2000). Both spectral and waveform correlation techniques were applied to the SCORE dataset, with time-lag results being approximately equal in quality. However, a third correlation technique provided time-lag measurements as good or better than the others with a calculation time shorter than the spectral correlation method. That method is called phase-only correlation, and the results to follow are a result of its use.

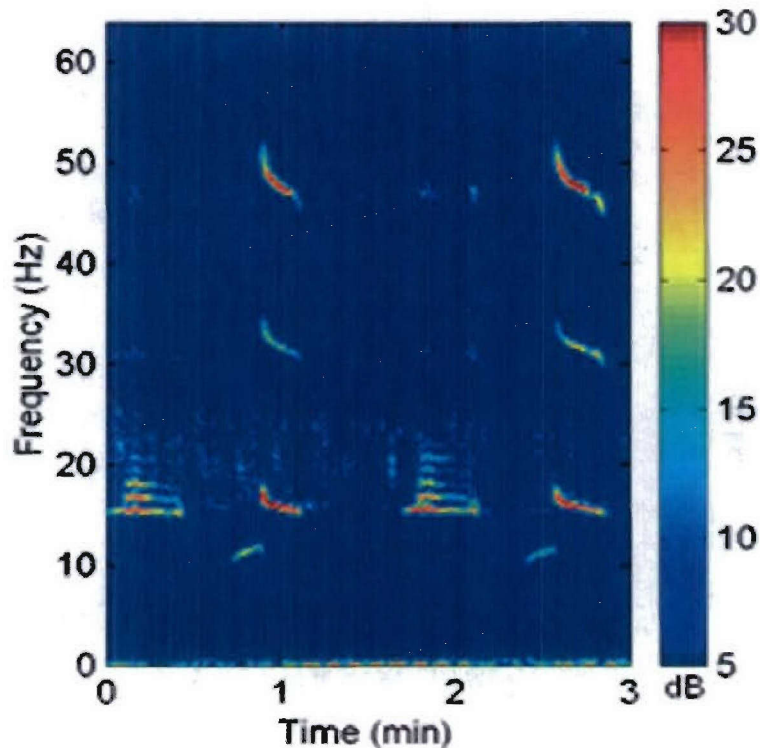


**Figure 11. Southern California Offshore Range (SCORE) Bathymetry contours (m) and seismometer locations (1-4) near the. Axes are for UTM Zone 11.**

In phase-only correlation, a 30-second window of simultaneous time series data is extracted from two receivers, and the amplitude and phase of their frequency components are determined via an FFT. Next, their frequency spectra are whitened by normalizing all amplitude values to the same constant, but phase information is maintained unaltered. Correlation is performed through complex multiplication of the whitened spectra, and a correlation function is made by an inverse FFT on the resulting product. The location of the correlation function peak determines the time-lag between the two receivers, and the peak correlation score provides a confidence level of the measurement. Additionally, one can define which frequencies will contribute to the correlation by zeroing amplitudes for frequency bins outside those bands of interest prior to taking the product of the two spectra.

Time-lags between all combinations of receiver pairs are measured for each time window of interest. Although the correlator returns a time-lag measurement for every time window

examined, only those measurements with high correlation scores are passed to the next module of the localization process. Figure 13 shows an example of pair-wise time-lags provided by the phase-only correlator after analysis of 2.5 days of data from seismometers #1 and #4; those timelags with high associated correlation scores are shown here and are used in the localization examples to follow. In Figure 13, slowly varying time-lag measurements indicate a noise source is changing bearing relative to the receiver pair. By setting thresholds on the correlation score, only the most confident of the time-lag measurements are used during ambiguity surface construction, thus minimizing incorrect localizations and freeing the correlation output from human examination.



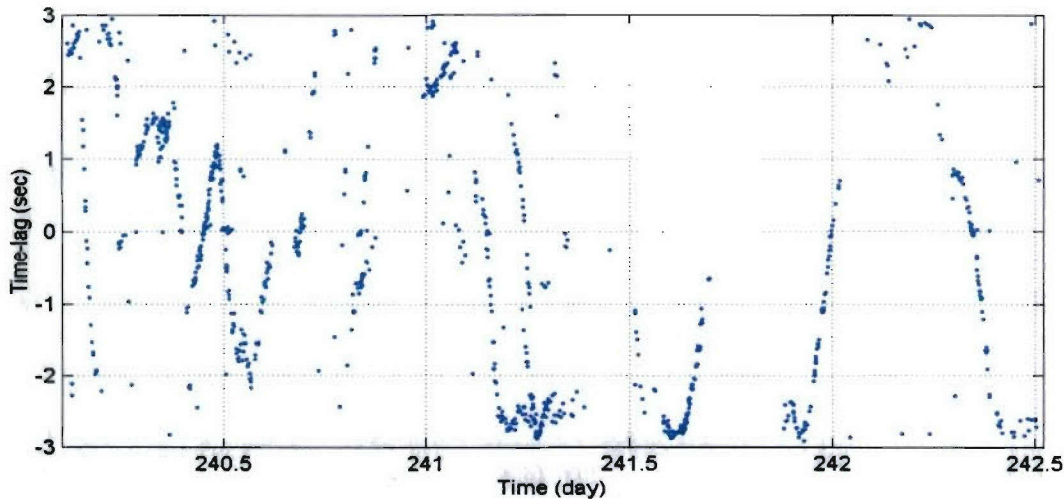
**Figure 12. Blue whale call spectrogram** of data from seismometer #1 starting at time 11:36 on 08/28/01. Spectral amplitude is in dB. Alternating type ‘A’ and ‘B’ blue whale calls are evident here and throughout the data set.

### *Replica Generation*

Another input needed for ambiguity surface construction is the replica. Here, replicas are predictions of the time-lags that would be measured by every receiver pair combination from a hypothesized source at every location within a grid of candidate positions around the array. Time-lags are predicted by first calculating the acoustic travel time from every hypothesized source to every receiver, then taking the difference in travel times between receiver pairs. Simulated sources are spaced 200 m apart in a 20-km square grid around the array.

The acoustic propagation model BELLHOP was used to calculate the acoustic travel times as it can account for depth-dependent soundspeed profiles and range-dependent bathymetry. Note that soundspeed profiles are range-independent, and a shallow source depth at 35 m was assumed. The water depth along a line between every source and receiver is extracted from a bathymetry grid of the area and is used in the modeling process, thus allowing multipath arrivals from bottom-

reflected acoustic paths to be included in the travel time calculation.



**Figure 13. Time-lags measured by the phase-only correlator** between seismometers #1 and #4 during August 28-30, 2001. Slowly varying time-lags indicate a source changing bearing relative to the receivers.

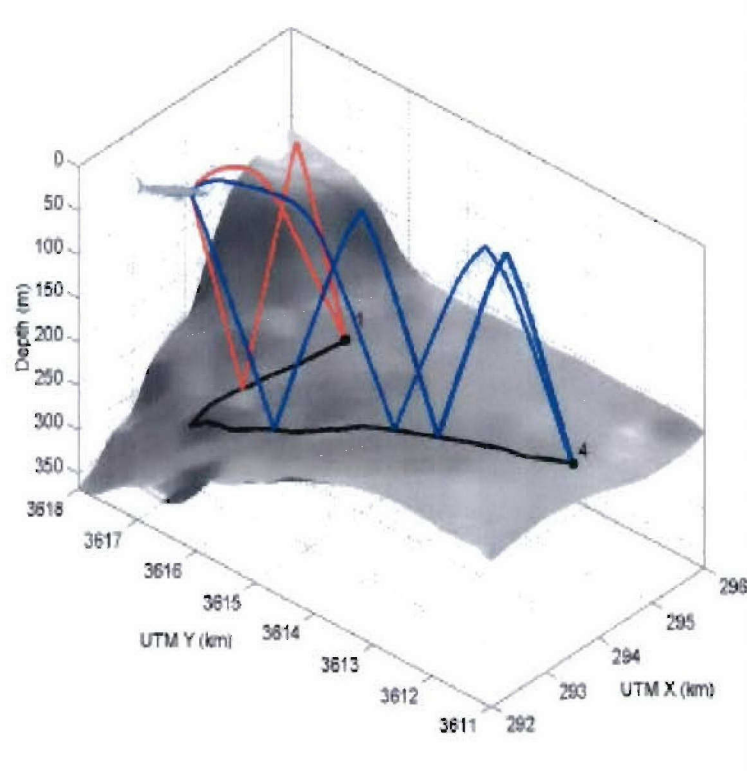
As an aid in visualizing the acoustic model output, Figure 14 shows the predicted acoustic ray paths from a hypothesized whale northwest of the array to seismometers #1 and #4. The curvature of the acoustic rays is due to the downward refracting effects of the soundspeed profile used in the modeling. Note how the paths from the whale to receiver #1 include both a direct (non-reflecting) path and a bottomsurface- reflecting path. In some long-range cases, there may be no direct ray path between source and receiver, as is the case in this example between the whale and receiver #4. The accounting of bottom reflections is one advantage of the model-based localization method over traditional hyperbolic techniques which assume a direct path between source and receiver even when none exist.

Each modeled ray path has an associated travel time, and for every source/receiver combination, an average of all the predicted travel times, weighted by the predicted amplitude of each arrival, is used as the called value of predicted travel time. Taking the differences between travel times completes the replica calculation. The replicas need only be calculated once, provided the receiver positions or environmental parameters do not change.

#### *Ambiguity Surface Construction*

The time-lag data and replica are used as inputs to construct an ambiguity surface that will provide the location estimate for the whale. For each candidate latitude-longitude coordinate in the search grid around the array, the predicted time-lags that would be seen between a pair of hydrophones are compared to the measured time-lag to determine the likelihood that the source is at a particular grid location. The likelihood score is then scaled according to the acoustic transmission loss predicted by BELLHOP, minimizing the likelihood of a detection at long range

from the array. Likelihood scores from one receiver pair are then assembled on a two-dimensional plan view of the area around the array, completing one ambiguity surface. Ambiguity surfaces from several receiver pair combinations are then summed to make an overall surface where source location estimates common to many receiver pairs stack to form a peak. The ambiguity surface peak is declared the best estimate of source position.



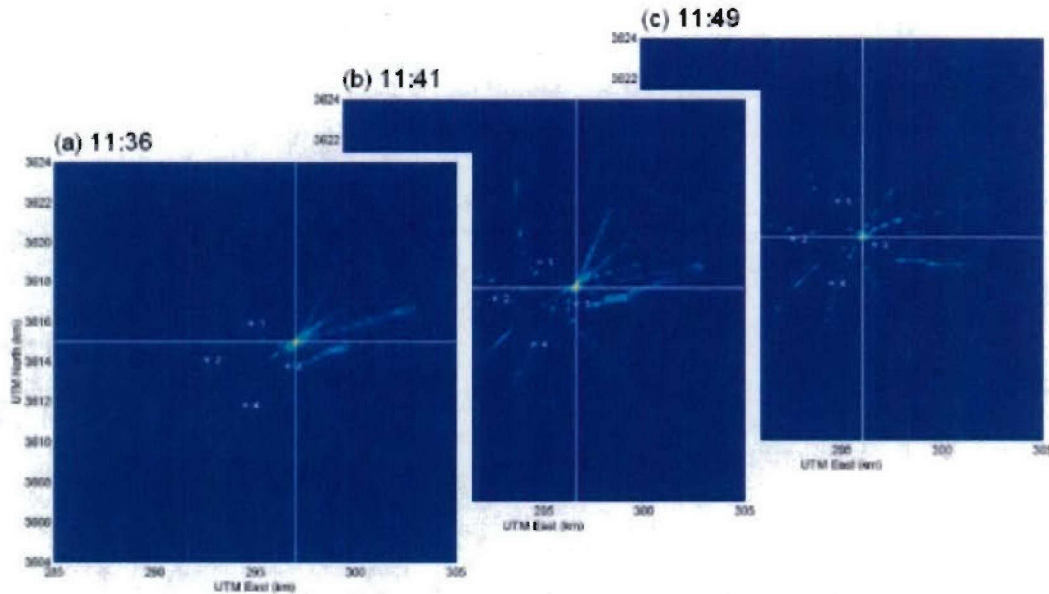
**Figure 14. Predicted acoustic ray paths** between a hypothesized whale and seismometers #1 and #4. Whale not drawn to scale. The range - dependent acoustic model allows for both direct and reflected ray paths to be included in the travel time calculation.

#### *Localization Examples*

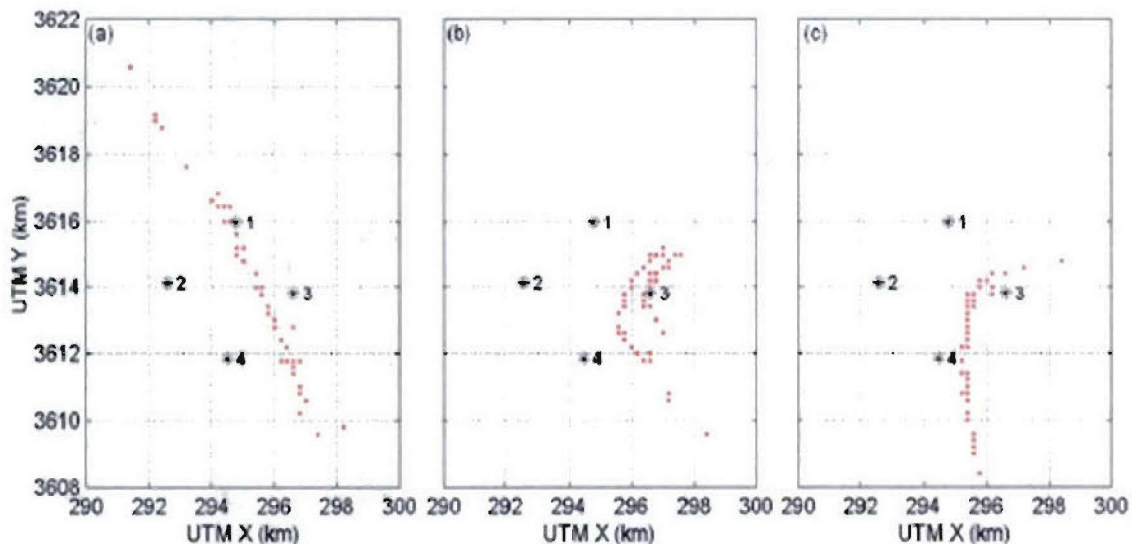
A sample of ambiguity surfaces showing blue whale localizations appears in Figure 15. Each surface represents a 20-km square plan view around the seismometer array, and bright peaks and crosshairs indicate a likely whale location. The three surfaces of Figure 15 show successive localizations over 13 minutes of August 28, 2001, and the peak location can be seen to move to the southwest over time. When ambiguity surfaces from many consecutive time windows are viewed in order, one can watch a localization peak rise and fall as the whale pauses between calls.

Repeated localizations like in this example can be used to follow the motion of a single target as it moves around the array. When the location estimates from many consecutive times are viewed together in a plan view, the track of a whale's course can be seen. Figure 16 shows examples of such whale tracking over several-hour windows on two different days. While tracking of the source is expected to be reliable within the array, the reasonable localizations several kilometers

outside of the array are very encouraging. Because the correlation score thresholds limit the contributions from the correlator, the tracks maintain a fairly tight focus and outlying points are minimized. The tracks are also expected to break up at long range as shown because the chances of having a high correlation score decrease with range from the receivers.



**Figure 15. Ambiguity surface of call tracks** around the array with seismometer positions (1-4) indicated. Axes are for UTM Zone 11. Ambiguity surfaces from model-based localizations indicate blue whale position estimates with bright peaks and crosshairs. Data are from August 28, 2001 at the following times: (a) 11:36 (b) 11:41 (c) 11:49. The location estimate can be seen to move to the southwest in successive frames.



**Figure 16. Point locations of the call tracks** around the array with seismometer positions (1-4) indicated. Estimates from many consecutive time windows, allowing tracking. Data are from the time windows: (a) 08/28/01 02:52-04:52 (b) 08/28/01 09:33-13:50 (c) 08/29/01 02:55-04:50.

## Conclusions and Future Implementation

We have presented a suitable method for monitoring blue whale by tracking their movements within an array of sensors. The algorithm is novel in its use of a range-dependent acoustic propagation model and construction of an ambiguity surface to show probable whale locations in a horizontal plane around a widely spaced array. Successfully applying the algorithm to the offshore California environment and marine mammals of interest demonstrates its robustness and portability. The modular design of the algorithm is a benefit in that different processing schemes can be easily substituted and evaluated, such as when the phase-only correlator replaced the original spectrogram correlator for this analysis. The model-based localization technique is suitable for use in an automated, real-time monitoring system. All of the tracking results presented above were made without user interaction, and calculation time is small once the replicas have been generated. An automated system could continuously monitor a Naval range for mammal activity, generate alerts, launch tracking routines, and flag times of interest for later study; high thresholds on correlation scores can prevent false alarms. Such tools can assist those studying whale behavior as well as those interested in marine mammal mitigation issues. Further algorithm improvements are envisioned. The largest assumption made by the algorithm is that of a constant source depth, but the ability to profile dive behavior is an interesting goal for behavioral studies. More sophisticated use of multipath arrival times, both measured and simulated, may provide the solution to resolving depth. Because this work used seismic sensors, there may be a way to exploit the three-axis nature of the seismometer data to get further directionality clues. Lastly, applying the algorithm to other ranges and species to further test its robustness is yet another goal, as is confirming acoustic localization estimates with other means such as visual surveys.

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## Whale Calling Statistics

One of the key issues for application of acoustic methods to marine mammal population estimation is developing an understanding of the behavioral context for call production and the statistical probability for calling given a particular species in a particular behavioral setting. Over the course of this project we developed better understanding of blue whale calling statistics within the SCORE range and this is described in detail below. We examined the diel variation of blue whale calling and its relationship to foraging. We gained detailed understanding of the seasonal and spatial variation in types of calls and rates of calling for blue whales.

### Diel Blue Whale Calling Patterns Offshore of Southern California

Acoustic monitoring of calling whales provides a means for estimating relative abundance and seasonal distributions of these highly mobile animals. However, abundance estimates from acoustic monitoring require consideration of the whales' calling behavior. 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; Klinowska, 1986; Carlstrom, 2005). 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, but much less frequently than for terrestrial animals because of the difficulty of studying these animals for extended time periods (Klinowska, 1986). Sleep and resting, tidal or lunar day 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 at night including common dolphins (*Delphinus delphis*) (Goold, 2000), North Atlantic right whales (*Eubalaena glacialis*) (Matthews et al., 2001), and harbor porpoises (Carlstrom, 2005). Studies of humpback (*Megaptera novaeanglia*) song in Hawaii found no diel variation (Helweg & Herman, 1994); however, later work in a nearby area where higher humpback densities occur found significant diel variation (Au et al., 2000).

Blue whales (*Balaenoptera musculus*) off California's coast are some of the best studied owing to their relatively good accessibility (Barlow, 1995; Calambokidis et al., 1999). The population of blue whales off southern California is estimated to number about 2000 (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 (McDonald et al., in press), the function of calling is not well understood. 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 (*Balaenoptera physalus*) in which males produce loud song 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 (Thompson et al., 1996; McDonald et al., 2001). 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). We focus on B calls, and do not examine D calls in this paper.

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 (2001) of recordings 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 approximately 100 miles west of San Diego, California (Figure 1 & Table 1). Approximately every two to three months, cruises were conducted to recover data from the ARPs, refurbish the instruments with new batteries and data disks, and conduct shipboard visual surveys.

**Table 8.** *Seafloor autonomous acoustic recording package (ARP) locations* off the coast of southern California

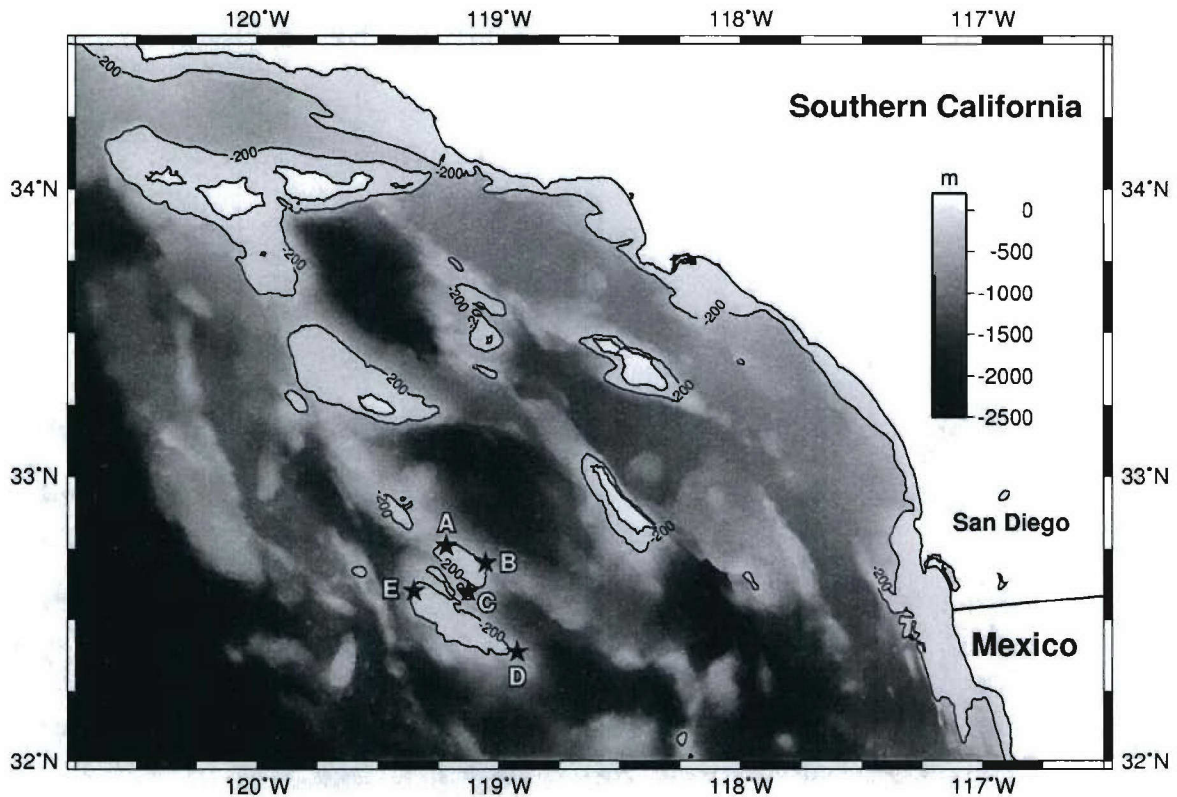
Site	Location		Depth
A	32° 45.62' N	119° 13.00' W	120 m
B	32° 42.08' N	119° 03.24' W	250 m
C	32° 35.74' N	119° 07.58' W	150 m
D	32° 23.29' N	118° 55.42' W	430 m
E	32° 36.16' N	119° 21.15' W	150 m

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, and release and data logger electronics. The ARPs were configured to continuously record 16-bit samples (96 dB of dynamic range) at a sample rate of 1 kHz onto hard disk drives. An ARP hydrophone consisted of lead-zircon-titanate (PZT) ceramic cartridges (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 18) was selected for detection since at 48 Hz and 20 seconds long, its SNR

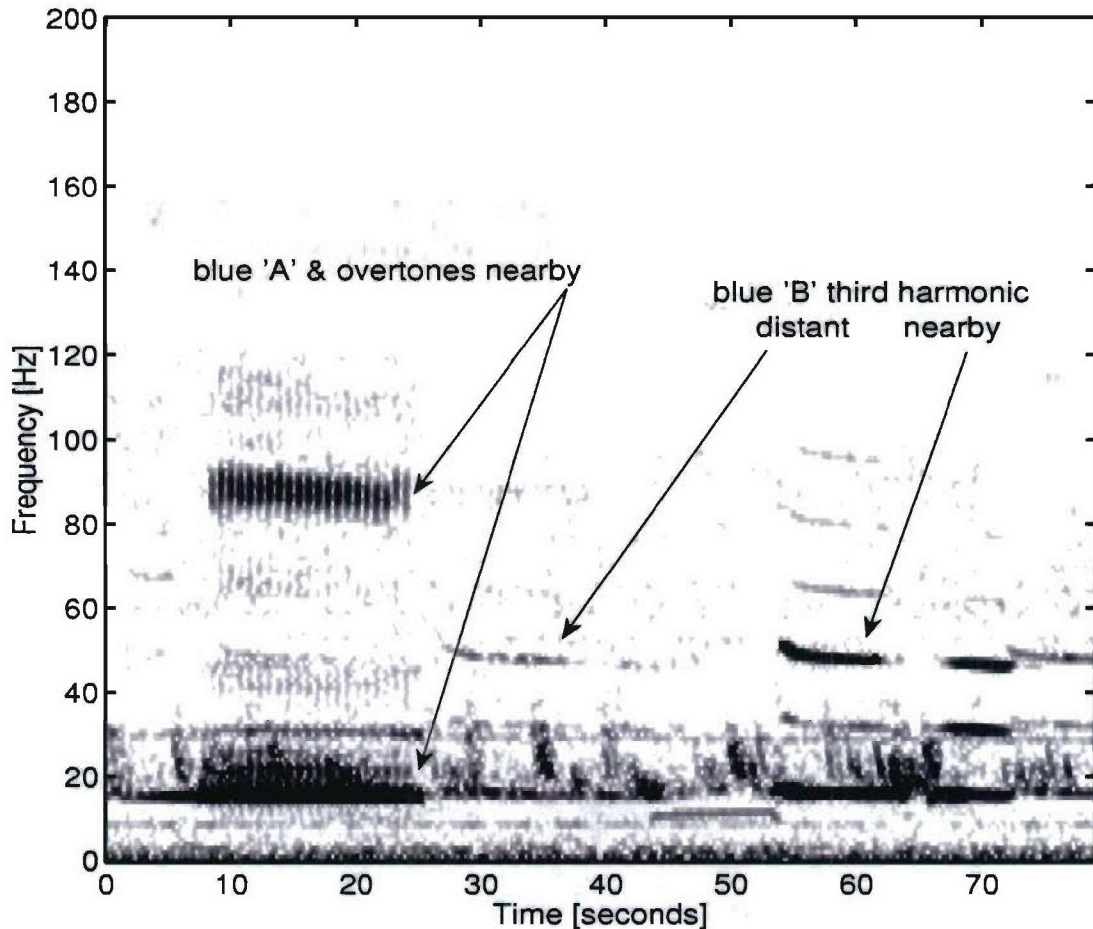
often is higher than the fundamental frequency at 16 Hz. The third harmonic is at a frequency well above the often present fin whale calls (~35 Hz to ~15 Hz down sweeps) and where ship and ambient ocean noise levels are typically less than at lower frequencies.

To detect B calls we used the software program, Ishmael (Mellinger, 2002), a multi-function 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).



**Figure 17. Southern California Bight bathymetry map** shown with 200 m contours; the five stars depict the acoustic recording packages (ARPs) locations on Cortez and Tanner Banks (Table 8).

To calculate the spectrograms used with the detection algorithm, fast Fourier transforms (FFTs) of the time-series waveforms were performed with 2048 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 four sequential continuous linear down sweeps with the first starting at 52.0 Hz and the fourth ending 10 seconds later at 47.9 Hz. The kernel was based on only the first 10 seconds of the call because the received sound levels often varied past this time in the middle part of the call (Figure 18), making detections less reliable.



**Figure 18. Spectrogram of blue whale A (pulsed) and B (tonal) calls, as well as 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).**

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 to computer disk the time and a time-series data file of the detected call. 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 were found. 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. We chose a detection threshold which produced less than 4% false detections and less than 10% missed calls using our manually detected training data.

Blue whale B call detections were processed using the software programming language, MATLAB® (<http://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 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 degrees 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. 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 United States Naval Observatory Astronomical Application Department (<http://aa.usno.navy.mil>). Hourly patterns used 24, one-hour 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/hr) for each time period. The data were mean adjusted by subtracting each day's mean number of detections/hr from the detection rate of each time period for that day to remove biasing effects caused by variations in the daily detections rates throughout the year.

We tested the null hypothesis that the number of detections per hour is constant over a 24 hour 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.

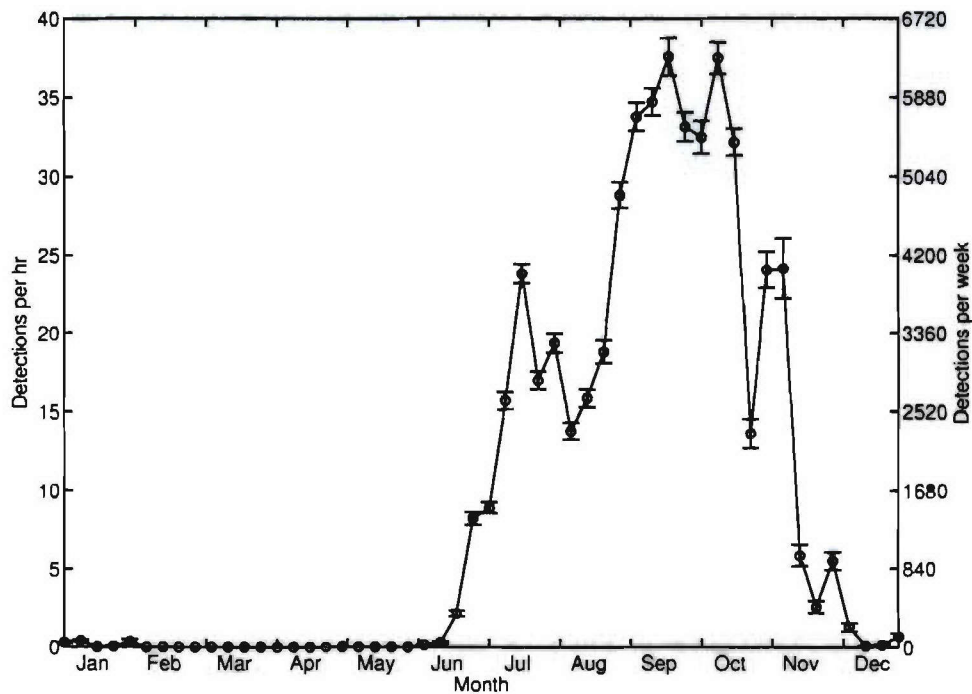
### **Results**

Analysis of the weekly average number of detections/hr reveals a seasonal cycle of blue whale calling beginning in late spring and lasting until late fall (Figure 19). During mid-summer, the average rate was about 15-20 detections/hr, whereas during late summer/early fall, the rate increased to approximately 30-35 detections/hr. 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 9).

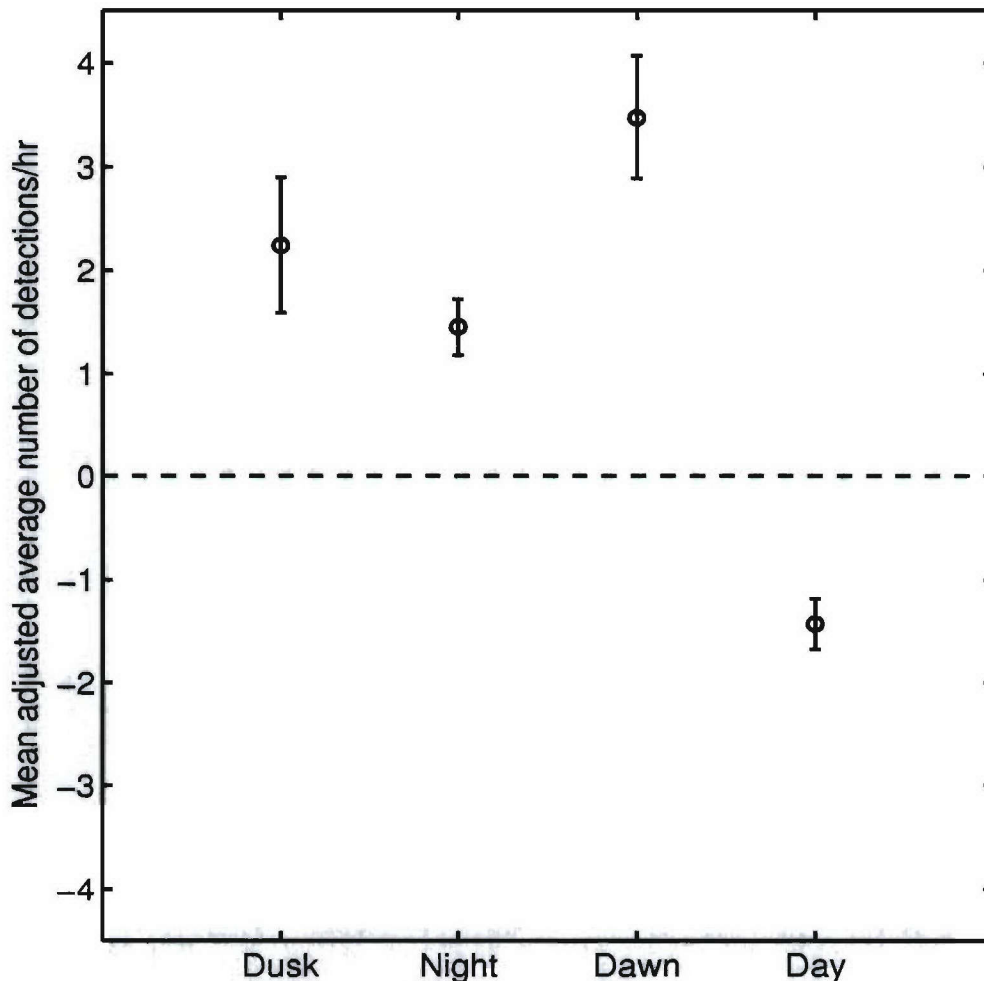
The null hypothesis that the call detection rate was the same for the four diel time periods was rejected (Kruskal-Wallis ANOVA,  $H_3$ ,  $207 = 75.68$ ,  $P < 0.001$ ). The mean adjusted average number of detection/hr for the four diel time periods and their SEs for  $N = 207$  days were  $2.24 \pm 0.66$  (dusk),  $1.45 \pm 0.27$  (night),  $3.48 \pm 0.59$  (dawn), and  $-1.43 \pm 0.24$  (day) (Figure 20). The multiple comparison test showed that the time periods dusk, night, and dawn were not significantly different from each other, but all three were significantly different from the day time period.

**Table 9. Number of blue whale B detections for each recording period and site.**

	Jan – Feb (52 days)	Feb – Apr (68 days)	Apr – Jun (51 days)	Jun – Aug (63 days)	Aug – Oct (63 days)	Oct – Dec (68 days)	Total
A	-	0	-	-	-	-	0
B	254	-	-	15347	61277	-	76878
C	311	0	129	29685	33734	-	63859
D	603	-	-	-	-	13460	14063
E	-	-	-	24562	44574	-	69136
Total	1168	0	129	69594	139585	13460	223936



**Figure 19. Number of call detections per hour averaged in one week time periods and per instrument for 2001. Error bars are  $\pm$  SE values. The right vertical axis shows the total number of detections in the one week time periods per instrument.**

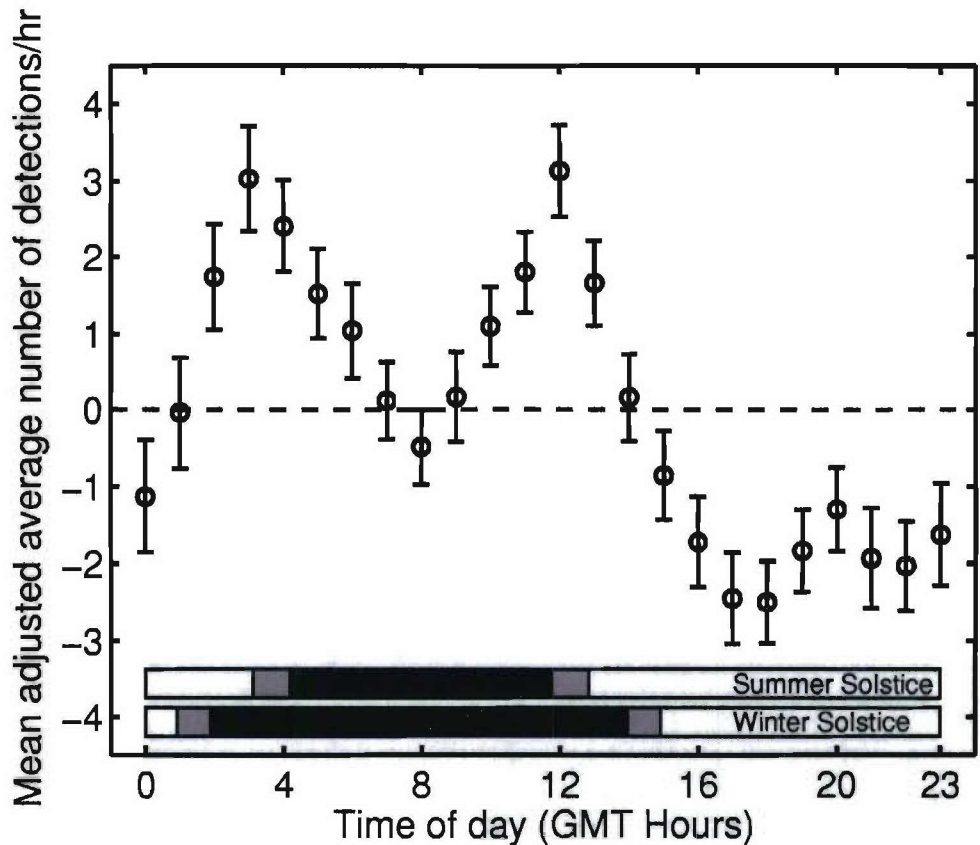


**Figure 20. Mean adjusted average number of detections per hour** in four diel time periods for  $N = 207$  days. Daily diel time periods were obtained for 2001 at  $32^{\circ} 36'N$ ,  $119^{\circ} 08'W$  from the United States Naval Observatory Astronomical Application Department (<http://aa.usno.navy.mil>). Error bars are  $\pm$  SE values.

Mean adjusted average detection rates for 24, one-hour time periods showed more detail in the daily calling pattern than the diel time period averages (Figure 21), 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 night time minimum between the two peaks.

### 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., 2001a)



**Figure 21. Mean adjusted average number of detections per hour** in GMT-based one hour time periods during 2001 (N = 207, Error bars are  $\pm$  SE values). Horizontal bars at bottom of plot show day (white), dawn and dusk twilight (gray), and night (black) time periods for the two extreme light regimes, summer and winter solstices.

There was a diel pattern for blue whale calling with most calls detected during the summer and fall for our study area offshore from southern California. 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 (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 (2001b) 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

(McDonald et al., in press). Alternatively, calls may serve a different social function such as territory defense. Calling may be non-social and function to sense their environment for navigation purposes (Clark & Ellison, 2004) as do odontocete whales (i.e., echo-location). Or, perhaps calling is used for a combination of the above.

Whether blue whales call to attract mates, display fitness, or to navigate, 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 offshore of southern California, blue whales forage 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, and presumably call less when occupied with foraging during the day when the krill are aggregated at depth. However, Croll et al (2002) proposed 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 night time minimum in calling in our data may be an indication of increased surface skim feeding (Fiedler 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 (Thode et al., 2000; Oleson et al., 2004), which suggests that feeding blue whales are less likely to call since foraging places them at depths greater than where they 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 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 estimation of relative abundance and seasonal occurrence from acoustic monitoring, as well as contribute to understanding why blue whales call.

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## Patterns in Blue and Fin Whale Call Occurrence in the Southern California Bight

Understanding the spatial and temporal distribution of marine mammal calls is another key element of using acoustics for population estimation. Over the course of this project we developed a detailed understanding of blue whale calls within the SCORE range and this is described below.

Blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales produce low frequency, stereotypical sounds which have proven to be useful cues for monitoring these species distribution and large-scale movements (eg. Thompson and Friedl 1982, Moore et al. 1998, Stafford et al. 1998, Watkins et al. 2000, Stafford et al. 2001, Burtenshaw et al. 2004). As acoustic methods for baleen whale monitoring improve and become more commonplace, there is a growing need to understand how they may contribute to marine mammal stock assessment and habitat use (Mellinger and Barlow 2003). Autonomous acoustic recorders provide a means of long-term monitoring of baleen whale presence in limited access regions where visual surveys are inadequate, such as the Antarctic (Sirovic et al. 2004) and the Bering and Beaufort Seas (Clark and Ellison 1989). However, long-term acoustic records in regions with good visual estimates of baleen whale seasonality and abundance can provide new insights into the context of calling and habitat use, and provide additional information needed for the development of new survey methodologies for these species.

Northeast Pacific blue whales migrate annually between productive summer feeding grounds off California to lower latitude breeding ground near Mexico (Calambokidis et al. 1990, Reilly and Thayer 1990) and Costa Rica (Mate et al. 1999, Stafford et al. 2001). The seasonality of blue whales in Southern California feeding areas has been described from ship and aerial surveys, indicating that blue whales are present in the highest concentrations in the late summer, with dwindling numbers into the fall and winter (Forney and Barlow 1998, Larkman and Veit 1998, Carretta et al. 2000). Additionally, an increasing proportion of the blue whale population is thought to be using southern California waters since the early 1990's (Carretta et al. 2001). The presence of blue whale sounds, recorded on autonomous hydrophones moored throughout the northeast Pacific, have been used by several authors to monitor the seasonal movements of vocal whales among regions. Stafford et al. (2001) illustrated the north-south movements of these whales between the eastern tropical Pacific and the central and northeastern Pacific, and Burtenshaw et al. (2004) have shown that the greatest number of calling blue whales occurs off southern and central California in the summer and fall.

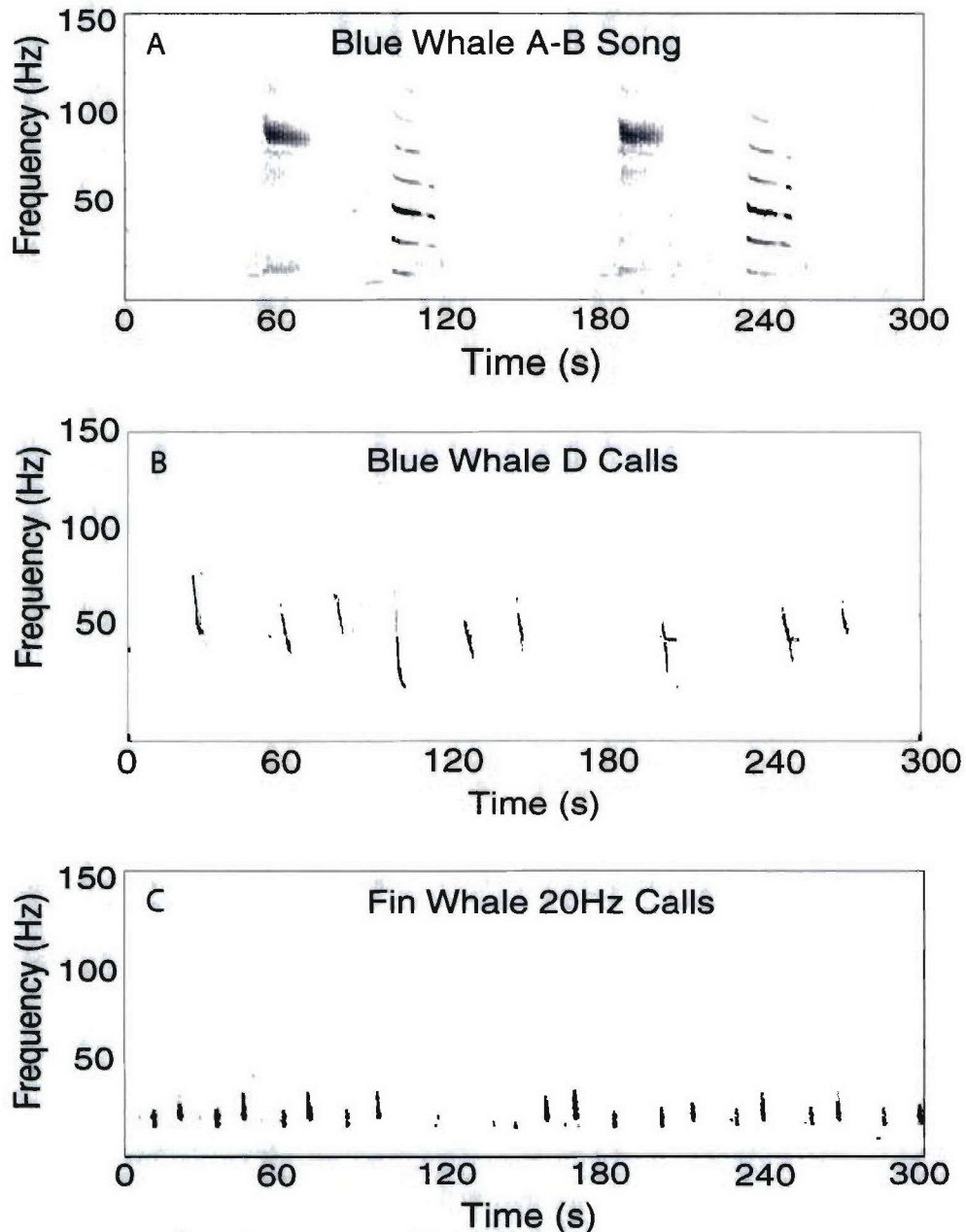
Little is known about the migration behavior of North Pacific fin whales, although they have been observed in all months off the coast of California (Forney and Barlow 1998, Carretta et al. 2000) and in the Gulf of California (Tershy et al. 1993). Visual surveys indicate that both locations show seasonal increases in abundance during the summer. In contrast, year-round acoustic observations from several different locations indicate that fin whales are heard in all months off northern California, Oregon, and Washington, with seasonal increases in reception in the fall and winter (Moore et al. 1998, Watkins et al. 2000), similar to call patterns off Hawaii (Thompson and Friedl 1982, McDonald and Fox 1999). While fin whales are known to occur in all months in the southern California Bight from visual surveys, there have been no long-term studies of fin whale acoustic presence in the region, with only incidental recordings of their presence in the summer and fall (eg. Clark and Fristrup 1997, Croll et al. 2001, McDonald et al.

2001).

Blue whales are known to produce at least four different sound types. Type A and B calls (Thompson et al. 1996) are long duration (~20 s), low frequency (16 Hz), harmonically rich sounds which can occur together in an alternating series of A and B calls (Rivers 1997, Stafford et al. 1998), termed song (Figure 22a), or as individual, singular calls (Oleson et al. in prep). Song A and B calls are most commonly heard from traveling solitary males (McDonald et al. 2001, Oleson et al. in prep), and may be involved in reproduction, while singular A and B calls have been recorded from pairs and groups engaged in a variety of behaviors (Oleson et al. in prep). Most acoustic descriptions of blue whale distribution and seasonality use the occurrence of A and B calls, while the call's distinction as song or singular is overlooked. A third call type known as the D call was originally described by Thompson et al. (1996), as a down-sweeping (90 Hz – 25Hz), short duration (1-4 s) call (Figure 22b). Recent work on the context of this call type indicates that it is heard from both sexes and occurs as counter-calls among feeding blue whales and in short sequences from individual whales (McDonald et al. 2001, Oleson et al. in prep). Further, D calls occur occasionally with a fourth call type, known collectively as variable AM/FM calls (Thode et al. 2000, Oleson et al. in prep).

While fin whales have been recorded producing several low frequency call types, they are most commonly heard producing slight variations on a single call type. Short duration (~1 s), low frequency down-sweep (35-18 Hz) (Figure 23c), was first identified in the North Atlantic as a fin whale call by Schevill et al. (1963), and since has been attributed to fin whales worldwide. Fin whale populations may be distinguished by patterns in their song intercall interval; however, no characteristic interval for the eastern North Pacific has been identified (Hatch and Clark 2004). Fin whale calls may also occur in call-counter-call sequences between traveling individuals (McDonald et al. 1995).

The majority of existing acoustic work on blue and fin whales has focused largely on the presence and geographic distribution of a single call type, without attention to more subtle differences in the occurrence of other calls in the species' repertoire. In particular, little attention has been paid to the seasonality, distribution, and context of blue whale downswept, D calls, a call type which may be the most useful for monitoring foraging areas. We suggest that the seasonal presence of certain call types in a localized area may indicate changing environmental conditions and whale behavior. We have collected nearly four years of continuous acoustic data at Cortez and Tanner Banks in the Southern California Bight. By detecting several blue and fin whale call types from these acoustic data, we have elucidated the differences in the patterns of three styles of blue whale calling (song, singular B, and D calls) and fin whale calling (song and counter-calling combined). While the overall seasonality of blue and fin whale calls remains stable over the four year time series, changing annual, daily, and spatial patterns of call reception are evident, underscoring the need to understand the ecological role of calling for these species.



**Figure 22.** Northeast Pacific blue and fin whale call types detected in this study. A) Blue whale A and B calls organized into a song pattern. These calls may also occur singly, with frequency and duration characteristics identical to those represented here. B) Blue whale downswept D calls, indicating the large variability in frequency content and seep rate. C) Fin whale 35-20Hz calls here in a call-counter call sequence. These calls are also organized into song patterns; however we did not distinguish fin whale song calls in this study.

### Methods

From 20 August, 2000 to 20 February, 2004, 1215 days (3120 instrument-days) of continuous acoustic data were recorded using Acoustic Recording Packages (ARPs) and Ocean Bottom Seismometers (OBSs) in the Southern California Bight. Recorders were positioned at one to four sites (average 2.4) around Cortez and Tanner Banks. The banks are approximately 180 km west

of San Diego, California, in the southern portion of the Southern California Bight (Figure 23), and rise to within 100m of the sea surface. The banks a popular feeding ground for several species of cetacean, including blue and fin whales. Cruises were conducted every two to six months to service the recorders, consisting of battery and data disk replacement and instrument Site 3hanges. Site positions are listed in Table 10. No data were collected from 5 February to 15 April 2002.

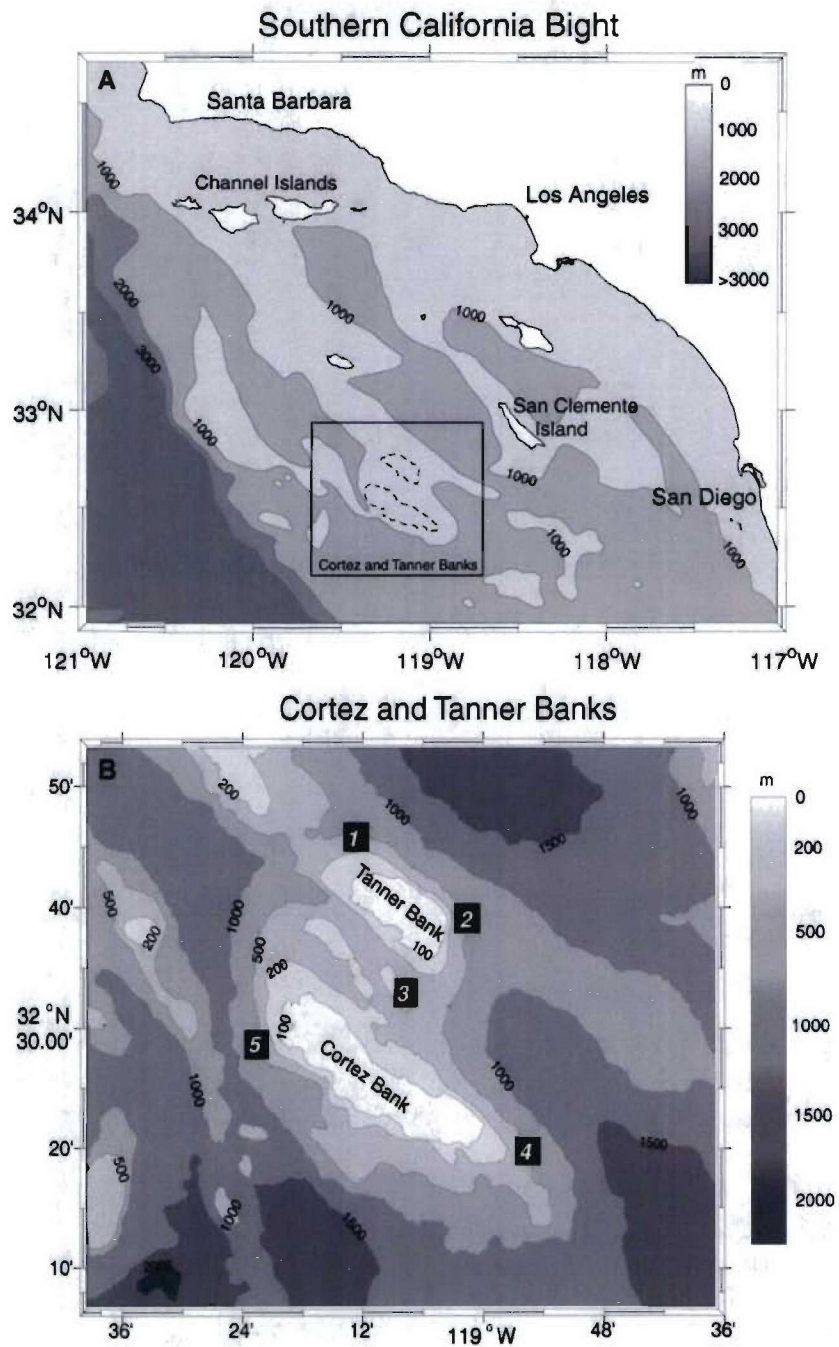
ARPs are bottom-mounted data logging systems with a 16-bit A/D converter, 36GB of storage capacity, a hydrophone tethered 10m above the seafloor, a release system, ballast weights, and flotation (Wiggins 2003). From August 2000 to June 2002 the deployed pre-amplified hydrophones had a sensitivity of -154dB re:  $V_{rms}/\mu Pa$  and a -3dB low-end roll-off of 5Hz. In July 2002, the hydrophone was replaced with one having an increased sensitivity (-157 dB re:  $V_{rms}/\mu Pa$ ) and lower electronic noise. Data were collected at either 500 or 1000 samples/sec sample rate, resulting in an effective bandwidth between 5 and 250 or 5 and 500Hz respectively. The sample rate was chosen based on the desired deployment duration and instrument recording capacity. The maximum recording duration at 500Hz was 400 days. During two periods, from June to July 2002, and from November, 2003 to February, 2004, Ocean Bottom Seismometers (OBSs) were used while ARPs were removed from the area for hydrophone replacement or for relocation to other regions. While OBSs were designed for monitoring seismic sounds, they also record the low-frequency sounds of blue and fin whales (McDonald et al. 1995). OBSs are bottom-mounted, with the only significant differences from ARPs being their reduced sample rate (128Hz) (Sauter et al. 1990).

*Table 10. ARP and OBS site locations 20 August 2000 to 20 February 2004.*

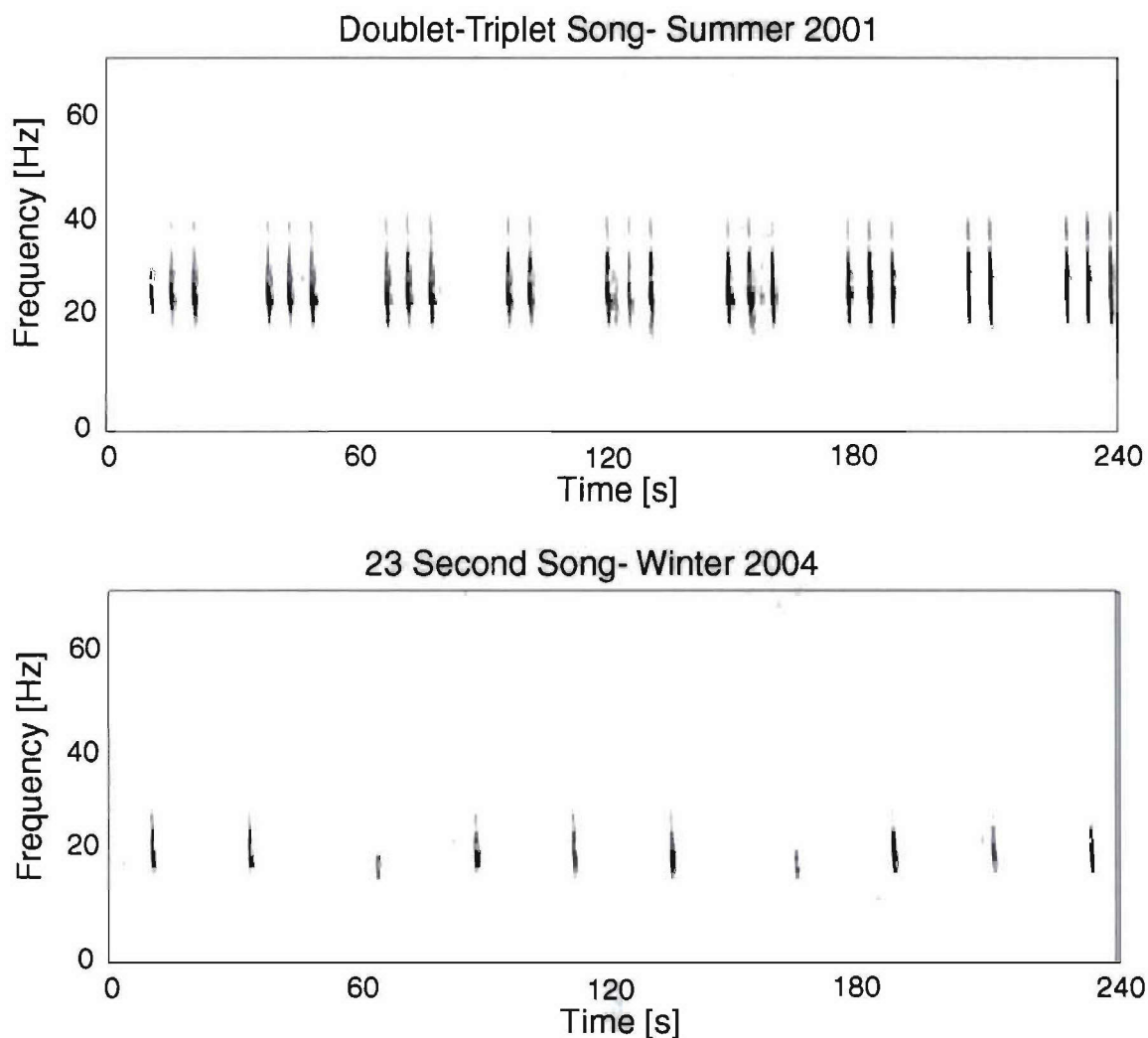
Site	Latitude	Longitude	Water Depth (m)
1	32 45.6	119 12.5	150
2	32 41.3	119 01.9	300
3	32 35.8	119 08.8	200
4	32 23.3	118 55.4	430
5	32 39.5	119 19.8	320

After instrument retrieval, the acoustic data were offloaded to processing computers and examined for the presence of blue and fin whales calls using the software program Ishmael (Mellinger 2002). The data were initially checked by a human analyst and were then run through an automatic detection algorithm to record the occurrence of calls. Ishmael provides three separate methods of automatic call detection: energy summation, spectrogram correlation, and waveform matched-filtering. Each of these methods was tested for accuracy at detecting blue and fin whale calls using a data-set previously scanned by an analyst. The goal was to minimize the number of missed calls and false detections (incorrect classification). Spectrogram correlation was the best detection method for these call types with fewer false detections than the energy summation method and fewer missed detections than matched-filter detection. Spectrogram correlation detects calls by cross-correlating a synthetic time-frequency kernel, representing a whale call, with the acoustic spectral data. The result is a detection function which indicates the likelihood a matching call is present (Mellinger and Clark 1997, 2000). This detection function must exceed a user specified threshold for a specified period of time before

call detection is recognized. After detection, a segment of the acoustic data is saved to computer disk.



**Figure 23. Southern California Bight (A) bathymetry showing Cortez and Tanner Banks study site. B) Cortez and Tanner Banks with monitoring locations noted as black lettered squares. Monitoring positions and depths are in Table 10.**



**Figure 24. Examples of fin whale song observed at Cortes and Tanner banks.** A) Doublet-triplet pattern found at site 3 in summer of 2001. B) Consistent 23s interval pulses with varying frequency content found at sites 2 and 3 in winter 2003-04.

The threshold, the detection function duration above the threshold, and the detection neighborhood (minimum time between detection events) were iteratively adjusted until the rate of false detections was less than 3%. A trade-off between the number of false-detections and the number of missed calls increased the number of missed calls to approximately 20%. Periods with low numbers of detections were manually checked for higher levels of false detection, and approximately 1000 detections per month were randomly chosen from each site to insure that the false detection rate remained at or below 3%.

Detection parameters for the blue whale B call and the fin whale call are shown in Table 11. The blue whale B third harmonic was chosen because its signal-to-noise ratio (SNR) is typically better than the fundamental and other harmonics. The A call was not chosen for analysis because

its pulsed character and generally lower SNR reduced its detection rate relative to B calls when using either spectrogram correlation or energy summation. The blue whale B call kernel was adjusted annually to respond to shifts in the frequency content of this call (JAH, unpublished data), and spectrogram equalization was required from 2002-2004 to reduce the increased effect of ambient noise from the change in hydrophone sensitivity. The use of spectrogram equalization did not change the rate of false detections or missed calls relative to the 2000 and 2001 datasets. Spectrogram equalization is a form of automatic gain control, which subtracts the absolute spectral level in each frequency bin from the spectrogram resulting in more consistent background noise levels through time. This type of signal conditioning is particularly useful for detecting nearly tonal calls, such as blue whale B calls, during periods of high shipping noise.

Blue whale D calls are highly variable in sweep rate and frequency content. These characteristics make it difficult to design a time-frequency kernel which can reliably detect this call type. As an alternative to automatic detection, D calls were picked by an analyst from one randomly chosen day per week at each site throughout the monitoring period. The analyst used Matlab code, written to quickly examine large sections of data and log the time of each call.

Following automatic detection of blue whale B and fin calls, intercall intervals were computed from the detection times to separate song and singular or counter-call detections. For the purposes of this paper, song is defined as a sequence of stereotypical calls or phrases occurring in a repeated pattern. Conversely, singular calls are defined as calls occurring irregularly, without a recognizable pattern. The intercall interval between each call and all other calls within 200s was computed to identify consistently occurring intervals, representative of song sequences. The song intervals were independently computed by an analyst using a smaller subset of the detections and then checked against automatically computed song intercall intervals. The identified song intervals were then used to sort call detections into song and singular categories.

Inter-annual and seasonal call occurrence patterns were examined by organizing detections and analyst picks into one week bins. The bins were normalized by the number of instrument-days per week to present average instrument-day call counts. Daily call occurrence patterns were determined by sorting each call type by the hour in which it occurred, and normalizing by the number of instrument-hours. Sunset and sunrise times were obtained from the United States Naval Astronomical Application Department for San Diego, California and averaged over the period of monitoring.

Spatial calling patterns at Cortez and Tanner Banks were studied by sorting detections for each site, and then sorting them for the temporal patterns as described above. Time periods of comparison were chosen based on the longest continuous periods within a calling season where more than two instruments were sampling the region. An estimate of detection distance at each site was derived from range-dependant transmission loss curves computed using the Bellhop algorithm of the Matlab-based Acoustic Toolbox (Porter 2002). Variability in detection distance is expected since average noise levels changed frequently, and the variability of the source level of various blue and fin whale calls is unknown. Therefore, the results were interpreted by ranking the relative detection distance at each site for comparison of the number of calls received.

**Table 11. Spectrogram correlation kernel parameters** for blue whale B call and fin whale call detection.

		KERNAL			
	Year	Frequency Start (Hz)	Frequency End (Hz)	Time Start (s)	Time End (s)
Blue whale B call	2000	52.5	51	0	1.5
		51	49.2	1.5	3
		49.2	48.8	3	4.5
		48.8	48.4	4.5	10
	2001	52	50.5	0	1.5
		50.5	48.7	1.5	3
		48.7	48.3	3	4.5
		48.3	47.9	4.5	10
	2002	51.5	50	0	1.5
		50	48.2	1.5	3
		48.2	47.8	3	4.5
		47.8	47.2	4.5	10
	2003	51	50.5	0	1.5
		49.5	47.7	1.5	3
		47.7	47.3	3	4.5
		47.3	46.8	4.5	10
Fin whale	2000-03	35	20	0	0.8

### Results

We found the detection of blue and fin whale calls to be variable on several temporal and spatial scales. From 20 August, 2000 to 20 February, 2004, Cortez and Tanner Banks were acoustically monitored for 3,120 instrument-days, resulting in the per instrument detection of 96,537 blue whale song B calls, 45,053 blue whale singular B calls, 58,006 blue whale D calls, and 1,299,757 fin whale calls. Additionally two blue whale song phrases were observed through sorting of call intervals, the first at 48s for successive B calls (eg. ABB), and the second at 128s for B calls interspersed with A calls (eg. BAB). Inspection of the acoustic data by an analyst indicated that fin whale song was occasionally present (eg. Fig 24); however, song characters were highly variable among whales and through time. Furthermore, the large number of fin whale call detections prevented the separation of counter-calls from potential song segments. No consistent song intervals were found over the four year time series, even when searching for specific song intervals observed by an analyst. Pattern in the blue and fin whale call detections will be described below according to their seasonal, annual, spatial, and diel variability.

### *Seasonality*

Blue whale calls were detected seasonally from April to January (Figure 25a) during each year of this study. Blue whale D calls occurred earlier in the season than other calls, from April through November, with a peak occurrence in June and July and again in September and October. Blue whale B calls occurred later in the summer and fall, from June to January. Blue whale B singular calls, while co-occurring with song B calls, represent a higher proportion of the total number of B calls detected at the beginning and end of the calling season. Likewise, the proportion of 128s B-call intervals was greatest at the beginning and end of the calling season. Both song and singular B calls peak in September with an average exceeding 400 calls per day for song and approaching 200 calls per day for singular calls.

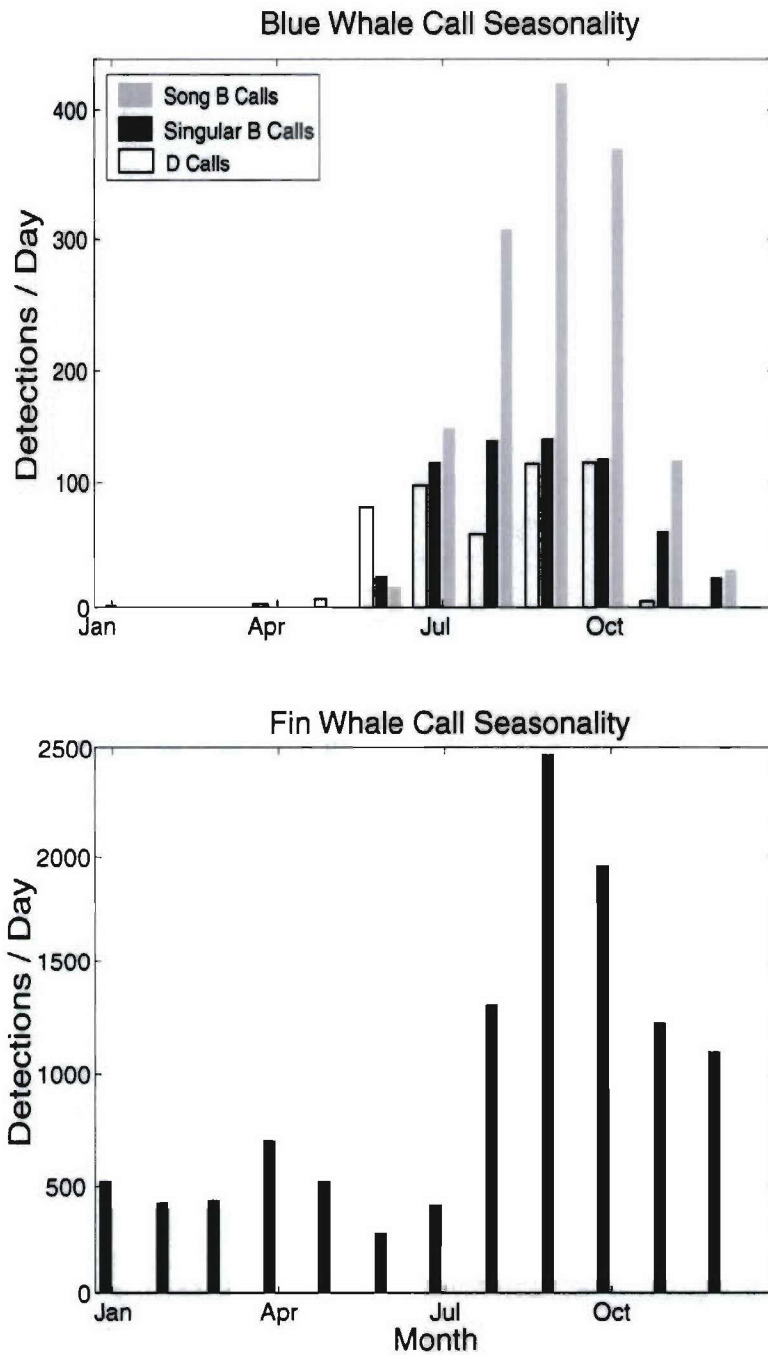
Fin whale calls were recorded in all months of the year, with peak detection in September and October (Figure 25b), and an average detection rate of nearly 2500 calls per day. Late winter and spring accounted for the fewest detections of fin whale calls, with a low of nearly 250 calls per day in early March; and a slight peak in April of approximately 750 calls per day.

### *Annual Variability*

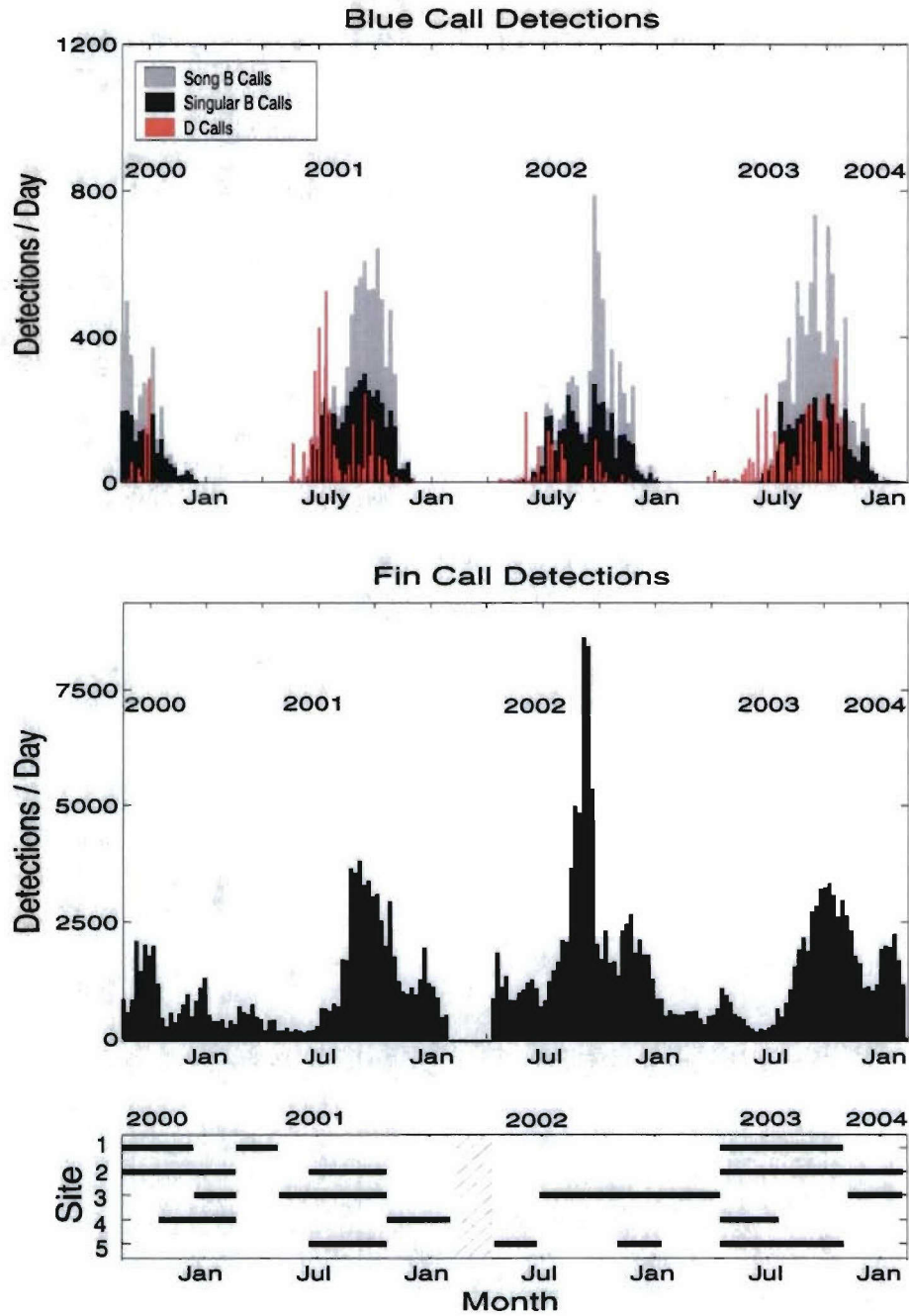
Year-to-year variations in blue and fin whale call detections were apparent. There was an increase in the number of days in which blue whale calling was detected from one year to the next (Table 12), with changes in the timing of the arrival and departure of calling whales between years. Both blue and fin whale call detection rates changed annually, most notably with the early arrival of blue whale calls in the spring and their delayed departure in the winter (Figure 27a). Also notable is the secondary seasonal spike in fin whale detection between November and January after a relative drop in detections in late fall to early winter. This bi-modal seasonal pattern in fin whale calling was not evident in the annual average shown in Figure 25b, because the timing of the decrease and second peak in fin whale call detection rates was not consistent, and was averaged out across years. Some caution must be used when interpreting year-to-year changes as the number and choice of monitoring locations changed from one year to the next (Figure 27- bottom panel), potentially influencing call detections. For instance, in 2002 only Site 3 was monitored for much of the summer and fall season potentially increasing the variability in detection rates compared to other years.

**Table 12.** *The number of days in which blue and fin whale calls were detected each year at any site. Year is defined as March 1 – February 28 to allow for extension of the blue whale calling season into the next calendar year. Data from 2000 were excluded since they did not represent an entire blue whale season. Blue D calls days are shown in parenthesis to indicate the extrapolated number of days based on the number of those actually picked over the year.*

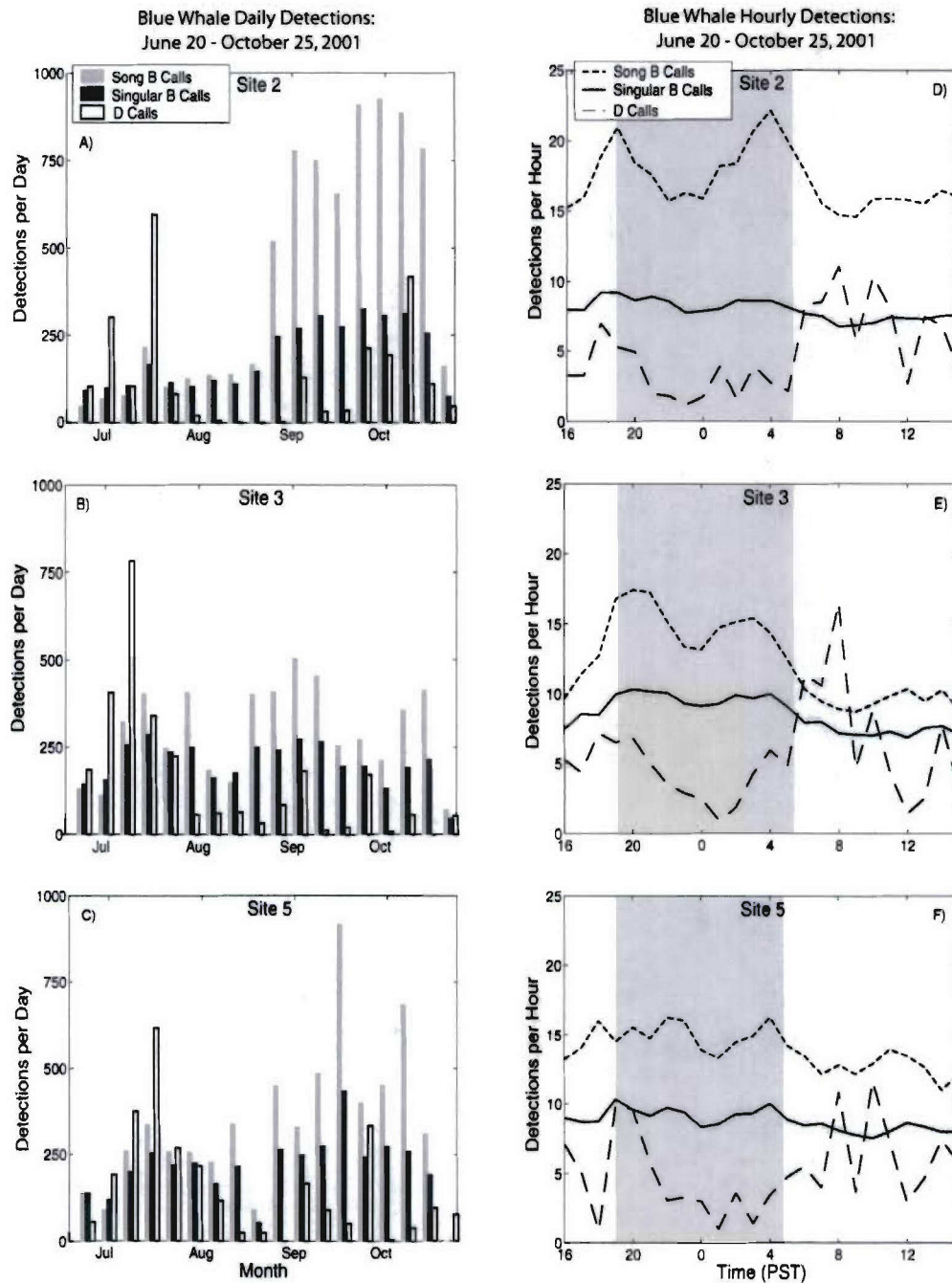
Call Type	2001-02	2002-03	2003-04
Blue ABA	201	242	256
Blue ABB	202	240	252
Blue Singular B	200	238	255
Blue D	(207)	(211)	(241)
Fin (All)	365	294	365



**Figure 25.** Blue and fin whale average annual calling seasonality at Cortes and Tanner Banks. A) Blue whale song, singular B, and D call seasonality. B) Fin whale annual call seasonality



**Figure 26. Blue and fin whale call detections** from 20 August, 2000 to 20 February, 2004. A) Song and singular B calls, and D calls are indicated. B) Fin whale call occurrence. C) Sites monitored over the study period. Grey hatching indicates no data available.



**Figure 27. Blue whale call occurrence at three sites** from 20 June to 25 October, 2001. A-C) Daily call occurrence by blue whales at sites 2, 3 and 5. D-F) Diel occurrence for blue whale call types at sites 2, 3, and 5. Notice the pattern of preferred song production at dusk and dawn at sites 2 and 3 and preferred D call production during daylight hours at all sites. Grey shading indicates the period between dusk and dawn.

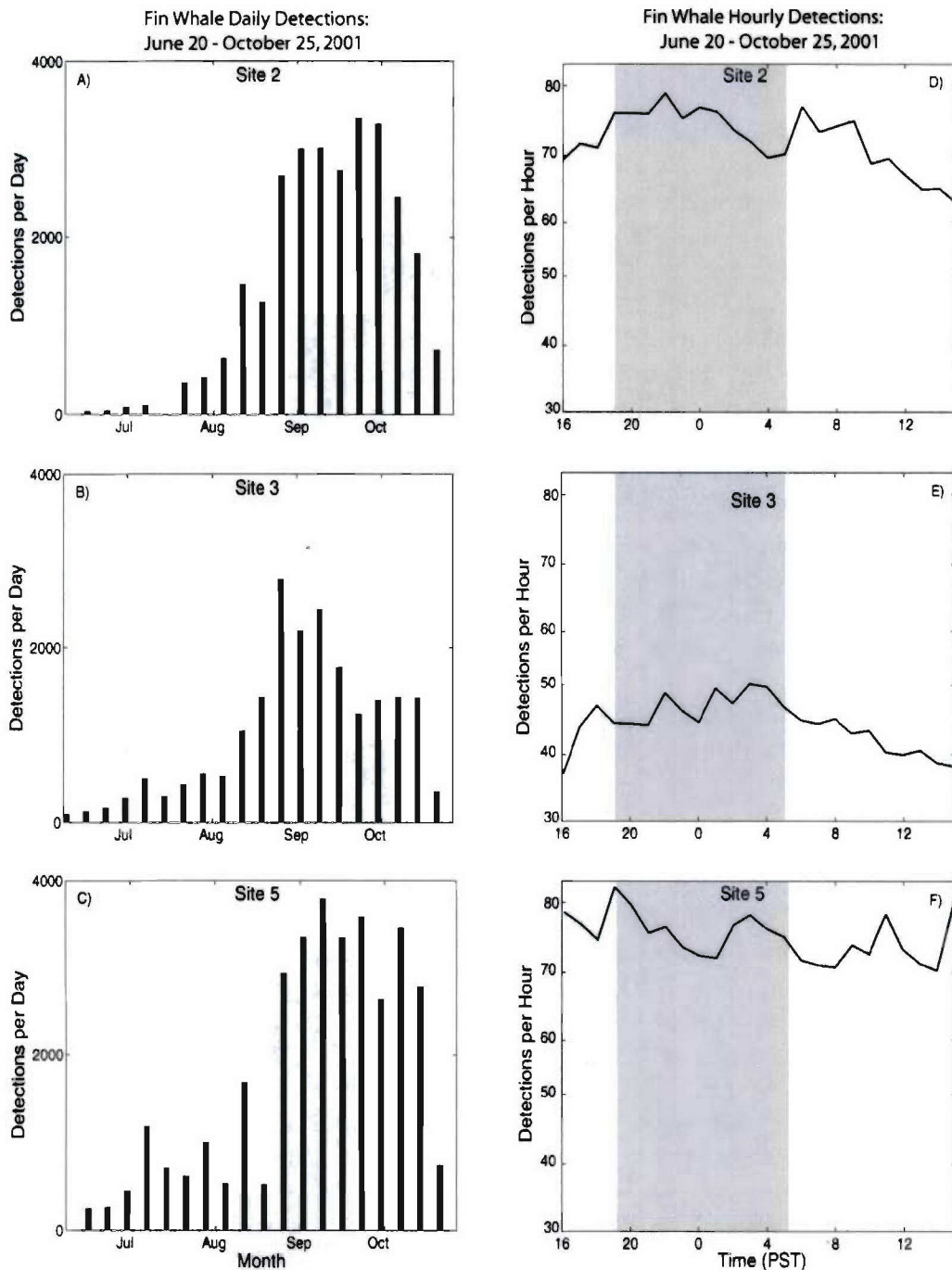
### *Spatial Variability*

Annual variations in calls detection rates can be examined on a site-by-site basis. All sites were not continuously monitored for the entire study, and the overall picture of blue and fin whale presence described above is an average from five sites monitored at Cortez and Tanner Banks. However, on several occasions the same set of sites were simultaneously monitored allowing for a comparison of call detection rates from similar periods.

During two time periods, from 20 June to 25 October 2001, and 16 April to 4 November 2003, three sites were simultaneously monitored providing insight into the detection rate of various blue and fin whale call types in different regions of the study area. For the period in 2001, Sites 2, 3, and 5 were monitored providing information from the northwest edge of Cortez Bank (Site 5), between the banks (Site 3), and the southeast corner of Tanner Bank (Site 2). During this period there were clear differences in the detection rate of blue whale song, singular, and D calls at the three sites (Figure 28a-c). All three sites had the greatest D call detection rate early in July, and decreasing detections through October. Song call detection increased from June through October, though more rapidly at Sites C and E than at Site 2. Site 2 maintained the highest song counts in September and October at nearly 1000 calls per day. Singular B calls followed a similar pattern to song B calls with the greatest overall proportion of singular calls detected at Site 3. Changes in fin whale call detection were similar between sites (Figure 29) with the greatest difference being in the overall reduced number and a late season decrease in calls recorded at Site 3.

From 16 April to 4 November 2003, the northwest (Site 1) and southwest (Site 2) edges of Tanner Bank were concurrently monitored, along with the northwest corner of Cortez Bank (Site 5). Recordings from 2003 indicated a June peak in D calls along Tanner Bank, with very few D calls heard along Cortez Bank (Figure 30a-c). D calls occurred in high numbers late in 2003 as well, with a peak in late October at sites 1 and 2. The highest number of blue song calls was recorded at Site 1, which also had the highest proportion of songs calls relative to singular B calls. Nearly twice as many song calls were detected at Site 2 in 2001 compared to the same period in 2003. This pattern is opposite to that of D calls, which were also greater at Site 2 in 2003. Site 5 song, singular, and D call detections are greater in July of 2001, while later season call rates are similar between years.

Fin whales call detection also varied spatially in 2003. Detection of fin whale calls decreased in late April followed by an increase in September and October, while Site 5 maintained the lowest detection rate (30% less) and lacked the May peak observed at sites 1 and 2 (Figure 30). Compared to 2001, fin detections at Site 5 were nearly double the number observed during the same period in 2003, while Site 2 detection rates were similar between years.



**Figure 28.** Fin whale call occurrence at three sites from 20 June to 25 October, 2001. A-C) Daily fin whale call occurrence at sites 2, 3, and 5. D-F) Diel occurrence for fin whale calls at sites 2, 3, and 5. Grey shading indicates the period between dusk and dawn.

### *Diel Variability*

The hourly occurrence of calls was computed for each Site 4 during the two periods of concurrent monitoring described above. Blue whale song calls were distributed in a diel pattern at sites 2

and 3 with corresponding 32% and 38% more calls detected two to three hours before dawn and at dusk than during the remainder of the day (Figure 28d-f) in 2001. Site 5 had more singing at night than during the day, while the dawn and dusk peaks were not as pronounced as the other sites. Blue whale singular B calls did not have a significant diel pattern of occurrence. Blue whale D calls appeared 50 – 70% more frequently during daylight than at night at all sites, although a slight increase in detection rate was also observed near dusk. The distribution of hourly call counts were examined to determine the prevalence of the diel pattern, resulting in strongly diel patterns of calling for two to five days in a row from June through August, persisting for increasingly longer periods later in the summer and fall. Periods of reversed calling patterns (day and night peaks) or no daily pattern were interspersed between periods with clear diel arrangement. While hourly deviation of up to 14% were observed in fin whale call occurrence, there was no consistent diel pattern at any Site 4 during this period, with the exception of a slight (10%) increase in calling after sunset at Site 2 (Figure 29d-f). Hourly fin whale call counts indicated occasional dawn/dusk or day/night patterns; however the absolute change in call counts did not exceed 20% on average, and the patterns generally did not persist for more than one or two days.

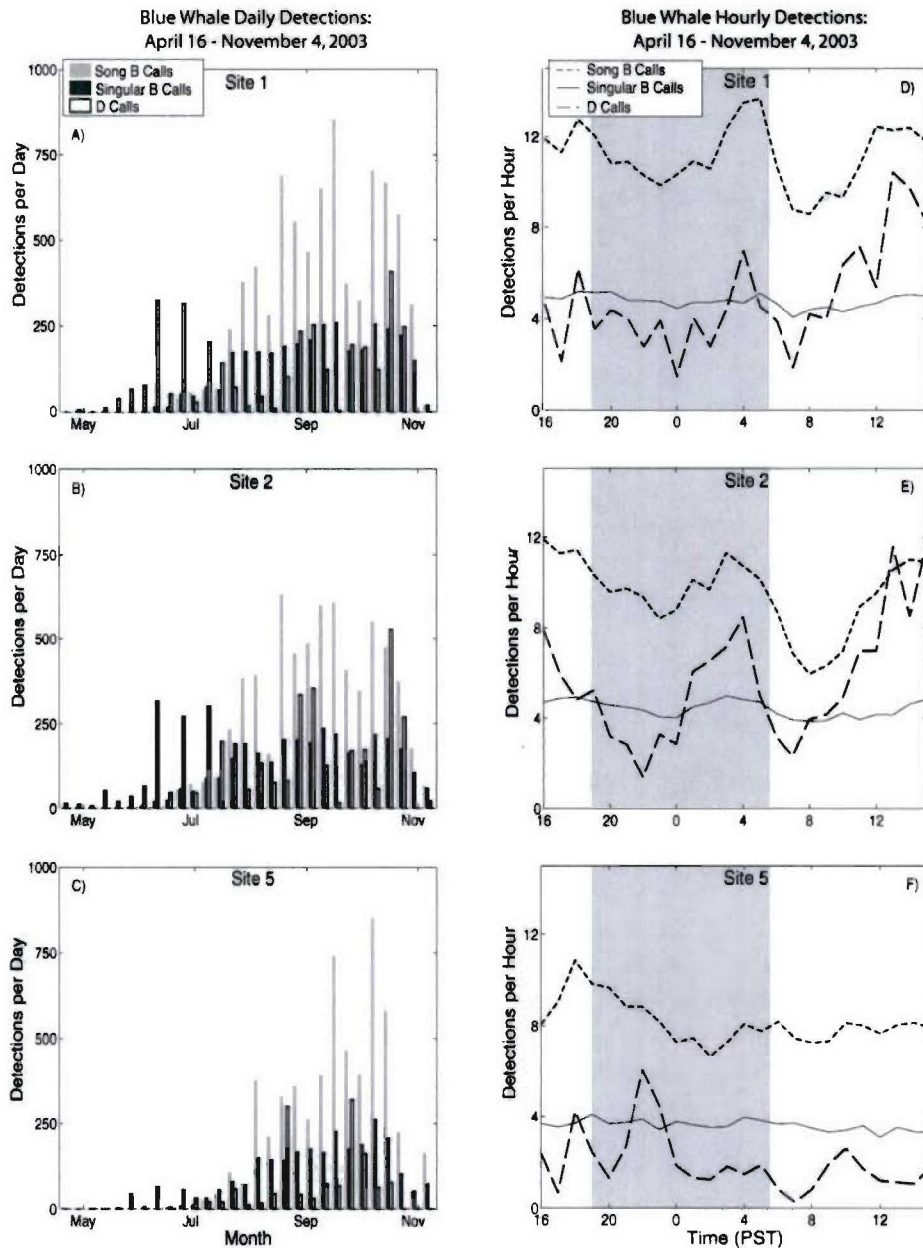
The diel call patterns observed from 16 April to 4 November 2003, varied somewhat from those seen during 2001. In 2003, blue whale song detections peaked near dawn and dusk similarly to 2001 (Figure 29d-f); however, sites A and B also showed elevated levels of singing at midday, while Site 5 detections peaked only two hours before dusk. D calls were also organized into a diel pattern, though the pattern at each site was different. Both sites A and B showed detection peaks for D calls at mid day, while Site 2 also had a peak preceding dawn. There was a slight peak in D detections at Site 5 following dusk. Fin whale calls exhibited a slight diel pattern in 2003 at sites 1 and 2; however, the magnitude of the differences from dawn and dusk to day and night (up to 20%) were less than for blue whales during the same period (Figure 30d-f).

### **Discussion**

Cortez and Tanner Banks are wide, flat, shallow zones (100-200m) along the western escarpment of the Santa Rosa-Cortez Ridge, within a region of complex bathymetry, including the San Nicholas Basin to the east and a gradual deepening toward the Patton Escarpment to the west (Figure 23). The banks are exposed to the prevailing southward flow of the California Current, which advects highly productive waters over the region and promotes high zooplankton biomass (Durazo et al. 2001, Schwing et al. 2002, Venrick et al. 2003). These favorable oceanographic conditions make the Cortez and Tanner Banks, an ideal site for examining the presence of blue and fin whales acoustically, as feeding whales seasonally frequent the banks in search of their euphausiid prey, and migrating whales pass to the east and west of the banks in search of feeding grounds to the north and on return to their tropical breeding grounds to the south. Additionally, a bathymetrically dynamic region such as Cortez and Tanner banks impacts local oceanographic conditions and the migration behavior of the whales' euphausiid prey (Brinton 1967) likely creating localized patches of high and low prey concentration (Genin et al. 1988, Genin et al. 1994, Haury et al. 2000) which govern the distribution of feeding whales (Croll et al. 2001) and therefore the rate of different call types temporally and spatially.

Our observations of blue whale calls at Cortez and Tanner Banks offer the first comparison of the occurrence of three separate types of blue whale calling. Most previous acoustic studies of blue

whales have used only the presence of A and/or B calls, and have not distinguished call types. Each call type may be associated with a different behavioral setting (Oleson et al. in prep). Song calls are produced by single traveling male whales (McDonald et al. 1995, Oleson et al. in prep), and are distinct from singularly occurring A and/or B calls, which are also produced by males, but from a wider variety of behavioral contexts (Oleson et al. in prep). The downswept D call has been observed to be produced by feeding whales of both sexes (Oleson et al. in prep), and may be the most advantageous call type for acoustically monitoring the presence of blue whales in presumed high-quality habitat regions.



**Figure 29. Blue whale call occurrence at three sites from 16 April to 4 November, 2003.** A-C) Daily call occurrence for each call type at sites 1, 2, and 5. D-F) Diel occurrence for blue whale call types at sites 1, 2, and 5. These daily patterns are different from those shown in

Figure 27. Grey shading indicates the period between dusk and dawn.

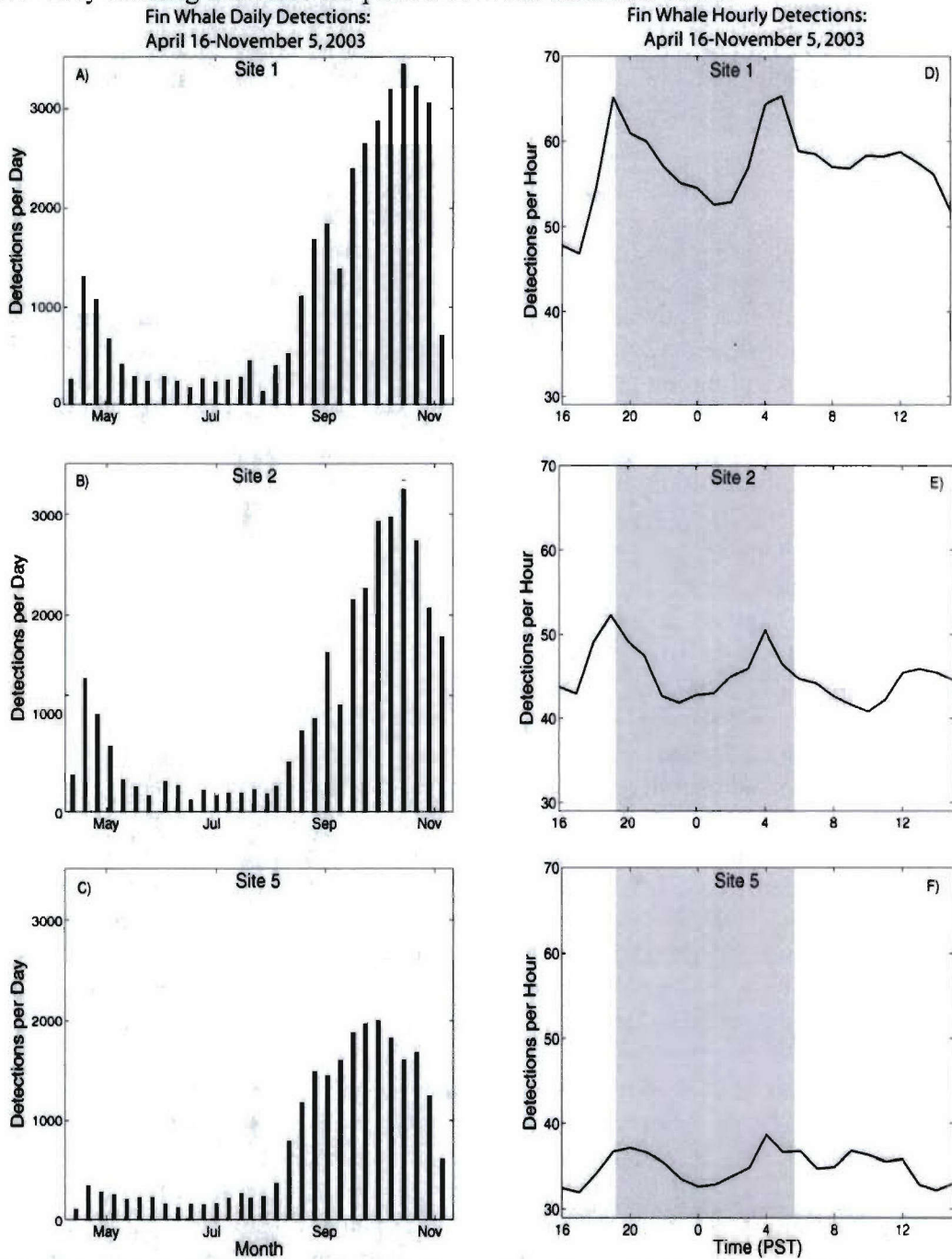


Figure 30. Fin whale call occurrence at three sites from 16 April to 4 November, 2003. A-C) Daily call occurrence at sites 1, 2, and 5. D-F) Diel occurrence of fin whale calls at sites 1, 2, and 5. This pattern is different from that observed during 2001 (Figure 28). Grey shading indicates the period between dusk and dawn.

While we have not been able to separate fin whale song from other uses of the 20Hz downsweep, it is clear that both song and call-counter-calls are present in the Cortez and Tanner Banks region. The large number of fin whale calls (up to 8900 calls per day) and the absence of a consistent

song pattern prevented the automated distinction of fin whale song from other call types. However, the description of several different song phrases by an analyst (Figure 24) suggests that fin whale song is more diverse than that of blue whales, and may vary between individuals and temporally. It is likely that the advent of more advanced detection methods for use in high density calling areas may eventually make the distinction between song and other 20Hz fin whale calls possible.

Data from nearly all previous long term studies of blue and fin whale acoustic seasonality and distribution have utilized SOSUS hydrophones, sensors placed in the deep sound channel capable of monitoring hundreds of kilometers (Moore et al. 1998, Stafford et al. 1998, Burtenshaw et al. 2004). The data from our study are highly localized in comparison, monitoring a few tens of kilometers at most; however, it is this type of localized study which may provide the greatest insight into the role of calling in the behavioral ecology of these species. We cannot address long range movements and migration patterns with these data, however, local movements and differential detection patterns at closely spaced sites may provide insight into the differential use of a localized area by these highly mobile species.

Our seasonal observations of blue whale B calls and fin whale 29Hz calls are similar to those of other acoustic studies in the northeast Pacific, despite differences in monitoring and detection methods. We found blue whale presence to be highly seasonal, while fin whales were detected year round. The peak of call production for both species occurred in the fall (Fig. 24) and the production of blue and fin whale call types varied throughout the year supporting the idea that different call types serve different functions. The analyses of Curtis et al. (1999) and Burtenshaw et al. (2004), investigating the seasonal occurrence of blue whale sounds in the Southern California Bight from data collected on SOSUS hydrophones, found seasonal peaks in blue whale calling in September and October, coincident with the pattern of blue whale B call occurrence presented here. Fin whale call patterns have not been as widely studied in the North Pacific; however, Moore et al. (1998), in an analysis of SOSUS hydrophone data, found very few fin whale calls at Site 1 (offshore of Oregon) with the majority of calls recorded in the winter. Sites further to the north (Site 3 and 5- offshore Washington and Vancouver Island) recorded more fin whale calls with variable detection rates throughout the year. Fin whale call seasonality has not been previously examined in the Southern California Bight.

The difficulty in separating fin whale song from other patterns of fin whale calling has also been demonstrated in other studies of fin whale acoustic seasonality. Watkins et al. (2000) used SOSUS beam-formed data to examine fin whale call presence and found only a few fin whale calls in the southeastern North Pacific (near Oregon) in the summer. However, type J calls, which were defined by Watkins et al. (2000) as “too many whales to separate” in a given day, were scored as a single detection and dominate the seasonal pattern from September through November and continue through January. Grouping “concentrated calling” separate from the counting of individual calls by Watkins et al. (2000) resulted in an earlier seasonal peak may actually be occurring. Type J calls may also largely consist of counter-calling fin whales, in contrast to the more easily identified consistent-interval song calls, which likely account for the individually counted whales in the Watkins et al. (2000) study.

In addition to seasonal cycles of blue and fin whale calling, our four year time series also offers

the opportunity to observe annual changes in the detection rate of call types. While different sites at Cortez and Tanner Banks were occupied in different years, the timing in the arrival and departure of blue whales, and the seasonal peaks of fin whale calling are generally consistent between sites allowing for inter-annual comparisons of spatially-pooled acoustic detection rates. The observed increase in the number of days per year in which blue whale calls were recorded from 2001 to 2003 (Table 12) may indicate increased numbers of animals in the population or increased proportion of the population using the region for foraging and traveling. Additionally, the large increase in D calling early in 2001 relative to other years may indicate particularly favorable feeding conditions during that period, as D calls are known to be produced by feeding whales and feeding occurs in regions where euphausiid concentrations exceed two order of magnitude above average density (Croll et al. 2001). While the number of days in which fin whales are recorded each year does not change during our study, the number of calls and the timing of winter and spring calling peaks is variable among years. Shifts of up to two months (November to January) are evident in the winter peak in fin whale calling, likely also related to local oceanography. The call-type composition of the winter and spring peaks are not known and may represent animals from other regions or singing animals. Changes in the timing of the acoustic arrival and departure of blue whales in southern California waters among years has been previously linked to changing oceanographic conditions, such as El Nino (Burtenshaw et al. 2004). The climatology of the Southern California Bight has changed in recent years, with 1999 bringing relatively cool, pigment-rich waters, and increasing zooplankton biomass (Durazo et al. 2001, Schwing et al. 2002, Venrick et al. 2003). These productive conditions may suggest increased prey availability for blue and fin whales. A future study may consider oceanographic observations spatially coincident with our acoustic observations to directly compare blue and fin whale prey abundance with the presence of blue and fin whale calling.

Spatial patterns of blue and fin whale calling are probably caused by a combination of the local bathymetry at each site, limiting acoustic detection range, and the increases in prey biomass due to the impacts of the shallow bathymetry on the southward advection of highly productive water. Studies of fish biomass on shallow banks may provide some insight into the local distribution of blue and fin whales in the region. While it has been hypothesized that topographically induced upwelling may cause the high fish biomass commonly observed around seamounts and banks (Uchida and Tagami 1984, Genin 1987), and particular at Cortez and Tanner Banks (Orcutt 1969), this is unlikely due to the long residence time and limited advection of the resultant nutrient-enriched waters which must occur for the effects of localized upwelling to cascade through the local food web (Genin and Boehlert 1985). High resolution remotely sensed ocean color in the Southern California Bight reveals no persistent or localized patches of chlorophyll above seamounts and banks (Palaez and McGowan 1986). High fish biomass is likely caused instead, by the trapping of their vertically migrating euphausiid prey above the shallow topography during their daytime descent. While this is advantageous for local bottom fish, the combination of predation and advection may create a highly patchy environment near shallow topography which may persist for hours or days (Haury et al. 2000), leading the highly localized feeding areas around the banks for blue and fin whales, potentially contributing to the different production rates of certain call types among sites (Fig. 28-30).

Further, the diel patterns of production of call types at different sites at Cortez and Tanner Banks may also be governed by local oceanographic conditions. Two previous studies of diel patterns of blue whale B call production found significantly greater calling at dusk, night and dawn than

during the day when averaging over long-time periods (Stafford et al. in press, Wiggins et al. in press), similar to the long-term signal described here. While this diel pattern of B call production indicates increased singing at night when feeding is less likely to take place, our fine-scale analysis of the persistence of the diel pattern indicates the signal is interrupted over the scale of days such that singing may increase during the day possibly related to shifts in local oceanographic conditions. Further, the overall diel pattern of D calls indicates increased calling during the day coincident with feeding activities, as would be expected if this call is associated with foraging. However, even this signal breaks down when examined at different sites and times. The relationship between the production of certain calls and the local environment is an important topic for further study, potentially providing a more robust oceanographic link between the calling behavior of these species and prey availability.

The seasonal patterns resulting from this long-term study of blue and fin whale acoustic presence are in general agreement with those described from visual surveys, with two notable differences. While the overall timing of blue and fin whale abundance in the Southern California Bight is captured by both visual and acoustic methods, the acoustic records described here show a longer time period during which both blue and fin whales can be detected acoustically, where they were not reported visually. Additionally, the timing of both species peak in acoustic detection differs by one to three months from the peak in visual detections, suggesting distinct acoustic versus visual detectability of each species.

There are several factors which may influence the detection of these species acoustically, potentially biasing estimates of abundance based on either visual surveys or acoustic monitoring alone. First, the individual rate of calling is not known for either species, such that it is not possible to determine if the peak in call detections corresponds to a higher number of calls produced per individual or more individuals calling. We have made no attempt in this study to determine how many whales were contributing to the overall call detection rate; however the average intercall interval for blue whale song is remarkably stable both within and among years, suggesting that while an individual whale may be producing sound for longer periods of time, they are not producing more calls within a fixed time, with one possible exception. Our analysis of the seasonality of song intercall intervals shows an increased production of short (48s) interval calling in the middle of the calling season, altering the per whale detection rate of song calls during this period. Second, the non-acoustic behaviors of calling versus non-calling whales may create a bias in the visual availability of these whales during a visual survey. As blue whale feeding activity is more common in the summer, and feeding whales spend more time at the surface recovering after long feeding dives (Acevedo-Gutierrez et al. 2002), feeding whales may be more visible than non-feeding whales. Observations from acoustic recording tags suggest that blue whales are not singing during feeding and that singing whales tend to be traveling (Oleson et al. in prep). Traveling whales spend proportionately less time at the surface between dives (Acevedo-Gutierrez et al. 2002) likely making them more difficult to observe during a visual survey. Singing is known to be done exclusively by males, and therefore is probably related to breeding. The dominance of singing late in the season (fall-winter) is suggestive of its use for mate attraction, pairing, or guarding. Finally, the detection range of an acoustic survey is quite large compared to that of a visual survey. We have not adjusted our counts of blue and fin whale detections by the relative detection distance at each site, however, the sighting distance of a visual observer is on average only a few km, while our acoustic detection distance is likely tens of kms increasing the probability of detection, particularly during periods of low density.

It is not yet possible to estimate the abundance of blue or fin whales using acoustic detection alone. Many factors remain unknown, including the proportion of animals calling at a given time, the amount of time a single animal might call, and the function of most call types. However, through long-term acoustic monitoring it is likely that we may be able to monitor trends of abundance for these species by tracking the magnitude of calling through time and may be able to develop habitat models for the species by studying the associations between oceanographic variables and the presence of certain call types. We have shown that variability exists both temporally and spatially in blue and fin whale calling, variability which must be accounted for when attempting to draw conclusions about the behavior and distribution of these species across large areas.

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## **Environmental and Population Scale Modeling**

Correlating whale presence with environmental data is one approach to defining habitat for marine mammals. Habitat models and population models may be helpful as a predictive tool for understanding marine mammal presence within Naval ranges such as SCORE. In the following we examine how blue whale populations may be defined using acoustic data and how satellite productivity data may be correlated with blue whale presence in the southern California offshore region.

### **Biogeography of Blue Whale Song: Identifying Populations**

Traditional studies based on external morphology, osteology, and results of on-going genetic analyses, have not produced a clear picture of blue whale population structure or phylogeography (Reeves et al., 1998). Collecting samples is not only logistically and geographically challenging, it is also extremely difficult to obtain samples with sufficient power to detect structure. In addition, over the ecological time scales relevant for management, traditional markers may fail to detect population structure because they may evolve too slowly and may not reflect present day movement and association patterns. Biochemical analyses of pollutants or the fatty acid signatures in blubber may better reflect the recent past, but it is doubtful that the animals themselves use these externally cryptic characteristics to determine associates. In contrast, the study of acoustic characters is a potentially rich source of data which can help delimit the population structure of blue whales worldwide (Cummings and Thompson, 1977; Thompson et al., 1979; Edds, 1982; Stafford et al., 1999a; Mellinger and Clark, 2003). Distinct regional differences in song should be compared with genetic and morphological data when defining blue whale populations as songs reflect interacting groups of animals, and thus are also likely to be good indicators of population identity. Moreover, acoustic recording of songs offers a relatively cost-effective means of obtaining samples of sufficient size for population structure analyses.

The production of high intensity, low frequency, long duration acoustic calls is a trait common to blue whales worldwide (e.g. Cummings and Thompson, 1971). These calls often form repetitive multi-part songs, which have been documented to be constant in character over decadal time scales (c.f. Thompson, 1965; McDonald et al., 2001). Although the function of song is unknown (see below), it is safe to assume that these are social signals used by the animals themselves to mediate social interactions and maintain associations between interacting animals. This paper reports on the characteristics, geographic range and seasonality of blue whale songs worldwide. We describe nine distinctive regional types of songs, which are produced with stereotyped character in distinct geographic regions with distinct oceanographic characteristics.

### **Background**

Commercial whaling harvested more than 360,000 blue whales, primarily in the Southern Ocean, but with significant numbers from almost every part of the world's oceans (Clapham and Baker, 2001). Stock changes or other adjustments in population structure may be responding to these, and other environmental and anthropogenic changes, over the post-whaling era. However, despite considerable effort by the IWC, the systematics of blue whales remains problematic. This uncertainty, in turn, hinders efforts to effectively monitor and manage blue whale populations at

global and regional scales. Currently, blue whales are divided into four subspecies based on morphologic and geographic distinctions (Rice, 1998) and these have been further subdivided into populations for cetacean management and endangered species recovery plans (Gambell 1979; Donovan 1991, Reeves et al., 1998). However, the subspecies and population divisions are poorly understood and the distinctions among them are vague beyond their presumed geographical separation (Reeves et al., 2004). *Balaenoptera musculus musculus* includes all blue whales in the northern hemisphere. In the North Atlantic, eastern and western subdivisions were recognized, while in the North Pacific as many as five population subdivisions were thought to exist. *B. m. intermedia* is the high latitude Southern Ocean and Antarctic waters blue whale. Whaling data suggest discrete feeding stocks, and consistent with these the International Whaling Commission has assigned six stock areas in the Southern Ocean. *B. m. breviceuda*, the pygmy blue whale, is distributed in sub Antarctic waters of the Indo-Pacific Ocean and south-eastern Atlantic Ocean (Zemsky and Sazhinov, 1994; Kato et al., 2002; IWC, 2003b:264-65). *B. m. indica* is from the northern Indian Ocean. Unfortunately, the utility and validity of these subspecies descriptions is uncertain because osteological studies have been based on only a few specimens (Omura et al., 1970) and external measurement comparisons often yield equivocal or even contradictory results (Gilpatrick et al., 1997). The existing subspecies and population designations may remain provisional until more detailed morphologic and genetic information becomes available.

#### *Blue whale acoustic repertoire*

Blue whale calls are among the most powerful ( $188 \text{ dB}_{\text{RMS}}$  re:  $1 \mu\text{Pa}$  @ 1m) and lowest frequency (16-100Hz) sounds made by any animal (Cummings and Thompson, 1971; McDonald et al., 2001). These calls are often, but not always, made in regular succession and form a recognizable pattern in time, which we call song. The songs are divided into units, which are continuous segments of sound, and phrases, which are repeated combinations of units (Payne and McVay, 1971; Mellinger and Clark, 2003). Blue whale call units are classified as primarily pulsed or tonal. We define a unit boundary as any abrupt change in call character (frequency, sweep rate or modulation rate) regardless of whether there is a pause between units. From one to five call units are combined to produce a phrase, and a song is composed of many repeated phrases. Breaks in the song typically coincide with respiration, but otherwise the songs may continue for many hours (Cummings and Thompson, 1971; McDonald et al., 2001). The units are sometimes combined in different sequences, these apparently having rules or syntax, by which only some combinations are allowed. When units are combined in more than a single sequence we refer to this as mixed mode phrasing. When only one sequence has been observed we refer to this as single mode phrasing. In addition to the songs reported here, blue whales produce calls in irregular patterns or as call and counter-call between two or more individuals. These calls are often downswept tones (80-30 Hz) of moderate duration (2-5 sec), with seasonally variable occurrence (Thompson et al., 1996; McDonald et al., 2001). To the best of our knowledge, these downswept calls are produced by blue whales worldwide, although further research may reveal regional variations in their character or usage.

#### *The function of blue whale song*

The function of blue whale song, as with other mysticete songs, is not well understood. Social functions proposed for mysticete calls (calls in this case referring to all types of mysticete vocalizations, including song) include foraging, mating and parental behavior, long range

contact, assembly, sexual advertisement (male-male or male-female), greeting, spacing, threat and individual identification (Tyack, 1999; Tyack, 2000; Clark and Ellison, 2004). However, only rarely has a specific call been associated with a given behavioral event. Regarding mysticete song specifically, in species such as humpbacks and fin whales, the evidence to date indicates that only males sing (Watkins, 1981; Darling and Bérubé, 2001; Croll et al., 2002). Much of the prevailing speculation on the function of song in these species has revolved around if, and how, singing functions as a mating display (Payne and McVay, 1971; Tyack, 2000; Darling and Bérubé, 2001; Darling, 2002; Croll et al., 2002) but recent data indicate that males also sing during migration and on feeding grounds, suggesting that there is much yet to learn about the function of song (Norris et al., 1999; Clark and Clapham, 2004).

In blue whales, it is known that male blue whales produce song (McDonald et al., 2001), but it remains unknown if female blue whales also sing. Animals vocalize throughout the year with peaks from midsummer into winter (Burtenshaw et al., in press; Širović et al., in press) Field observations suggest that singers are solitary animals (Calambokidis, pers. comm.). Diel chorusing at dusk and dawn increases the number of singers during these time periods (Thompson, 1965). When singing blue whales have been tracked, either visually or acoustically, they swim at 2-10 km/hr while producing songs (Kibblewhite, 1967; Northrop, 1971; McDonald et al., 1995; Thode et al., 2000; McDonald et al., 2001). Blue whale songs can be detected for hundreds, and under optimal conditions, thousands of kilometers (Stafford et al., 1998). Such sounds are ideal for communication between individuals of a widely dispersed and nomadic species. During a single season, the fundamental frequency components of a song type are precisely synchronized within a population of singers. For this reason, social integration may be a key function of blue whale song, that is, the song may allow two or more whales to coordinate their activities.

#### *Individual, temporal, and spatial variation in blue whale song*

From personal observation based on the data presented below, the songs of individual blue whales are known to be variable, but individual variability within a song type is much less than that which distinguishes among song types. Variability within a song type has been shown to be useful to distinguish between individual whales off California over the hours long time periods during which whales were observed (McDonald et al., 2001). Individual signature information in blue whale song has been reported for many days in North Atlantic blue whales (Clark, 1995). More work is needed to determine if and how individuals vary their calls spatially, seasonally or functionally and whether individual whales ever change song type (Stafford and Moore 2004).. The utility of relatively subtle individual variation to further subdivide blue whale populations acoustically remains a topic for further research.

A distinguishing feature of blue whale song is the apparent constancy of the regional song types over time (see below), in contrast to the songs of the better-studied humpback whale. An important difference between blue whale song and humpback song, or bird song, is the apparent lack of mutation in blue whale song over decades of observation. Blue whale song appears to be copied nearly perfectly across generational boundaries. In songbirds, flexibility in song is well known; individuals may innovate and improvise, copy neighbours or change song type to match a local dialect or habitat (Morton, 1975; Payne, 1996; Kroodsma, 1999; reviewed in Catchpole and Slater, 1995). In humpbacks, a similar phenomenon is known to occur where a single singer arriving from a different population apparently caused an entire population to switch to the new

song (Noad et al., 2000). The dramatic changes in humpback song from month-to-month and from year-to-year combined with the much more complex form of humpback song (Payne et al., 1983) serves to caution against analogies with blue whale song.

Regional or spatial variation in blue whale song is among the better documented of the baleen whales, although the data have yet to be compiled on a global scale. Previous studies have used the characteristics of vocalizations to determine the seasonal presence and movement of blue whales through a region (e.g. Clark, 1995; Stafford, 1999; Moore et al., 2002) including the possibility of populations mixing within a region (Stafford et al., 2001) and have used differences in blue whale song to identify populations and to distinguish populations from neighbouring ones (e.g. Northeastern vs Northwestern Pacific (Stafford et al., 2001; Moore et al., 2002) and Antarctic versus others (Stafford et al., in press). For our global comparison (below) we build upon the excellent work in these previous studies.

#### *The case of using vocalizations as a proxy for population identity*

In many species, vocalizations are the predominant means by which individuals communicate; species-level and regional variation is well known and song can be a powerful isolating mechanism among taxa (Marler, 1957; West-Eberhard, 1983; Slabbekoorn and Smith, 2002). Due to recent advances in bioacoustics, vocal differentiation has become increasingly important in the taxonomy of many terrestrial species and the structure of vocalizations is becoming common in the descriptions of populations and closely related species of birds (Baptista, 1975; Catchpole and Slater, 1995; Martens, 1996; Wright, 1996; Irwin et al., 2001a), mammals (Maeda and Masataka, 1987; Gautier, 1988; Bearder, 1999; Kingston and Rossiter, 2004; Siemers and Schnitzler, 2004), amphibians (Ryan, 1990) and insects (Wells and Henry, 1998; Gray and Cade, 2000). Acoustic characteristics may be the key distinguishing feature used in the identification of otherwise “cryptic” taxa, (e.g. nocturnal primates, Anderson et al., 2000; green warblers, Irwin et al., 2001b), resulting in significant increases in diversity (Price, 1996; Bearder, 1999).

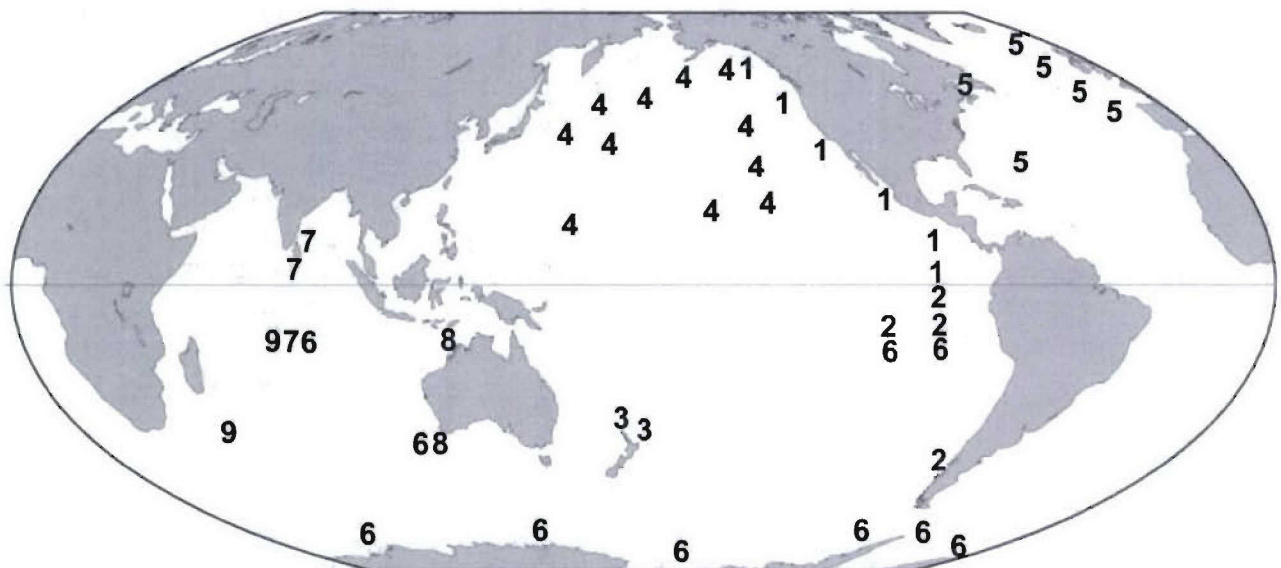
While regional diversity in vocalizations is well-known, some researchers regard vocal displays as too ephemeral and too influenced by ecological (e.g. habitat matching) and social (including learning and imitation and mating with individuals singing other songs) factors to be useful in elucidating genetic relationships (Harvey and Pagel, 1991; but see Wimberger and de Queiroz, 1996). In birds, the relationship between song dialects and population structure show conflicting results (reviewed in Catchpole and Slater, 1995 and Slabbekoorn and Smith, 2002). Some studies find little evidence of genetic differentiation (Fleischer et al., 1988; Wright and Wilkinson, 2001) while others show a strong correlation between dialects and genetic variation (MacDougall-Shackleton and MacDougall-Shackleton, 2001) sometimes indicating higher level divergence (Irwin et al., 2001b). Several factors contribute to these differences, including the social function and the timing of vocal learning relative to dispersal (Wright and Wilkinson, 2001). In addition, genetic subdivisions may exist but go undetected (Bossart and Prowell, 1998; Taylor and Dizon, 1996, 1999) or be too recent to be reflected genetically (Hatch and Clark, 2004).

Cetacean biologists have long noted the potential utility of whale songs as an indicator of biologically meaningful stocks in blue whales (Cummings and Thompson, 1979; Edds, 1982), humpback whales (Payne and Guinee, 1983; Cerchio, 2001), fin whales (Thompson et al., 1992;

Hatch and Clark, 2004) and Bryde's whales (Oleson et al., 2003). Geographic variation of non-song calls is also known in killer whales (Ford, 1991), and sperm whales (Weilgart and Whitehead, 1997), but the implications for non-song variation are likely to be different than for songs. Mellinger and Barlow (2003) provide a recent review on intraspecific acoustic structure in cetaceans with notations on temporal stability. Recently, Hatch and Clark (2004) examined the concordance between fin whale song and genetic divergence among eleven geographic regions in the North Atlantic and North Pacific. The acoustic differences were not reflected in estimates of genetic divergence among regions, suggesting that the patterns of acoustic dissimilarity may reflect demographic discontinuities in behaviour and/or movement that are too recent to be reflected genetically but that exist on the shorter time scales relevant to management (i.e., decadal) time scales. As a more complete understanding of the acoustic repertoire of each whale species is acquired, we may be able to distinguish regionally distinctive sounds from those common throughout the species' range in these and other species, and to test these acoustic patterns for concordance with patterns of morphological and genetic variation.

*Biogeographic characterization of blue whale song worldwide*

Our objective is to describe blue whale song on a world wide scale. Our approach intentionally oversimplifies; as our focus is to look for the overarching principles, while for many biologists, the focus is on the subtleties of natural variation as grist for the evolutionary mill. Much additional research is needed to more fully describe the individual, temporal, seasonal and microgeographic variability of the acoustic repertoire of blue whales. The intriguing exceptions to the rules may indicate there is more to the story than that provided here, but our objective is to highlight the value of acoustic information as a tool in marine mammal conservation and management.



**Figure 31. Distribution of blue whale song, classified into nine regional types (numbers). See Table 13 for regional designations.**

**Methods**

We have reviewed recordings and spectrograms of blue whale songs from publicly available

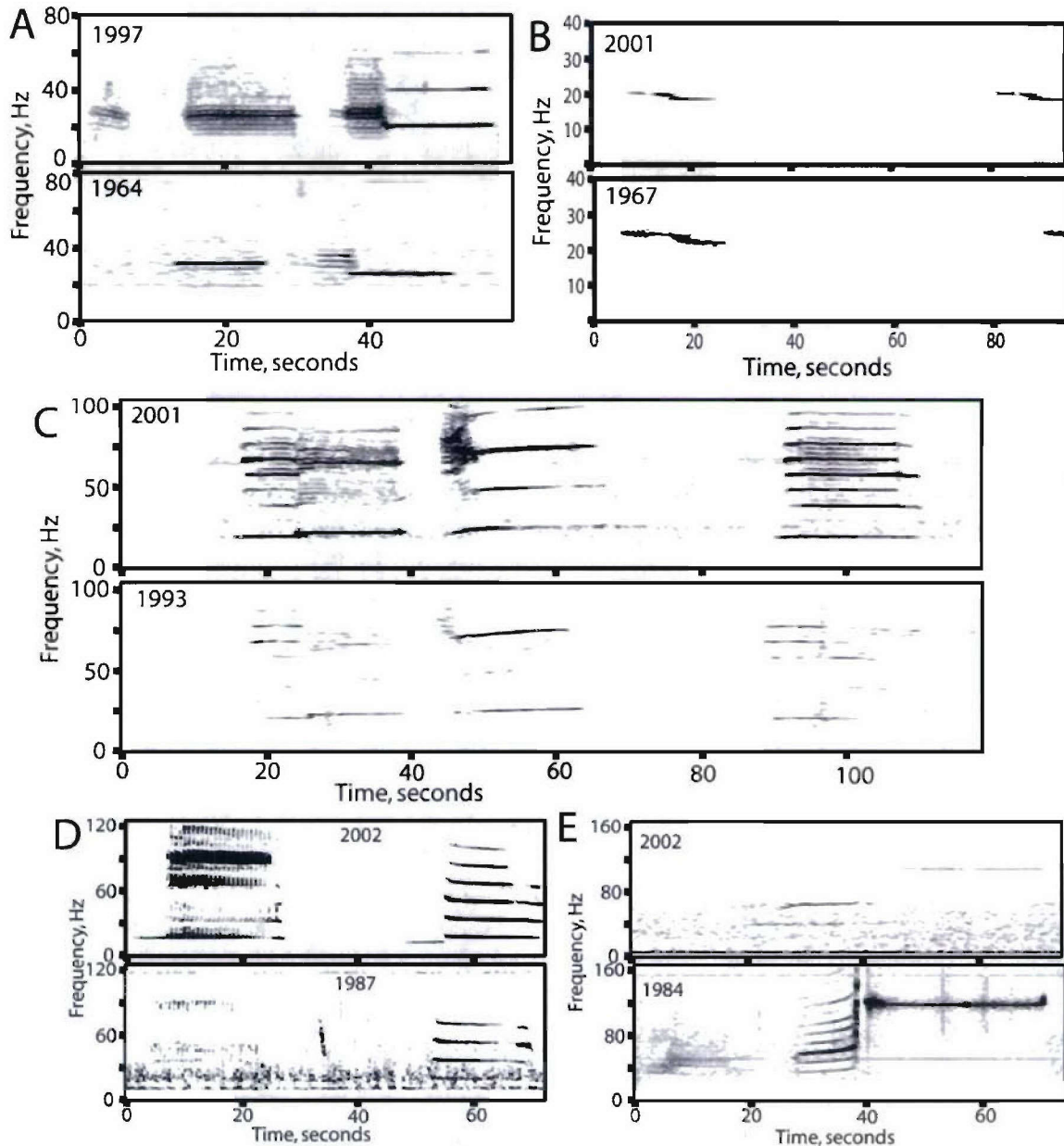
literature, from recordings offered to us by colleagues and from our own research. From these data, we looked at spectrograms from as few as 10 songs for some of the best well known Indian Ocean song types to as many as 100,000 songs for the Northeast Pacific where millions of song recordings are now available. A typical acoustic encounter with a singing blue whale results in recording about twenty songs before either the whale stops singing or the signal to noise ratio becomes undesirably low, thus the number of whale encounters examined scales more or less by a factor of twenty fewer. To compare songs among regions, the differences are apparent visually in the spectrograms, but we also chose acoustic metrics including the frequency at beginning and end of each unit, unit duration, inter-unit gap duration, the pulsive or tonal nature of each song unit, the pulse rate when applicable and the number of units in the song. To investigate temporal variation within a region, we looked as many as 15 different years of recordings from the Northeastern Pacific song and as few as two different years of recordings for the Indian Ocean song types. We establish “acoustic-types” for each of the geographic regions described with the acoustic measures above, much as morphologists identify “morpho-types” when a new species is described.

### Results

Blue whale song can be categorized into nine types each of which we associate predominantly with a geographic region. (See Table 13 for a listing of source data.) The best known songs are from the Pacific Ocean, which has four song types. The Indian Ocean, though poorly studied, has at least three song types, whereas, the Atlantic Ocean and Southern Ocean each have a single song type. Additional song types may remain to be discovered. For instance, no recordings are available for the South Atlantic. Locations for all known blue whale recordings are shown in Figure 31, the locations being numbered corresponding to the song type listed in table 13. Stability of the song character is illustrated in Figure 32. Changes in song character through time are small relative to differences between song types, the common change being a slow and regular drift in the frequency of the tonal components. Spectrogram displays of each song type are grouped into three figures, the first two (Figures 32 and 33) are grouped based on similarity of character, while Figure 34 illustrates the Northern Indian Ocean types which do not readily group with the others in call character.

**Table 13. Blue whale song type by region.** The type locality and type reference refer to the best/first/most complete published reference for each song type. Song character is stable over the known time spans, listed as the year of the first and the most recent recordings known. See the text for the time span references.

Type	Region (Abbreviation)	Type Locality	Type Reference
1	Northeast Pacific (NEP)	California	McDonald <i>et al.</i> , 2001
2	Southeast Pacific (SEP)	Isla Guafo, Chile	Cummings & Thompson, 1971
3	Southwest Pacific (SWP)	New Zealand	Kibblewhite, 1967
4	North Pacific (NP)	Aleutian	Stafford <i>et al.</i> 2001
5	North Atlantic (NA)	Eastern N. Atlant.	Clark and Charif, 1998
6	Southern Ocean (SO)	West Ant. Penins.	Širović <i>et al.</i> in press
7	North Indian (NI)	Sri Lanka	Alling <i>et al.</i> , 1991
8	Southeast Indian (SEI)	Fremantle	McCauley, 2000
9	Southwest Indian (SWI)	Diego Garcia	This Paper



**Figure 32. Blue whale song stability.** Recordings from New Zealand (A), the Central North Pacific (B), Australia (C), the Northeast Pacific (D) and North Indian Ocean (E) illustrate the stable character of the blue whale song over long time periods. All song types for which long time spans of recording are available show some frequency drift through time, but only minor change in character. These examples were chosen because recordings over a significant time span were available to the authors in raw form, and not because these song types are more stable than the others. The stability of song character in the other types and for longer time spans in these types is available to various degrees in copyrighted spectrograms and/or written descriptions. The missing first units in the 1964 New Zealand example and 2002 Sri Lanka example are probably due to lower signal to noise ratio, rather than to change in the song.

### *Northeast Pacific*

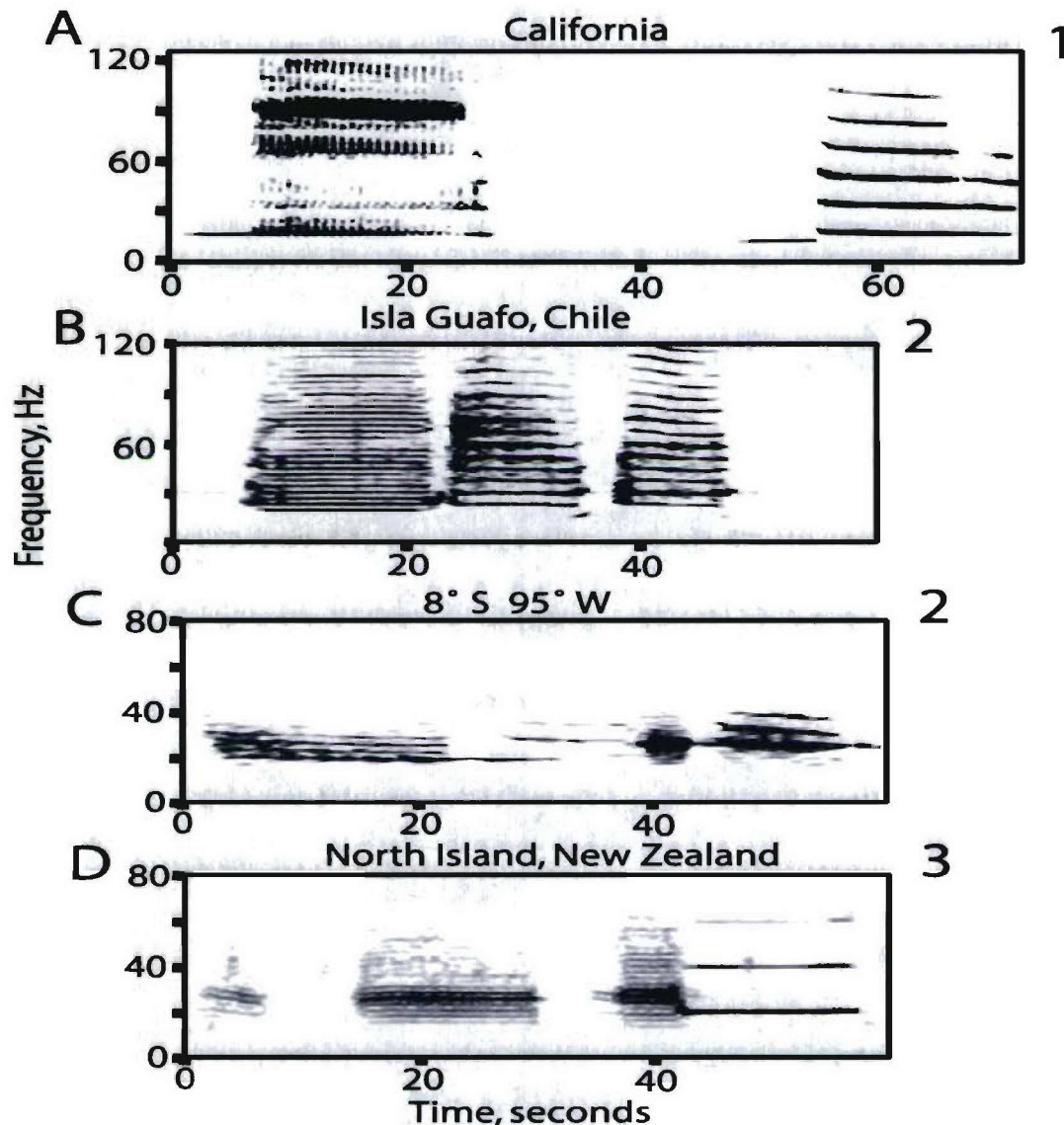
Blue whale songs have been recorded off the coast of California since 1963 (Thompson, 1965), the northeast Pacific song being the best documented for any worldwide. The character of this song has remained stable over the past four decades. This song has two call units (Figure 33a, Table 14). The first unit (A) is pulsed with multiple, time-offset non-harmonic components. The second unit (B) is tonal, with a series of harmonically related higher frequencies. Single mode (ABABAB or ABBBABBB) phrasing is common, with the A unit always initiating the song sequence.

The geographic range for the Northeast Pacific blue whale song (type 1 in Figure 31) is primarily along the west coast of North and Central America. The type locality is off the coast of California, where these calls have been well described (Thompson, 1965; Rivers, 1997; Stafford et al., 2001; McDonald et al., 2001). In the northern part of this region, off the coast of Washington, Oregon and British Columbia, they are heard seasonally, beginning in the summer and continuing into the fall and early winter (Stafford et al., 2001; Stafford, 2003; Burtenshaw et al., in press). In the south of their range, at the Costa Rica Dome region and in the Gulf of California, calls from these whales are present year-round, but with a peak occurrence in the winter and spring (Thompson et al. 1987; Stafford et al., 1999a). This pattern suggests a seasonal movement with a spring peak presence in the Costa Rica Dome region, and fall peak presence off the California coast and points further north, substantiated by photo-identification studies (Calambokidis et al., 1999) and satellite tagging (Mate et al., 1999). These calls also have been heard further offshore, where they mix with the North Pacific song type (Stafford et al., 2001; Stafford, 2003).

### *Southeast Pacific*

Southeast Pacific blue whale song has been described off the west coast of South America (Cummings and Thompson, 1971; Stafford et al., 1999b), maintaining the same character for 27 years. This song contains three pulsed call units, closely spaced in time and with a total duration of 37 seconds (Figure 33b, Table 2). The call units are repeated about every 100 seconds, with single mode phrasing (ABCABC).

The southeast Pacific blue whale song (type 2 in Figure 31) is observed along the west coast of South America and adjacent offshore waters, with the type locality in the Isla Guafo region of southern Chile (Cummings and Thompson, 1971). In the northern part of the range, off the coast of Peru, the songs are recorded year-round, but in greater numbers during the austral fall and winter (March-August) (Stafford et al., 1999b). In the south of their range, the song has been heard in the summer (Cummings and Thompson, 1971). These data suggest a seasonal movement with a winter peak presence in tropical waters, and summer peak presence further south. Sightings and whaling data confirm blue whale presence in southern Chile year-round (Tønnessen and Johnsen, 1982; Aguayo-Lobo et al., 1998; Findlay et al., 1998). A variant of this song has been detected on the Eastern Tropical Pacific hydrophones south of the equator (Stafford et al., 1999b). This song (Figure 33c) consists of four pulsive units, making it more similar to the Isla Guafo song type than the New Zealand song type, although it is somewhat intermediate in character. As more data becomes available, it may be appropriate to categorize this variant as a separate song type.



**Figure 33. Blue whale songs for the coastal Pacific:** (A) Northeast Pacific – California, recorded June 2001 near San Clemente Island, California, (B) Southeast Pacific – Chile, recorded May 1970 near Isla Guafo, Chile, (Cummings and Thompson, 1971). Spectrogram produced from archival tape in Hubbs SeaWorld Sound Library, (C) 8° S 95° W – recorded 1996 (Stafford et al., 1999b) and (D) Southwest Pacific – New Zealand, recorded December 1997 near Great Barrier Island, New Zealand. Recording from the Center for Monitoring Research collected as part of the Comprehensive Test Ban Treaty.

#### *Southwest Pacific*

Southwest Pacific blue whale song has been recorded off North Island, New Zealand (Kibblewhite et al., 1967), with no apparent change in character over the 33 year time span between recordings (Figure 32, Figure 33d). This song consists of three pulsed call units (A, B, C) followed by a tonal call unit (D), with a total duration of about 55 seconds (Figure 33c, Table 14). The first pulsed unit (A) has lesser amplitude than the following units (B and C). The call units are repeated about every 108 seconds, with single mode phrasing (ABCDABCD). This

song has been recorded in waters off North Island, New Zealand: twice near Three Kings Island (Kibblewhite, 1967), and on four occasions near Great Barrier Island, scattered throughout the year (author's unpublished data).

#### *North Pacific*

North Pacific blue whale song, first reported from Midway Island recordings made in 1968 (Northrop et al., 1971), consists of 2-4 tonal units with frequencies near 20 Hz (Figure 34a and 34b, Table 14). Six different call units have been reported, with varying usage over the North Pacific (e.g. Stafford et al., 2001), suggesting that it may be possible to break this song region into finer subdivisions. The call units typically last for 5-20 seconds. Figure 34a shows representative calls recorded near Midway Island (Northrop et al., 1971). The call units are repeated about every 85-95 seconds, with single mode phrasing (ABABAB). Figure 34b shows song recorded near Wake Island (author's unpublished data) with three tonal units (A, B, C). The phrasing of the Wake Island call is single mode, with a repeated second unit (ABBCABBC). Other variants for the North Pacific blue whale song type have been reported by Stafford et al. (2001).

The range for the North Pacific blue whale song type (Type 4 in Figure 31) is primarily from the Aleutian Islands, stretching to about 40 °N (Moore et al., 2002). Lesser numbers of calls are heard as far south as Hawaii and Wake Island (Watkins et al., 2000; Stafford et al., 2001). In the Aleutians region, these songs are abundant in the summer and fall, and are detected nearly every hour on fixed hydrophones. Aleutian calling is diminished during the winter and is nearly absent in the spring. This pattern suggests a strong seasonal movement with summer and fall spent at high latitude and spring spent at lower latitudes.

#### *North Atlantic*

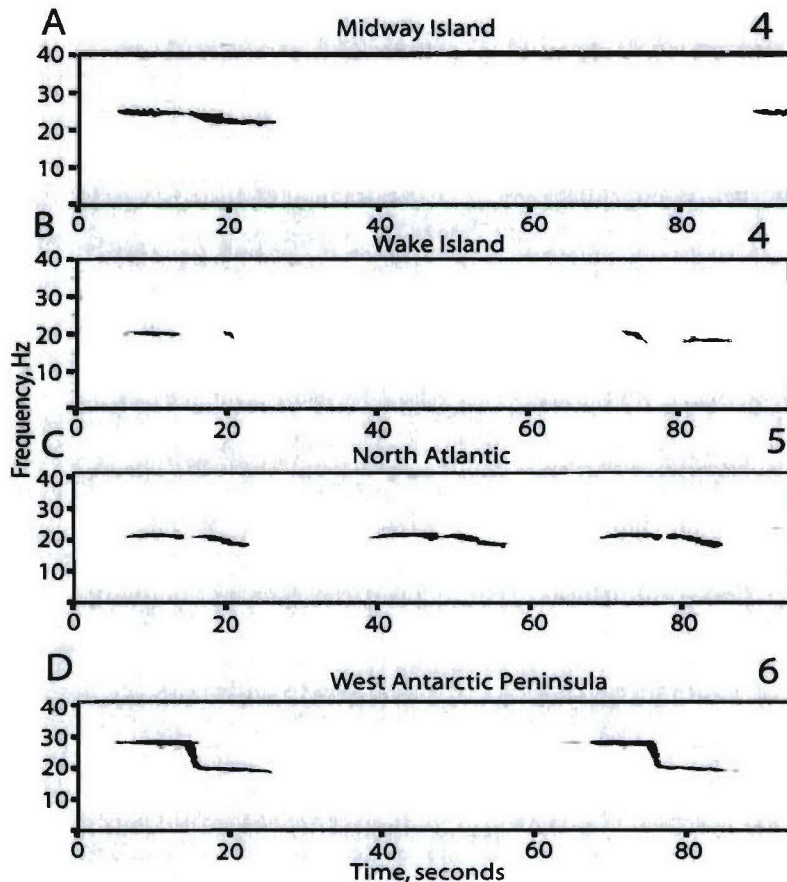
North Atlantic blue whale song was first described in detail in the St. Lawrence River Estuary (Edds, 1982) as consisting of a single tonal unit near 19 Hz (Figure 34c, Table 14), although descriptions date back to 1959 (Weston and Black, 1965). The most thorough description of this song type is found in Mellinger and Clark (2003). Each phrase consists of two units, although there is sometimes no gap between the two units as is the case in Figure 34c. The first unit is of nearly constant frequency, with a duration of about 8 seconds, while the second unit sweeps down having a duration of about 11 seconds (Mellinger and Clark, 2003).

The range for the North Atlantic blue whale song (Type 5 in Figure 31) stretches from the Arctic Ocean south to at least 35°N. Off the coast of Great Britain it is reported year-round (Clark and Charif, 1998). Using military hydrophone arrays, a singing blue whale was shown to move along a northeast-southwest track in the western north Atlantic during February – March 1993 (Clark, 1995). The probable pattern for North Atlantic blue whale song is year-round residence at high latitude, with some seasonal movement to lower latitudes during spring.

#### *Southern Ocean*

Southern Ocean blue whale song recently has been reported offshore from Antarctica (Ljungblad et al., 1998; Matsuoka et al., 2000; Širović et al., in press). The song consists of three tonal units with frequencies near 20 Hz (Figure 34d, Table 14). The phrase is repeated about every 65 seconds, typically with single mode phrasing (ABCABC), although mixed mode phrasing also has been observed.

The reported locations for Southern Ocean blue whale song recording suggest a circumpolar distribution around the Antarctic Continent (Type 6 Figure 31). A year-round presence is documented from fixed hydrophones deployed near the West Antarctic Peninsula (Širović et al., in press). The Southern Ocean blue whale song has also been recorded at tropical latitudes during the southern winter (Stafford et al., in press).



**Figure 34. Blue whale songs for pelagic ocean settings.** (A) North Pacific – Midway Island, recorded on December 1967 near Midway Island (Northrop et al., 1971). Spectrogram produced from archival tape in Hubbs SeaWorld Sound Library, (B) North Pacific – Wake Island, recorded January 1997 from the Wake Island MILS hydrophone array. Data provided by the Center for Monitoring Research, (C) North Atlantic, recorded in 1993 in the northeast Atlantic between Iceland and Spain. Data from the Integrated Undersea Surveillance System (Clark, 1996), and (D) Southern Ocean – West Antarctic Peninsula, recorded February 2002 at 66° S, 71° W off Adelaide Island (Širović et al., in press).

#### *North Indian*

North Indian Ocean blue whale song is best known offshore from Sri Lanka (Alling and Payne, 1988; Alling et al., 1991). The song consists of four units, three pulsive and one tonal (Figure 35a, Table 14). The call units are repeated about every 210 seconds, with single mode phrasing (ABCDABCD).

The North Indian Ocean blue whale song (Type 7 Figure 31) is reported from the near-shore waters of Sri Lanka, (Alling and Payne, 1988; Alling et al., 1991), where it was recorded on two consecutive seasons, both in the spring, and the whales are reported to be present between January and May. It is also known from deep ocean hydrophones near Diego Garcia (Tolstoy and Bohnenstiehl, 2002; Maya Tolstoy, pers. comm.).

#### *Southeast Indian*

The southeast Indian Ocean blue whale song (Type 8 in Figure 31) has been observed in waters off northern and southwestern Australia, in the Timor Sea (Lindsay Hall, pers. comm.) and near Fremantle (McCauley et al., 2000; McCauley et al., 2001). These songs were heard in the southern summer and fall (January-March), although data are not available for other seasons. This song contains four pulsed call units and one tonal call unit, with a total duration of about 120 seconds (Figure 35b, Table 14). The call units are repeated about every 180 seconds, with single mode phrasing (ABCDEABCDE).

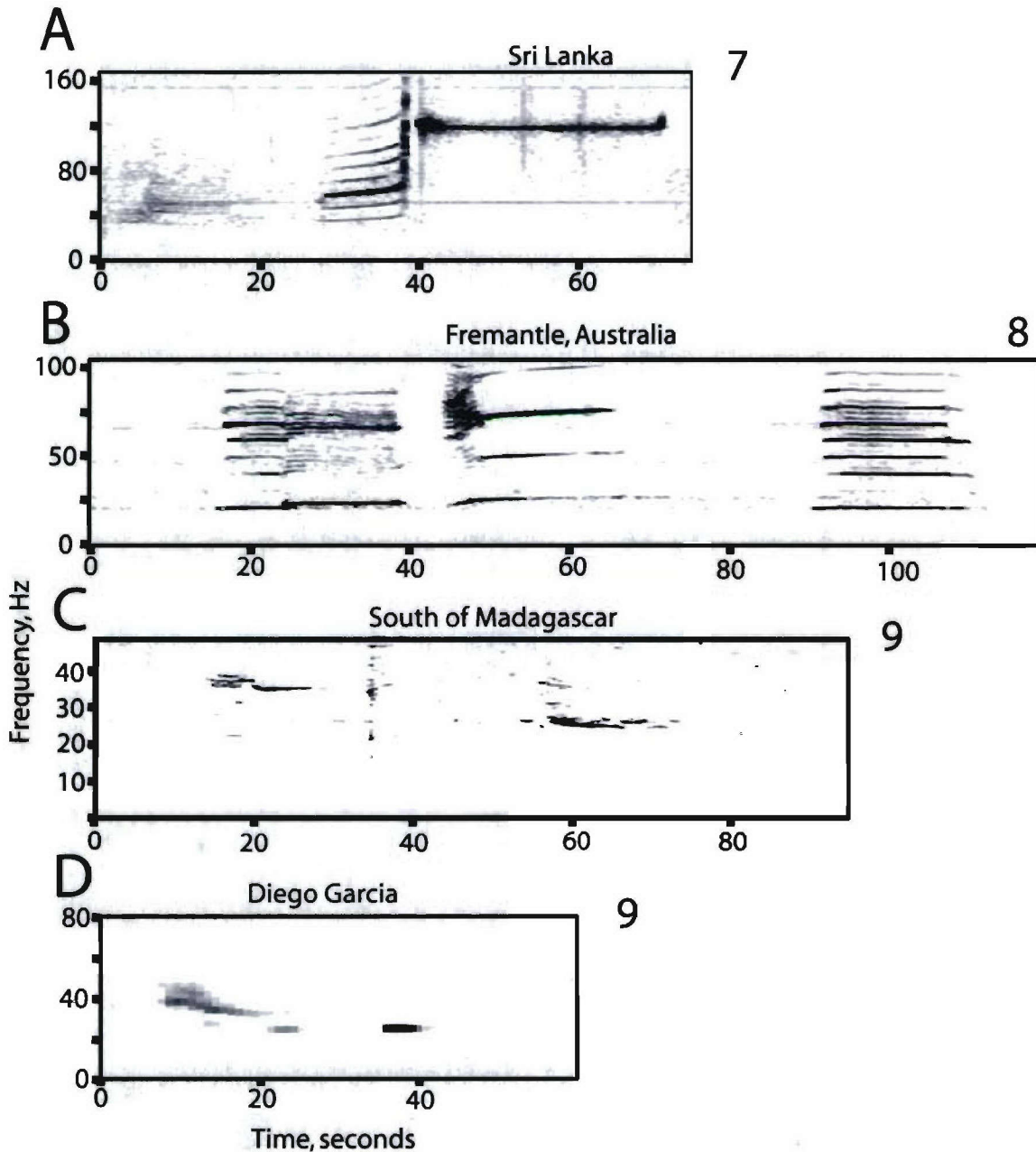
#### *Southwest Indian*

The southwest Indian Ocean blue whale song has been recorded south of Madagascar (Ljungblad et al., 1998) and on a fixed hydrophone array south of Diego Garcia Island. The Madagascar songs consist of four call units with a total duration of about 60 seconds (Figure 35c, Table 14). The call units are repeated about every 90-100 seconds, with single mode phrasing (ABCDABCD). The Diego Garcia variant of this song consists of five units, two pulsive and three tonal (Figure 35d, Table 14). The call units are repeated every 200 seconds, with single mode phrasing (ABCDEABCDE).

The southwest Indian Ocean blue whale song (Type 9 in Figure 31) has been observed south of Madagascar, at 32°S (Ljungblad et al., 1998). The songs were heard in the southern summer (December) on two successive years. No data are available for other seasons. A seasonality analysis of the Diego Garcia song is in progress (Maya Tolstoy, pers. comm.).

### **Discussion**

Blue whale song types can be helpful in defining population boundaries. There are distinct differences, outlined above, between songs recorded in different regions. We have identified nine acoustic types, many of which are known to have remained stable for decades (Table 14). These results suggest that there are at least nine distinct populations of blue whales worldwide, with the possibility of more as acoustic data are collected in unstudied areas. These distinct differences between areas provide another data set for comparison with genetic and morphological data when defining blue whale populations (e.g. Le Duc et al., 2003; C. Conway, pers. comm.). As Mellinger and Barlow (2003) recommend, in regions where there is a lack of data, or lack of resolution using traditional markers, evidence of distinct differences in songs between areas may be used as the provisional population structure when making management decisions. For these reasons, we provisionally recommend nine acoustic populations of blue whales worldwide.



**Figure 35. Blue whale songs for the Indian Ocean:** (A) North Indian Ocean – Sri Lanka, recorded April, 1984 within 5 miles of the entrance to Trincomalee Harbor (Alling and Payne, 1988). Spectrogram produced from archival tape at the British Library, Natural Sound Archive, London, (B) Southeast Indian Ocean – Fremantle, recorded west of Perth, Australia (courtesy of R. McCauley), (C) Southwest Indian Ocean – Madagascar, recorded December 1996, south of the Madagascar Plateau (after Ljungblad et al., 1998), and (D) Southwest Indian Ocean – Diego Garcia, recorded October 2000, south of Diego Garcia, by the Comprehensive Test Ban Treaty Organization

Song # Loc	Units Total# Tonal# Pulse#	Unit A			Unit B			Unit C			Unit D			Call Cyc. Time	Resp. Time	Dive Time
		F T P	G	F T P	G	F T P	G	F T P	G	F T P						
1 NEP	2 1 1	16-88 19 1.2	28	18-15 19 0									118	160	660	
2 SEP Chile	4 1 3	20-32 13-15 3.8	0-2	20-31 9-10 7.7	1-3	390 0.8 0	0	20-31 8-9 7.7					102	178	798	
2 SEP 8°S 95°W	4 0 4	20-19 22 3.3	4	28-27 10 7	0	26 3.5 7	3	26-24 10 7					116	--	--	
3 SWP	4 1 3	18-35 6 2.6	10	18-35 13 2.6	10	18-35 6 2.6	0	20 12 0					108	220	730	
4 NP Midway	2 2 0	25 12 0	0	25-23 12 0									90	249	990	
4 NP Wake	3 3 0	22 10 0	5	22-18 3 0	50	22-18 3 0	5	18 10 0					90	245	720	
5 NA	2 2 0	19-18 8 0	0-14	18-16 11 0									73	194	679	
6 SO	3 3 0	28 10 0	0	28-20 1 0	0	20-19 10 0							65	180	--	
7 NI	4 1 3	60-100 12 3.6	12	50-150 11 13	1	130-110 29 0	4	35-93 9 19					210	153	--	
8 SEI	5 1 4	15-80 20 1.6	0	15-80 22 2	5	15-80 2 2	0	20-26 23 0	23	20-100 20 8			198	--	--	
9 SWI Mada	4 2 2	36-42 5-8 1	0	26 10-12 0	25	28-15 1-2 0	0	27 15-20 1					100	--	--	
9 SWI DG	5 3 2	42 3 5	0	42-30 5 10	0	33-30 6 0	0	25 4 0	12	25 5 0			200	--	--	

F = frequency (Hz), T = unit time (sec), P = pulse rate (1/sec), G = inter-unit gap (sec)

**Table 14. Blue whale song unit characteristics by region.** The typical blue whale song phrase consists of three call units, of which one or two are pulsed and one or two are tonal. The call unit average duration is 11 sec. The phrase repetition rate averages 118 sec. Only about one-third of the song cycle is spent calling, with quiet periods occurring between units and between phrases.

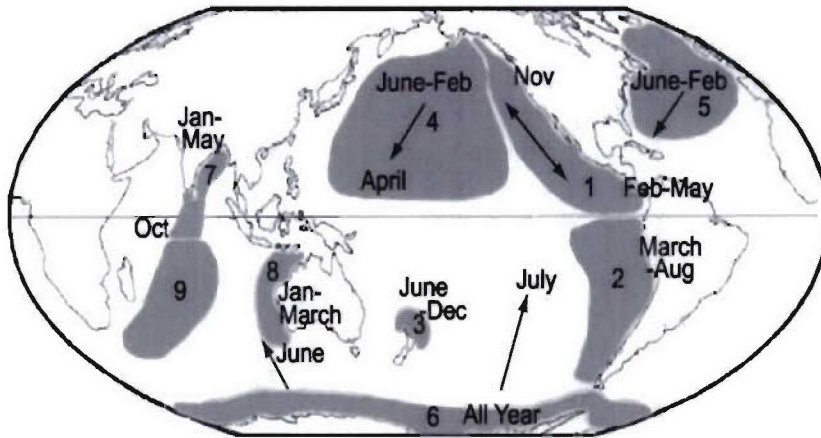
Blue whale song may be grouped into three categories based on similarity of character. Song types bordering the Pacific Ocean, which may be grouped together due to common characteristics, are: California, Chile and New Zealand (type 1, 2, and 3; Figure 33A, B, C). These songs have the following characteristics: (1) pulsed call units, (2) when present, tonal call

units contain higher harmonics, and (3) song cycle times of intermediate length (102-118 sec). High latitude North Pacific, North Atlantic, and Southern Ocean songs (type 4, 5 and 6; Figure 34A, C, D) have a simple character, with only tonal call units lacking harmonics, and a short cycle time (35-90 sec). Indian Ocean songs (type 7, 8, and 9; Figure 35A, B, C, D) have the highest level of complexity. There are similarities in the structure of the Fremantle song (type 8) and Sri Lanka song (type 7). They have a comparable number, type, and ordering of call units, with long song cycle times (198 and 210 sec).

Acoustic characters are increasingly being investigated as a cost-effective means of obtaining data with which to determine population identity and structure (Mellinger and Barlow 2003). The recording of sound at sea also offers a relatively a fast and efficient means of gathering information on marine mammal populations remotely and in difficult visual or sea conditions and locations (e.g. Širović et al., in press). Furthermore, because vocalizations may evolve more rapidly than traditional markers, such as genetic or morphological characters, acoustic recordings may be particularly useful in detecting cryptic, insipient and sibling cetacean populations and/or species.

These data and those from other recent studies provide a growing body of evidence that geographic differences in whale calls can provide useful information for discovering and determining population boundaries. As noted above, recent study of the acoustics of fin whales (Hatch and Clark 2004) shows that fin whale song varied significantly among regions in two ocean basins although the differences were not reflected genetic differentiation, suggesting that the patterns of acoustic dissimilarity may represent recent discontinuities in movement/behavior that exist on the shorter time scales relevant to management. Recent study of the acoustics of minke whales suggests a simple downswept call is used across geographic regions, but a complex song-like vocalization variously referred to as the “star-wars”, “thump-train” or “boing” sound is regionally distinctive (Gedamke et al., 2001; Mellinger et al., 2000; Jay Barlow, pers. comm.; Wenz, 1964; Thompson and Friedl, 1982; authors unpublished data). In minke whales, the limited data available is consistent with the hypothesis that the complex sound appears to be produced only during the breeding season while the simple sounds are produced throughout the year.

Understanding the regional variation, function and significance of differences among blue whale song requires a variety of approaches. Future work is likely to include a quantitative analysis of the differences within a call type and between call types to better quantify the categories suggested here and help distinguish the variants in a more quantifiable way. Such analysis would likely parameterize the start frequency, end frequency, duration and gap for each unit of a song and apply statistical methods such as used by Anderson et al. (2000). For the better studied songs such as the Northeast Pacific, there are millions of calls recorded to which such a system could be applied, while other regions such as the Indian Ocean need more data to meaningfully measure the variation within the song types for comparison to other types. Future work is also needed to tease apart the various historical, ecological, morphological and behavioral factors that influence these geographic patterns while investigation into the relative complexity of blue whale calls may provide insights into the differences in the intensity of selection and density of individuals among regions as predicted by studies of birds (Catchpole, 1980; Price, 1998; Kroodsma, 1983). Ultimately, the goal is to understand the potential significance of acoustic differences in the evolution of blue whale populations; if it's a part of their systematics, it should be a part of ours.



**Figure 36. Blue whale residence and population divisions** suggested from their song types. Arrows indicate the direction of seasonal movements.

### Conclusion

Blue whale songs provide a new means for characterizing blue whale population structure worldwide. Song types may be a useful indicator of population identity because they are social signals, which are likely to reflect present day movement and association patterns. Recent advances in technology make the collection and analysis of long-term acoustic records practical, even for remote regions of the world's oceans and at moderate costs. The availability of these data will enhance the potential for blue whale song to play a key role in describing population structure worldwide. We provisionally recommend nine acoustic populations for management.

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### **Remote Sensing of Blue Whale Habitat in the Northeast Pacific**

Blue whales (*Balaenoptera musculus*) are found in all the world's oceans, and are known to migrate long distances on a seasonal cycle. A distinct population of blue whales inhabit the northeast Pacific, ranging from the Gulf of Alaska to waters offshore from central America (Mate et al., 1999; Gregr et al., 2000; Stafford et al., 2001). The cyclic annual migration of the northeastern Pacific blue whale population is associated with feeding at high-latitudes throughout the highly productive summer and fall, followed by a southbound migration to tropical regions to give birth and mate in the winter and spring. Details of their migration route, timing, and possible segregation by gender or maturity remain unknown. Although this population was nearly driven to extinction by commercial hunting, their population appears to be recovering, currently estimated at about 2,000 individuals (Forney et al., 2000), with an estimated growth rate of 6% since 1995 (Barlow, 1995). Large aggregations are often observed throughout the summer and fall feeding on patches of euphausiids near the California Channel Islands, a region known for its high biological productivity (Croll et al., 1998; Fiedler et al., 1998).

Acoustic and satellite remote sensing is well suited to characterizing the seasonal movements and habitat of the northeast Pacific blue whale given the large scale of their seasonal migration. Passive acoustic detection using fixed hydrophones distributed throughout the northeast Pacific provides the large-scale spatial and temporal coverage needed to characterize the migratory patterns of calling blue whales. Satellite imagery provides an efficient means for monitoring oceanic conditions such as chlorophyll-a levels and sea surface temperatures (SST), which serve as indicators of blue whale habitat quality. Local upwelling, thus water column mixing, creates cold surface waters and surface chlorophyll concentrations that are representative of mean chlorophyll concentrations throughout the euphotic zone (O'Reilly and Zentlin, 1998). Satellite derived SST and chlorophyll-a concentrations reveal the seasonality of upwelling and the northward progression of coastal phytoplankton blooms along the North American continent.

Using remote sensing we have continuously monitored the acoustic activity of blue whales and their habitat during 1994-2000 using data from six sites. Our analysis suggests that calling blue whales primarily aggregate offshore of central and southern California in the mid summer and fall. A less dense, but important region of aggregation occurs offshore from Vancouver Island later in the season, in late summer and fall. Primary productivity off southern California typically peaks in the spring allowing zooplankton, and particularly euphausiids, to grow to maturity by summer, coinciding with the arrival of blue whales. Anomalous atmospheric and oceanographic conditions, such as El Niño, disrupt primary productivity, euphausiid distribution and abundance, and alter the seasonality of calling blue whale presence in these primary feeding locations.

### **Background**

#### *Northeast Pacific Blue whale calls*

A trait common to blue whales worldwide is the production of high intensity, low frequency, long duration acoustic calls which are produced in repetitive patterns or songs. The study of blue whale calls provides a means for characterizing various blue whale population movements. In an environment where visibility is limited and individuals may be widely dispersed, the benefits of

communicating through acoustic calls that propagate for up to hundreds of kilometers are apparent (Payne, 1995). The unique call pattern of northeast Pacific blue whales distinguishes them from other blue whale populations around the world, and may be a primary guide for intragroup recognition for mating or group cohesion. In this paper we use blue whale call intensity as a proxy for population density, although we recognize that call production may be gender specific (McDonald et al., 2001; Croll et al., 2002) or have other seasonal or behavioral correlates.

Northeast Pacific blue whale calls have both pulsed and tonal components. The first, or “A”, call unit is pulsive with a duration of about 20 sec. It has a fundamental frequency of about 16 Hz and overtones at five additional frequencies, with a particularly strong overtone near 88 Hz. The second, or “B”, call unit consists of 20 sec of slightly down-swept, harmonically related tones with a fundamental frequency at 16Hz and prominent third harmonic at 48Hz. These calls are often repeated in an alternating sequence by individual animals. The low frequencies, coupled with a loud source level (185 dB re uP at 1-m), enable these “A-B” call sequences to propagate great distances. For several months each year, these calls are the dominant oceanic ambient noise in the northeast Pacific at their tonal frequencies (Curtis et al., 1999).

A previous blue whale monitoring study used acoustic recordings from the US Navy Sound Surveillance System (SOSUS) arrays in the north Pacific and deployed hydrophones in the Eastern Tropical Pacific to monitor the distribution of northeast Pacific blue whale calls through 1996 and 1997 (Stafford et al., 2001). The northeast blue whale call type was recorded along the west coast of North America from July through December 1996, and in the Eastern Tropical Pacific primarily from February to May 1997, though it was heard at a lower level throughout the year at this southern location. Hydrophones in the central North Pacific region received these call types minimally throughout all of 1996, though not in November. This study demonstrated north-south and east-west movement of calling blue whales throughout segments of an annual migration in the northeastern Pacific.

### *Blue Whale Prey*

The distribution and movement of blue whales in the California Current region has been linked with zooplankton aggregations, in particular the euphausiid species *Euphausia pacifica* and *Thysanoessa spinifera* (Croll et al., 1998). The distribution of *E. pacifica* and *T. spinifera* extends from the Gulf of Alaska to southern California, with complimentary offshore and near-shore ranges, respectively (Brinton, 1976). Both species occupy relatively “cold” water and may be limited in their southern extent by the temperature of the mixed layer (Brinton, 1981). Their distributions and densities have been observed to change with altered oceanographic conditions, such as those brought about by El Nino (Brinton, 1981; Mackas, 1995; Tanasichuk, 1998; Tanasichuk, 1998b).

Euphausiid larvae occupying southern California waters are produced locally and their growth coincides spatially and temporally with the upwelling season. The upwelling proceeds north along the coast and is followed by major euphausiid larval recruitment (Brinton, 1976). There are distinct spawning bouts throughout the year and the relatively high success of the large spring cohort is closely related to the increased level of primary productivity available following typical spring upwelling (Brinton, 1976; Tanasichuk, 1998a). Although cohort analysis of *E. Pacifica* off southern California has shown differential survivorship and growth rates of cohorts throughout the year, maximum cumulative population biomasses are often attained during the summer and

early-fall (Brinton, 1976). A time lag, on the order of 7 months, is expected between the onset of environmental conditions that facilitate primary productivity and the maturation of grazing euphausiids from the major spring cohorts (Brinton, 1976).

#### *Oceanographic Setting*

Blue whale feeding grounds off the west coast of North America are associated with the California Current System - a zone of high primary productivity. The California Current typically transports nutrient-rich water from the north along the coast, where the structure of the continental shelf and coastal winds facilitate nutrient recycling and uptake by phytoplankton, as well as abundant grazing by zooplankton (Chelton et al., 1982; McGowan, 1984; McGowan, 1985; McGowan et al., 1998). A southward mass transport of nutrient-rich waters owing to the bifurcation of the West Wind Drift is thought to be the mechanism controlling primary productivity in the California Current, not mere coastal upwelling (Chelton et al., 1982). River outlets along the coast, such as the Juan de Fuca Strait and Georgia Strait off British Columbia and the Columbia River off Washington, provide additional nutrients, especially concentrated during heavy rainfall (Mackas et al., 1978; Crawford and Dewey, 1989; Mackas, 1992).

Off southern California, shelf breaks south of Point Conception, island slopes of the Channel Islands, and nearby seamounts create nutrient-rich conditions that support dense populations of zooplankton including krill (Fiedler et al., 1998). Additional regional upwelling is created by small and meso-scale eddies in the converging southward California Current System and the northward Southern California Countercurrent, increasing euphotic zone nutrient loads from winter to spring, detectable through satellite imagery of sea-surface roughness and SST (DiGiacoma and Holt, 2002). The strongest equatorial winds along the California coast occur in the spring, and larger cyclonic eddy-like circulation perpetuates the productivity to remain within the California Bight (DiGiacoma and Holt, 2002).

#### *El Nino Southern Oscillation*

Bisecting the span of this study, a strong El Nino Southern Oscillation (ENSO) event modified oceanographic conditions in the eastern Pacific during 1997-1998. The influence of extreme ENSO events on biological activity affects many trophic levels, including phytoplankton, zooplankton, pelagic fish, crabs, seabirds, and marine mammals. Ecological studies have noted shifts in community structure where southern (warm water) species extended their geographic range into northern waters, some even displacing the native species in the northeast Pacific (McGowan et al., 1998).

ENSO events are associated with a change in atmospheric pressure over the Pacific basin, causing the equatorial trade winds to decrease or even reverse (blowing west to east), the westward equatorial current to slow and the eastward equatorial undercurrent to strengthen (Chambers, 1998). Within months of these atmospheric changes, the thermocline levels throughout the Pacific begin to shoal in the west and deepen in the east. Warm equatorial waters are transported northward along the coast of North America and decrease the southward transport of rich subarctic water, thereby decreasing primary productivity detectable via satellite imagery (Goes et al., 2001) and zooplankton biomass in the California Current (Chelton et al., 1982; McGowan, 1984; McGowan, 1985; Lavaniegos et al., 1998). Following the 1997-1998 El Nino was a La Nina year (1999), marked by a lower SST, and increased chlorophyll-a concentrations

during the spring bloom (Goes et al. 2001). The spatial extent of the 1999 phytoplankton bloom was the largest ever observed in the equatorial Pacific (Chavez et al., 1999).

#### *Satellite remote sensing*

Satellite imagery provides an efficient means for monitoring oceanic conditions, such as chlorophyll-a levels and sea surface temperature. Past studies have used satellite imagery to investigate relationships between marine mammal and prey distribution. Jaquet et al. (1996) confirmed the existence of a correlation between surface chlorophyll concentration and sperm whale density, based on contemporary ocean color imagery and historical whaling records at various temporal (2 to 12 months) and spatial (220 to 1780 km<sup>2</sup>) scales. They also confirmed the existence of a time lag of at least 4 months and a spatial lag between peak chlorophyll levels and peak sperm whale densities, due to interactions traversing at least 3 trophic levels (Jaquet et al., 1996). Smith et al. (1986) found that the distribution of various cetacean species is linked to regional sea-surface chlorophyll concentrations derived from ocean color data. Woodley and Gaskin (1996) observed an association between right and fin whale habitat and satellite derived sea-surface temperatures.

### **Methods**

#### *Acoustic*

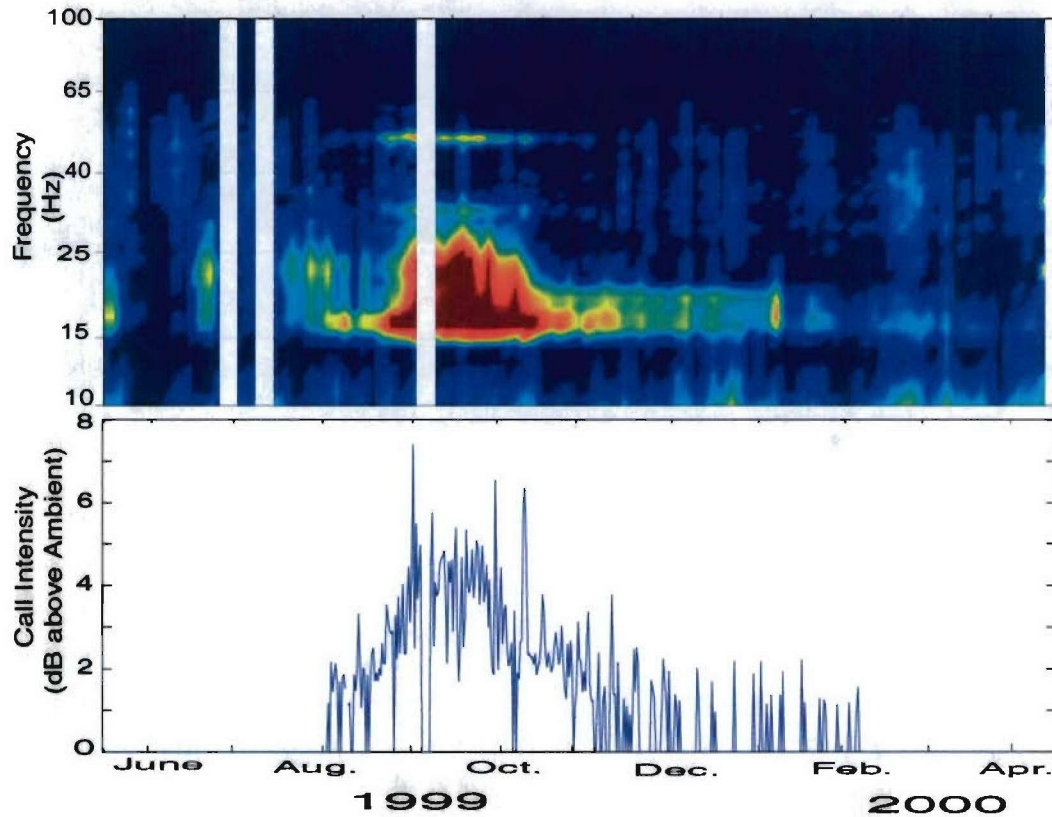
Acoustic monitoring provides continuous data on blue whale calling which allows for determination of the seasonality and the geographic range of calling individuals. Acoustic census techniques provide a proxy measure of the relative whale abundance within a region throughout the season, based on the occurrence of calls and the detection-range of the acoustic sensors.

#### *Monitoring*

From 1994 through 2000, nearly continuous acoustic data were collected from U.S. Navy Sound Surveillance (SOSUS) arrays in the North Pacific. These data were collected as a component of the North Pacific Acoustic Laboratory (NPAL) Acoustic Thermometry of Ocean Climate (ATOC) project, whose goal was to monitor basin-wide temperature changes in the Pacific through timing of acoustic propagation (Howe et al., 1995). At 5-min intervals, 170 s of acoustic data were sampled at 2000 Hz from single hydrophones at each array. The data from these 5-min intervals were subdivided into 10 groups (32768 samples per group) and the power spectra for each group were averaged and smoothed over 1 Hz bins from 0-500 Hz. Gaps occur in the time series owing to equipment malfunctions or damage to the submarine cables connecting the hydrophones to shore. Evaluation of these data as 5-min averaged spectra, provides seasonal calling trends for blue and fin whales, as well as noise due to shipping and wind (Curtis et al., 1999). It should be noted that averaged acoustic data provides aggregate population calling activity and cannot be used to monitor single calling animals in space or time. Although, Watkins et al. (2000) demonstrated that blue whale calls can be detected by these acoustic arrays at over 500 km distance.

To quantify the relative seasonal blue whale call abundance at six sites along the west coast of North America, we extracted blue whale call energy from the spectra by applying an automated detection algorithm to the data averaged into 12-hour bins. The blue whale call detection algorithm extracts the power within the fundamental frequency (16 Hz) and the third harmonic (48 Hz) of the blue whale “B” call and subtracts broadband ambient noise levels, to produce a time series of “B” call intensities. The algorithm is highly defensive against false detection by

comparing the signal intensity in the frequency bands of blue whale calls against broadband ambient noise and by applying a threshold of minimum power for detection. We further reviewed the output of the algorithm to remove periods where ships or storms distorted the signal to noise ratio, affecting our ability to clearly detect and classify the blue whale calls. Figure 37 shows one year of acoustic data from offshore southern California, along with the corresponding output of the blue whale call detection algorithm.



**Figure 37. Eleven months of ATOC noise spectral data from southern California North site from May 1999 to March 2000 showing the seasonal trend in blue whale presence in the region. The data are initially processed into 5-minute averages, and have been further processed into 3 day averages for this spectrogram. The presence of calling blue whales is indicated by the high intensity bands at 16, 32, and 48 Hz. The lower panel is the output of the blue whale detector algorithm run on 12 hour averaged spectra.**

*Oceanographic monitoring with satellite sensors*

Satellite imagery provides an efficient means for monitoring oceanic conditions such as chlorophyll-a levels and sea surface temperatures at the sites of acoustic monitoring. Global chlorophyll-a concentration estimates of the oceans' upper layers are produced and archived by NASA using the Sea-viewing Wide Field-of-view Spectroradiometer (SeaWiFS) ocean color sensor. The spectroradiometer measures the radiance backscattered by the earth's surface within eight spectral bands, ranging from visible to infrared light. This sensor is mounted on the OrbView-2 satellite, which has maintained nearly-global coverage every two days since August 1997. By measuring the spectral character of the light reradiated from the ocean's euphotic zone and using various ancillary data, chlorophyll-a concentrations can be estimated to gauge

phytoplankton production and accumulation in the surface waters. SeaWiFS chlorophyll-a estimates (9 km resolution, version OC4v4) have proven statistically comparable to ship-based surface chlorophyll-a measurements obtained within close spatial and temporal proximity (Kahru and Mitchell, 2001).

Satellite-mounted sensors to estimate sea surface temperature (SST) have been in orbit throughout the past two decades. The Multi-Channel Sea Surface Temperature (MCSST) data set has been processed with a single algorithm from November 1981 through February 2001, enabling consistency for interannual comparisons. The radiation data is obtained by an Advanced Very High Resolution Radiometer (AVHRR), mounted on each of NOAA's polar-orbiting satellites (NOAA-7, 9, 11, and 14). Each sensor measures the character of the radiation within 5 bands (two in the infrared range, two in the visible range, and 1 thermal), after which the data are sent to a ground station to be processed. These values are converted to sea surface temperature estimates and displayed as 18 km resolution weekly composites.

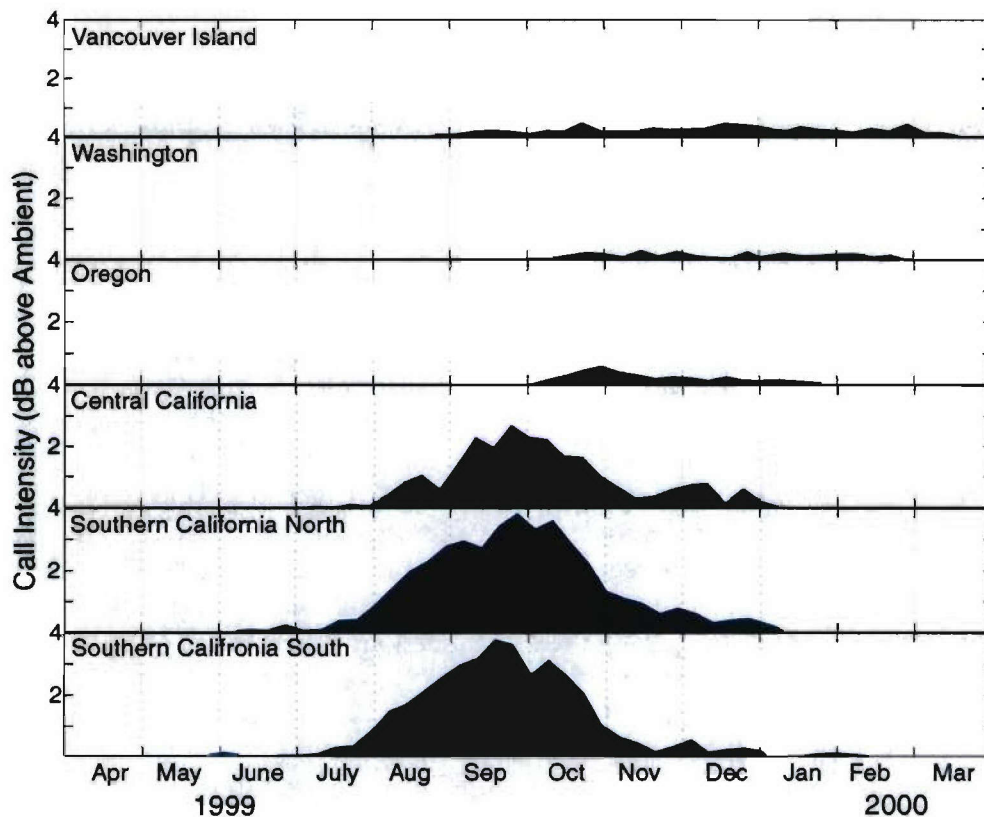
#### *Satellite image analysis*

We tracked surface chlorophyll-a concentrations using 9 km resolution, gridded, 8-day SeaWiFS composites (processed with version OC4v4), from its onset in August 1997 through 2000 (see attached CD-ROM). Similarly, we tracked sea surface temperatures using 18 km resolution, weekly AVHRR MCSST composites from 1994 through 2000. Chlorophyll-a and SST were measured within non-overlapping zones around each acoustic array, extending along the coast. This spatial scale (each roughly 500 km by 250 km) was used to account for oceanographic conditions surrounding each site that might affect prey abundance and distribution. We extracted the mean values as well as the minimum and maximum within each region using the imaging software WIM. We excluded estimates from regions having less than 5% coverage of valid pixels due to cloud coverage, to avoid unrepresentative classifications. We then compared the varied oceanographic conditions throughout the study area with the timing and character of the blue whale calling at each site.

## **Results**

#### *Seasonality of blue whale calls*

The migration and seasonality of calling blue whales in the northeast Pacific can be monitored with the ATOC hydrophone data. The ATOC hydrophone data suggest that blue whales begin migrating northward in the early summer, since they are first heard offshore from southern California in early to mid-June (Figure 38). As the summer progresses the whales are heard further north along the central California coast in early July, then offshore Oregon and Washington in mid-September. The only deviation from a strictly northward migration is the detection of blue whales near Vancouver Island in mid-August, about one month earlier than off Washington and Oregon. A more or less northward progression is consistent for all the years for which we have data (1994-2000), with minor fluctuations in the timing of the arrival, peak, and the departure from each region.



**Figure 38.** Seven year average (1994-2000) of blue whale acoustic intensity for each of six sites along the continental shelf of the western North America. Acoustic data is available from hydrophones at Vancouver Island, Washington, Oregon, central California, southern California North, and southern California South.

Blue whale calling intensity has a pronounced peak during mid-September in southern California, and during mid-October in central California (Figure 38). At these sites, calling gradually decreases during the fall, and blue whales are rarely detected after the end of January. Call energy detected at the northern sites (Oregon, Washington, and Vancouver Island) is significantly lower than at the southern sites, suggesting fewer calling whales are present in this region. There is typically little or no peak in blue whale detection at the northern three sites. Blue whales are detected through December off Oregon, through February off Washington, and well into March off Vancouver Island. The average number of weeks that blue whale calls are detected at the southern and central California sites is 32 weeks, while at the Oregon and Washington sites, calls span 21 weeks or less. Off Vancouver Island, the site furthest north, blue whales are heard for at least 30 weeks, similar in duration to their stay along California (Figure 38). These data suggest that blue whale presence is focused offshore southern and central California in the summer and fall, and that a more temporally dispersed presence of blue whales occurs offshore Vancouver Island, and to a lesser extent Oregon and Washington in the fall and winter. While the north-bound migration is easily tracked with the acoustic data, the southbound return to low latitudes is not apparent.

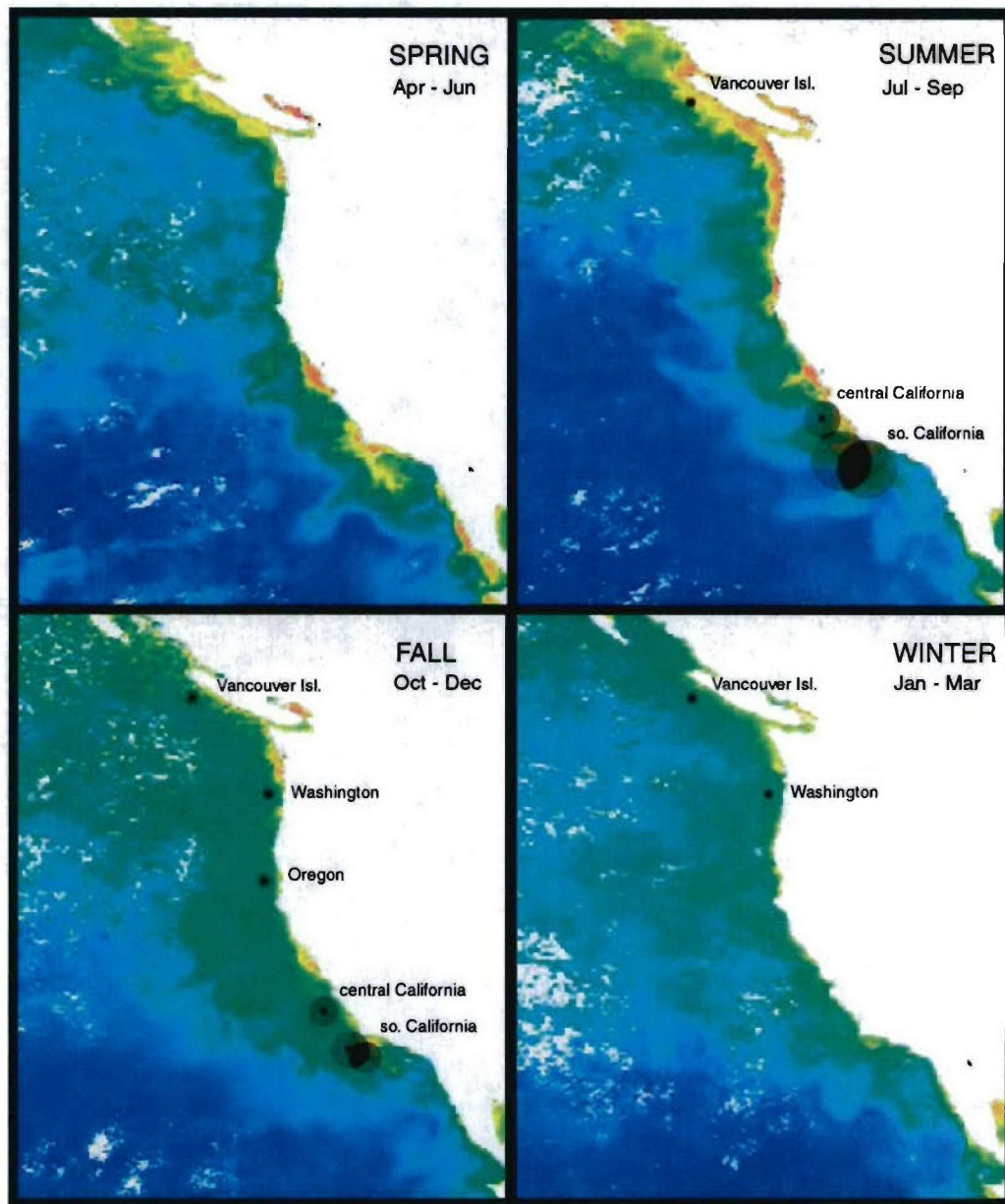
### *Environmental Patterns*

SeaWiFS imagery reveals seasonal trends in chlorophyll concentration that may aid in understanding blue whale migration patterns (Figures 39, 40). In general, chlorophyll-a levels peak over the continental shelf in the spring and persist throughout the summer. The spring chlorophyll bloom precedes the timing of the observed northward migration of calling blue whales by several months, suggesting that blue whale seasonality along the west coast of North America is closely linked to the distribution of euphausiids.

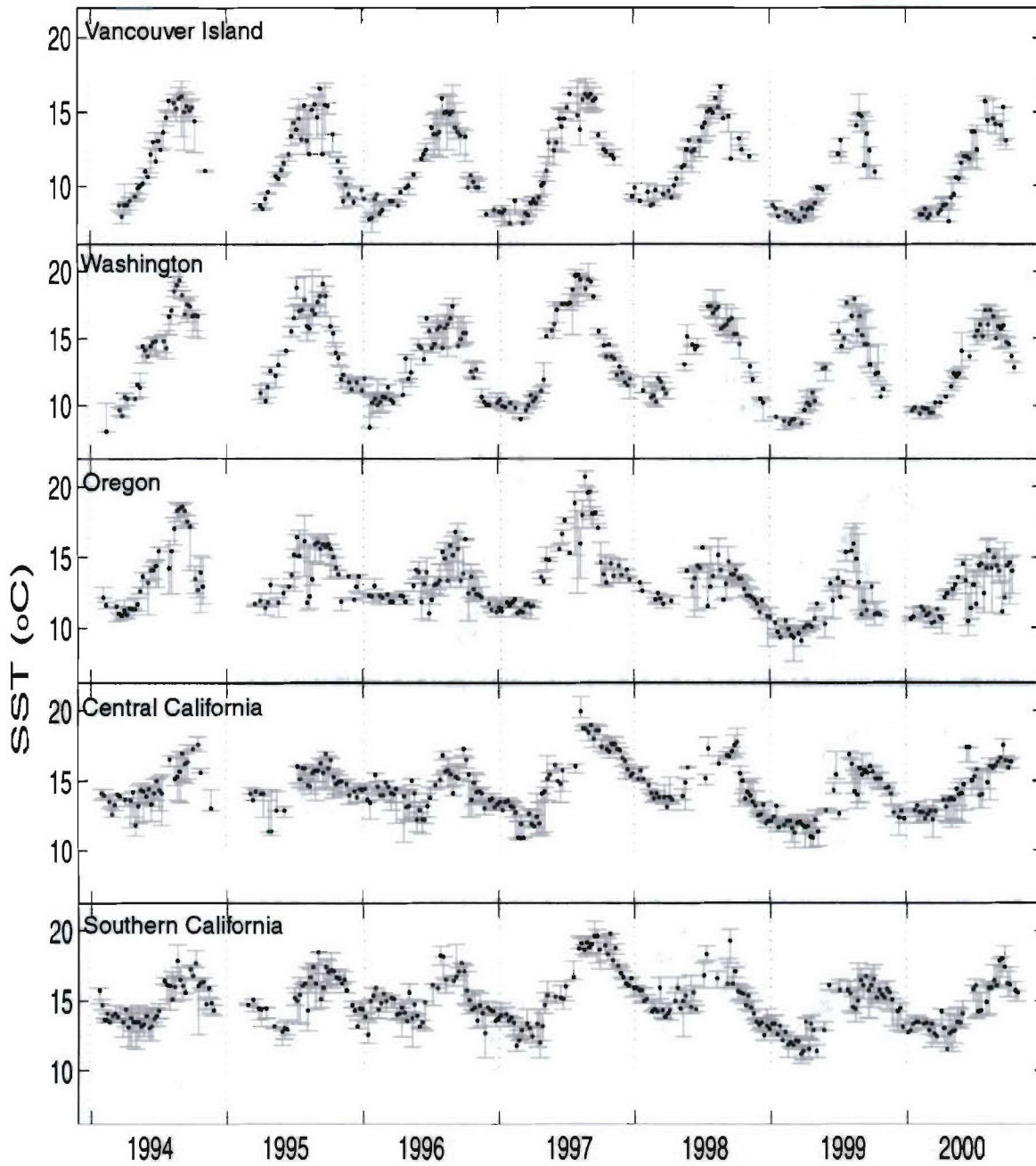
Seasonal changes in primary productivity (chlorophyll) are related to the availability of nutrients and hence oceanographic conditions. The satellite-derived SST data show the southward transport of sub-arctic waters increases in the spring, providing nutrients coincident with increased coastal upwelling and depressed surface temperatures (Figure 41). Off central and southern California these spring conditions result in increased chlorophyll levels from phytoplankton blooms (Figure 39, spring). Likewise, the region surrounding Vancouver Island experiences a strong early-spring phytoplankton bloom. Later in the spring, less intense phytoplankton blooms progress northward from California along the coast of Oregon and Washington. High productivity in the region off Oregon may be associated with run-off from the Columbia River, and the region surrounding Vancouver Island receives nutrients from the Juan de Fuca Strait and Georgia Strait (CD-ROM animation). The coastal phytoplankton bloom continues through the summer season and is advected off the shelf in highly productive offshoots of the southward flowing California Current (Figure 39, summer). The northern region (Washington and Vancouver Island) experiences a series of phytoplankton blooms over the shelf extending well into the fall (Figure 39, fall). Phytoplankton accumulate throughout the coastal region during fall, extending well offshore in relatively high surface chlorophyll concentrations. Surface chlorophyll-a levels become diffuse along the coast and decrease through the winter where they reach an annual low before the next spring phytoplankton bloom (Figure 39, winter). A time-series animation of surface chlorophyll concentrations for the study area is presented on an associated CD-ROM.

Average sea surface temperatures throughout the monitored zones display an annual variation of as much as 8 °C and are more pronounced in the northern regions (Figure 41). Surface temperatures increase throughout the summer, peaking in September, then decrease steadily through the end of the year with the onset of upwelling. Temperatures continue to drop until an annual low is reached during the peak spring upwelling.

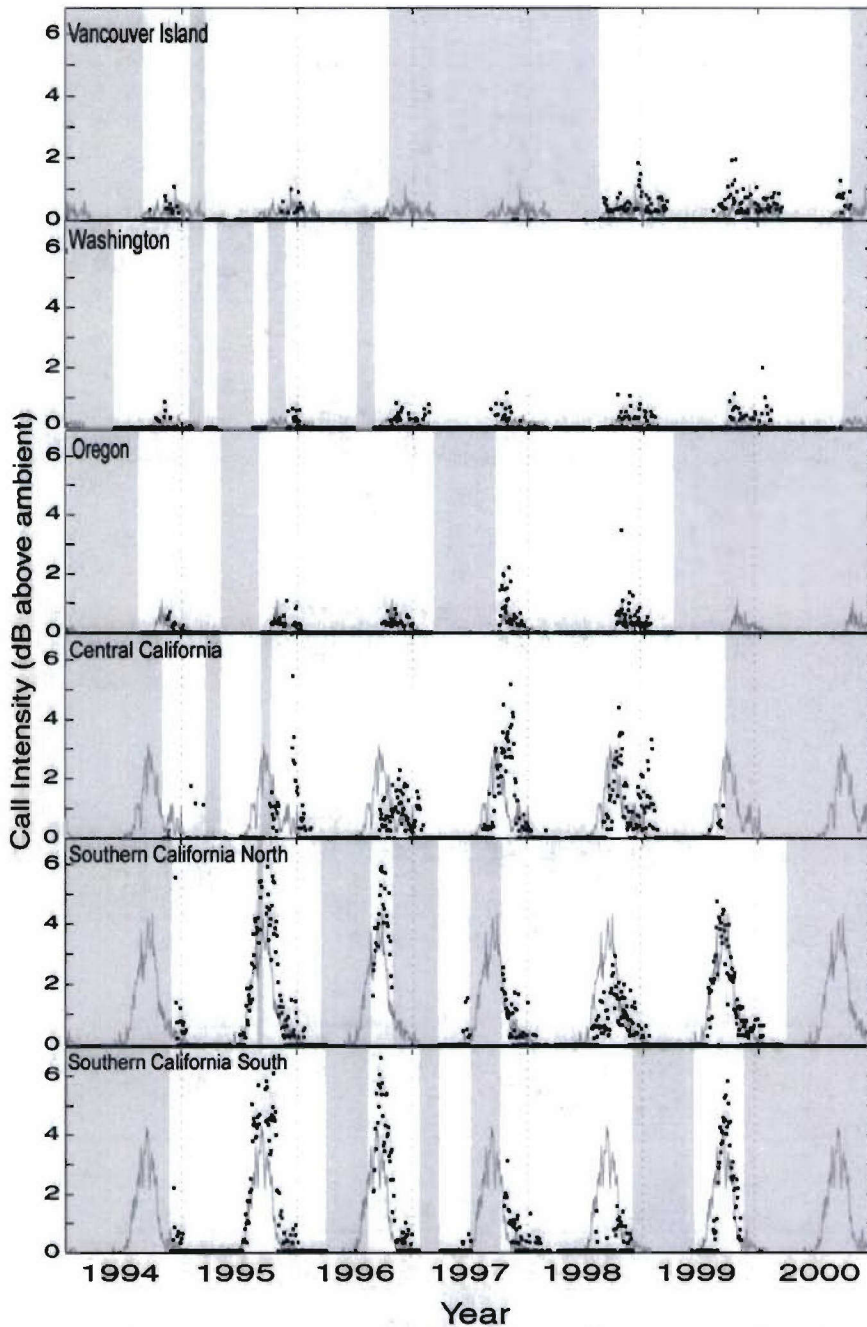
SeaWiFS chlorophyll imagery is unavailable prior to the summer of 1997; however, the conditions described above appear to apply to the previous three years (1994-1996), as moderate surface temperatures, and therefore upwelling patterns, were observed throughout this time via remote sensing (Figure 41).



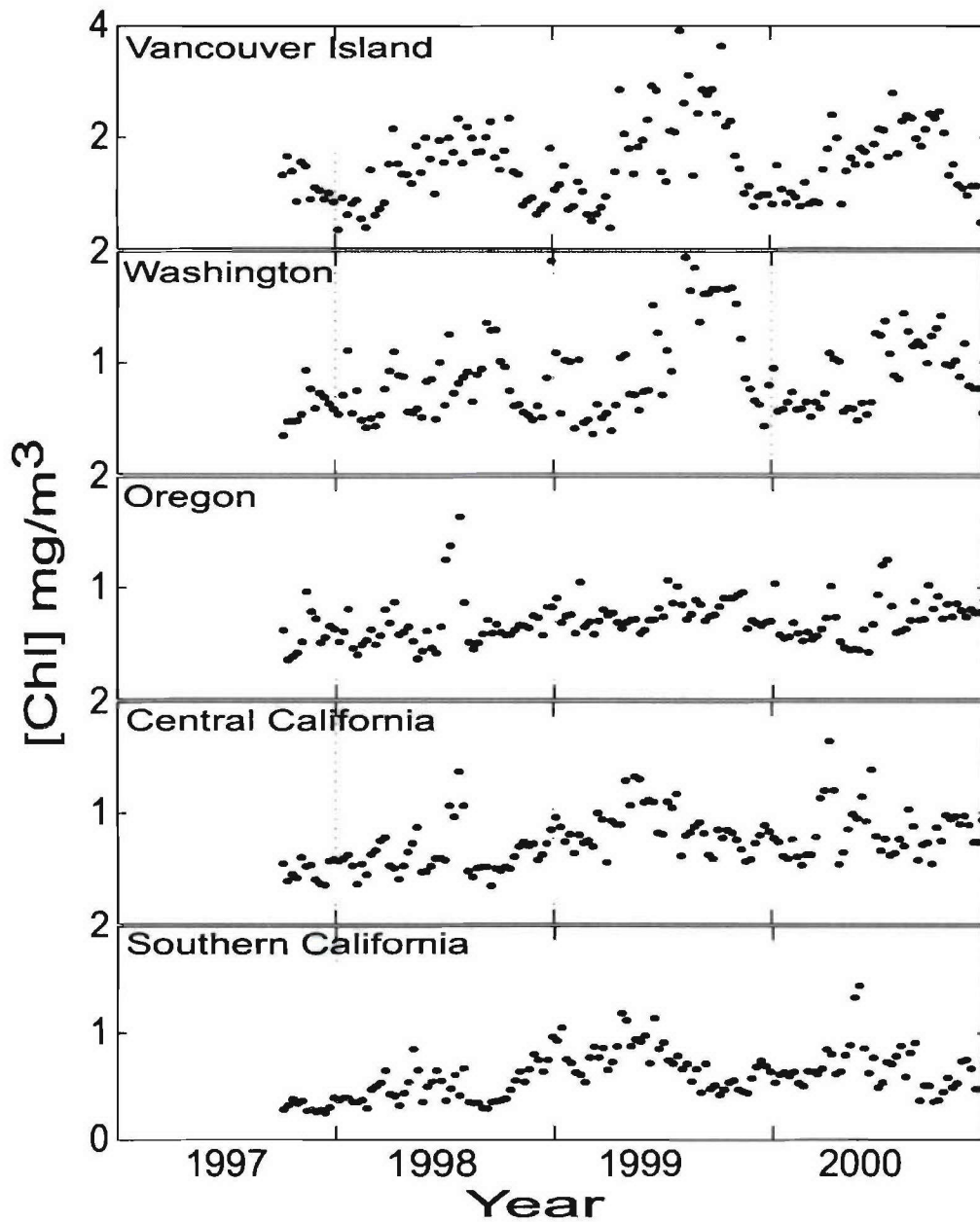
**Figure 39. Chlorophyll landscapes derived from SeaWiFS images over one month intervals.** The seasonal panels of chlorophyll-a concentration are from SeaWiFS in 2000 with relative blue whale calling intensity indicated by the size of the gray circle at each acoustic monitoring location. The spring panel is from May, the summer panel from September, the fall panel from November, and the winter panel from February. The monthly composite images were chosen to best illustrate the average seasonal conditions throughout the study region. The locations of the acoustic arrays are from Curtis et al. (1999).



**Figure 40. Seven day average sea surface temperature (SST) values (°C) from each of the 5 geographic regions studied here from 1994 to 2000. Minimum and maximum values indicated by the gray bars. The El Niño of 1998 is seen as increased surface temperatures, particularly during the spring when upwelling usually lowers the surface temperatures substantially.**



**Figure 41. Eight day chlorophyll-a concentrations ( $\text{mg}/\text{m}^3$ ) for each of the five regions studied here from the onset of SeaWiFS availability in September 1997 through 2000. The 1998 El Niño can be seen as the absence or relative weakness of the spring phytoplankton bloom, particularly at the southern sites.**



**Figure 42. Two day average blue whale acoustic intensity** in decibels (dB) above the ambient noise level at six sites. Periods of no data are indicated as gray shaded regions on the time line of each site. The seven year average of acoustic intensity and seasonality (from Figure 38) is shown for reference as the dark gray line on each timeline. The actual data for each 2 day period is shown as a black dot.

### *ENSO related deviations*

Notable deviations from the aforementioned oceanographic trends were observed during the El Nino period beginning in the summer of 1997. The largest anomalies occurred at the southern sites (Southern and Central California and Oregon) but were also apparent at the northern sites (Washington and Vancouver Island). Summer temperatures at the southern sites during 1997 surpassed peak surface temperatures of the previous three years by nearly 3 °C (Figure 41). The SeaWiFS imagery from September 1997 display fall chlorophyll levels well below seasonal levels of later years (Figure 40). The southern four sites also had notably warm fall and winter temperatures in the 1997/98 season. Throughout the region, anomalously weak phytoplankton blooms clung tightly to the coast, without much offshore drift (see CD-ROM animation).

A switch to anomalously cold surface temperatures, a La Nina condition, occurred in late-fall of 1998, and continued throughout 1999. Evidence of increased upwelling, and increased southward transport of nutrient-rich water, was apparent in the elevated chlorophyll levels at most sites during the spring bloom of 1999. Chlorophyll levels remained elevated throughout the summer and diminished in the fall, when more typical conditions returned in 2000.

During El Nino, when upwelling is diminished and the euphausiid distribution and abundance is altered, the distribution and relative abundance of blue whales is also anomalous (Figure 42). The calling whales deviated from their consistent migration pattern during the 1997/98 El Nino. The summer of 1997 coincided with increased calling intensity at central California and Oregon. Callers were present off southern California in the 1998 season, however, their level of calling was substantially reduced during the expected mid-September peak. Calling near central California occurred during the late summer and fall as expected; however substantial calling levels occurred late in the season when calling usually tapers off, indicating a delayed departure from that region in 1998. The seasonal duration of calling was extended near Vancouver Island and Washington compared to previous years and the amplitude of the calling intensity was greater than expected near Vancouver Island.

The movements of calling blue whales were again altered during the productive oceanographic conditions of the 1999 La Nina. Southern California sites returned to the usual calling intensity, however, at the northern sites (Washington and Vancouver Island), calling intensity and duration increased compared to previous years.

### **Discussion**

The strategy used by foraging blue whales to find krill swarms remain unknown; however, seeking aggregations of krill in consistently located and predictably timed concentrations may moderate some of the difficulties of foraging. Southern and central California offshore waters are consistent centers of upwelling, high primary productivity, and krill spawning, as well as calling blue whale aggregation.

Intense jets from the upwelling centers of mesoscale eddies (Chereskin, 2002) off southern and central California occur at breaks in the continental shelf creating highly productive waters which entrain phytoplankton and euphausiids (Brinton, 1981). The arrival of blue whales off Pt. Conception in early June coincides with substantial primary productivity accumulating within this gyre as seen in the CD-ROM animation. The peak of their calling in this region coincides

with expected peak euphausiid biomass, approximately seven months following the onset of the upwelling season and typical euphausiid spawning events. Southern and central California appear to experience a comparable influx of blue whale calling intensity, timing, and duration, likely due to common coastal primary and secondary productivity levels off California.

Calling blue whales are less densely aggregated and more temporally dispersed along the northern extent of the migration route from Oregon to Washington, while Vancouver Island seems to represent a secondary center for migrating callers or resident blue whales who call seasonally. There is a relatively consistent short duration of calling off Oregon, where individuals are likely passing through in transit to northern sites. The northern extent of our study region experiences a phytoplankton bloom in early-spring, when sufficient sun-light is available and northern currents and estuary outlets provide ample nutrients. Apparent strong and persistent upwelling throughout summer near Vancouver Island is seen in concentrated surface chlorophyll levels. These observations are consistent with results of an 11 year study around Vancouver Island (Mackas, 1992), where upwelled California Undercurrent water and Georgia Strait surface water occurred April through September, and ample nitrate inputs over the shelf were from the upper layer discharge of the Juan de Fuca Strait. Our observations of a late spring and fall highly concentrated chlorophyll occurrence in this region is consistent with Mackas (1992), where he also observed a mid-summer euphausiid bloom which remained concentrated over the shelf and a strong late-summer to fall peak occurrence of the two dominant euphausiid species, *E. pacifica* and *T. spinifera*, on the southern shelf (Mackas, 1992). The phytoplankton blooms and euphausiid growth cycle are consistent with the timing of peak blue whale calling in this region.

Our acoustic data do not reveal a southward migration after feeding at higher latitudes. It is possible that the whales are no longer calling during their return trip south, or that they are further off-shore where the hydrophones studied here do not detect them. Stafford et al. (2001) presented acoustic data from several SOSUS sites further off-shore in the northeast Pacific and reported blue whale calls at low detection rates at one site throughout the winter and spring, suggesting some portion of the population may be traveling further off-shore and calling during their migration south.

The SeaWiFS derived chlorophyll record suggests that the lowest chlorophyll levels occur throughout the winter (Figure 39, winter), likely because of winter mixing, offshore advection, grazing effects, and sinking particulates that dilute surface chlorophyll concentrations. This observation is consistent with seasonal processes noted in an extensive study of the vertical and horizontal distribution of phytoplankton throughout the western Atlantic continental shelf (O'Reilly and Zentlin, 1998). The decreased off-shore surface chlorophyll levels throughout the 1997/98 El Nino correspond with the California Cooperative Oceanic Fisheries Investigations (CalCOFI) ship-based observations from the waters off California in the 1982/83 El Nino (McGowan, 1985).

Though blue whales off central America have been observed foraging on euphausiid *Nyctiphanes simplex* and small pelagic crabs, their strong presence feeding throughout the California Current System may be evidence of a preference for the larger northern euphausiid species and/or a necessity for the population to exploit regionally dispersed feeding grounds. The relatively large

size of the northern latitude euphausiid species might attract foraging whales as it does migrating hake, who preferentially feed on large individuals of the same euphausiid species in northern waters during the summer (Tanasichuk, 1999).

#### *El Nino Southern Oscillation*

During El Nino, the decreased calling amplitude in the southern sites and the anomalously increased calling presence in the north suggests that the ENSO related warming choked off upwelling and thus prey in the south, while the north remained productive. It appears that during the El Nino event, fewer areas were able to concentrate the phytoplankton necessary to support euphausiid aggregations and grazing blue whales. The southern California sites appeared to host fewer calling blue whales in 1998, throughout the season. However, near Vancouver Island whales were heard at increased intensity for at least 30 weeks during 1998 and 1999. Similar increases in calling duration off Washington in 1998 and 1999 suggest either increased prey availability or increased northern movements by the whales searching for prey. Calling whales arrived at the northern sites earlier than usual, likely seeking prey. While Washington and Vancouver Island historically hosted numerous blue whales, they have been observed only in sparse numbers since being depleted by whaling in the early 1900's (Gregs et al., 2000). Their increased presence in 1998 and 1999, suggested both by calling amplitude and seasonal duration, is evidence for reutilization of resources in the northern latitudes by an increasing number of blue whales. There is a relatively consistent short duration of calling off Oregon, apparently not affected by the changes during ENSO, suggesting that individuals are merely passing through in transit to the northern sites.

Although Brinton (1976) suggests that the biomass of large euphausiid adults is determined by the upwelling strength of the previous year, the northward shift of blue whales in 1998, suggests that the effects of decreased upwelling on euphausiid biomass off southern California may be apparent within the same year. Varied life history strategies of single euphausiid species might indicate slower growth for a longer duration in sub-arctic waters, compared to faster maturation of krill individuals off California (Brinton, 1976). Euphausiid counts of *T. spinifera* and *E. pacifica* throughout southern California appear to decrease during El Nino events (CalCOFI data, 2002). Zooplankton counts were well below average during the El Ninos of 1958, 1982/3, and 1993 (CalCOFI data, 2002).

Euphausiid abundance fluctuations affect the survival of various predators. For example, short-tailed shearwaters (*Puffinus tenuirostris*) over the south-eastern Bering Sea shelf experienced a mass mortality due to starvation in the summer of 1997, when atypical atmospheric and oceanographic conditions caused decreased availability of their euphausiid prey (Baduini et al., 2001). Sockeye salmon (*Oncorhynchus nerka*), who also feed on euphausiids, had poor returns to Bristol Bay with lower than typical weights of survivors, in the summer of 1997 (Kruse, 1998). Similarly, Tynan (1998) found the Bering Sea right whale population had shifted their typical prey species and foraging grounds in the southeast Bering Sea during the 1997/98 El Nino. She observed them uncharacteristically feeding over the middle shelf in the summer of 1997, which experienced increased surface temperatures (2-4 °C) and an anomalous coccolithophore bloom, which was observed through SeaWiFS imagery, (Tynan, 1998) compared to their usual feeding on calenoid copepod species in deep water along the shelf break (Nemoto, 1963). Anomalous atmospheric and oceanographic conditions affect many species among varied trophic levels within the coastal and pelagic ecosystems (Napp and Hunt, 2001; Stockwell et al., 2001).

### *Scale and variable selection*

Gregr and Trites (2001) used whaling records to model critical habitat for five whale species in waters off British Columbia, exploring six predictor variables (month, depth, slope, depth class, SST, and salinity). The habitat model for blue whales was relatively insensitive to the predictor variables, partially due to the small sample size for this species. However, they were able to predict slight concentrations of blue whales off the shelf of Vancouver Island and the Queen Charlotte Islands, areas that we have found to be high in primary productivity (Figures 39 and 40) several months prior to the arrival of calling blue whales in that region (Figures 38 and 39). Our study suggests that their modeling could be enhanced with the inclusion of satellite derived continuous data and a larger sample size for blue whales, both of which are provided by remote sensing.

The scale of our study is large compared to that of Gregr and Trites (2001), which looked at 10 by 10 km boxes. We acoustically monitored up to several hundred km from each sensor (Watkins et al., 2000) and oceanographically monitored a 250 km by 500 km area around each acoustic sensor. We chose a large scale because of the time lag, and therefore spacial lag of our oceanographic variables. Phytoplankton are at least two trophic levels away from blue whales and the euphausiids have a maturation time of at least a few months, suggesting that monitoring concurrent chlorophyll and blue whale abundance may produce weak correlations. Gregr and Trites (2001) suggest that if animal distributions are a function of prey concentration caused by small scale eddies or gyres, little spatial or temporal lag would be expected; however, while euphausiids are concentrated by these circulation events, a time lag is required for them to reach a size appropriate for blue whale consumption, and therefore larger spatial scales or small scales including a time lag must be incorporated into the analysis. A multi-scale analysis, such as that by Jaquet et al, (1996) will be necessary to adequately describe blue whale habitat, particularly using only chlorophyll-a and SST as predictor variables. Large scale is also necessary to observe the effects of El Nino on regional primary productivity. Our CD-ROM animation illustrates that a phytoplankton bloom did occur off the coast of North America in the spring of 1998; however its spatial extent was limited and therefore the overall productivity of the region was below normal. This effect may not have been observed if smaller areas were chosen for the analysis.

The goal of our study was to identify the relationship between satellite-derived oceanographic variables, and acoustic proxies for whale presence. The temporal and spatial scales for both satellite and acoustic monitoring are well matched to the task of developing whale habitat models. Both satellite and acoustic monitoring provide continuous data, enabling analysis of the time lag between primary productivity and whale presence. The large spatial coverage of oceanographic and acoustic monitoring allows for the study of highly variable oceanographic environments and shifting whale presence. We have included only two of many variables available from satellite-derived oceanographic data. The addition of other variables, such as bathymetry, slope, sea surface height, sea surface roughness (wind speed), thermocline depth and isotherm depth (Chambers, 1998), may increase the predictive power of future models.

### **Conclusions**

The advent of remote sensing technology, both satellite and acoustic, has increased our ability to

monitor and study blue whales and their habitat. Since sound is a primary sense for cetacean navigation and communication, acoustics are an ideal way to continuously monitor their presence and movements. The spatial and temporal coverage provided by remote sensing surpass the abilities of ship based environmental measurements and marine mammal visual observations.

The analysis presented here correlates environmental parameters with calling blue whale presence and migration. Advances in acoustic census techniques and the addition of other satellite derived environmental parameters may permit more quantitative associations between blue whale distribution and habitat. Continuous satellite-derived oceanographic measures allow for the introduction of time lags into the analysis so that associations between habitat and acoustic activity can be modeled. These models are needed to better predict blue whale foraging grounds and other critical habitat.

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## Transitions to the Navy

SCORE is a Naval training facility under the command of the Fleet Area Control and Surveillance Facility, San Diego (FACSFACSD). SCORE conducts operations including multi-warfare and battle group evolutions, on and around San Clemente Island. The majority of the training exercises conducted at SCORE are designed to support the Commander of Third Fleet and Commander, Naval Air Force U.S. Pacific Fleet training and readiness requirements. Other events conducted at SCORE facilitate the test, evaluation, and development of weapon systems and tactics. All SCORE operations are monitored, controlled, and evaluated by Range Operations Center (ROC) personnel at NAS North Island.

As part of SCORE operations, underwater vehicles are tracked utilizing acoustic pingers (MK84). Track accuracy is nominally 10 meters for surface and underwater platforms using the acoustic tracking system. Submarines participating in Anti-Submarine Warfare (ASW) exercises are tracked with the underwater tracking system, as ASW operations are conducted on the underwater range. Shallow water operations are supported with surface and in-air tracking in the Tanner/Cortez Bank areas. An underwater shallow water tracking range is planned for the Tanner/Cortez Bank area, where our project focused on monitoring of baleen whales.

Anti-submarine warfare (ASW) training is accomplished at SCORE using underwater tracking with a hydrophone array called the Southern California ASW Range (SOAR). The SOAR range (Figure 1) is located west of San Clemente Island and encompasses approximately 670 square miles of 3-D underwater tracking area. The range routinely supports torpedo firing exercises as well as battle group training. Submarine Launch Mobile Mine operations are conducted in the waters of SHOBA (Shore Bombardment Area, see Figure 1). Mines are recovered via the MK-V Marine Mammal Program, providing precision position measurements. Mine Countermeasure training is accomplished through Kingfisher operator training and surface ship mine detection and avoidance training. The Kingfisher Training Range is located approximately two miles northwest of Eel Point on the western side of San Clemente Island.

There are several key ways the data and results of our project are being transitioned to the Navy and to the SCORE range in particular. First, the raw visual and acoustic marine mammal data that was generated by this project are being included in a marine resources assessment (MRA) that is being preparing for the Navy's Southern California Operating Area (SOCAL) (personal communication, Julie Rivers, CIV NAVFAC PAC). Our dataset provides the most intensive and comprehensive set of marine mammal observations to date within the SCORE range and surrounding areas. Second, we have developed new technology and algorithms that are finding application in other Naval ranges. For instance, we are now conducting long term acoustic monitoring, using the tools developed by this project, in the Navy's Quinalt Range, located off the coast of Washington. Likewise, we are involved in plans to conduct similar acoustic and visual monitoring in the Navy's proposed East Coast shallow water test range. As part of this project we collaborated with the Naval Post-Graduate School in collecting data from the SCORE underwater tracking range hydrophones, as a means for assessing how the installed hydrophones of the SOAR tracking range could be used for marine mammal monitoring. In addition, we helped to raise awareness of the potential for marine mammal tracking with Navy range hydrophones, so that consideration could be given to this potential for future hydrophone

installations in the SCORE region, such as the future shallow water test range planned for the Tanner/Cortez Banks region.

## Conclusions

We have significantly improved understanding of the seasonality and relative abundance of baleen whales in the SCORE area. There is a significant presence of these whales in the summer and fall, whereas, there is a greatly diminished presence in the winter and spring. We have shown how satellite productivity data is not a direct correlate to whale presence, as primary productivity substantially increases in the spring, whereas the whale presence does not increase for at least 3-4 months later. However, zones of high primary productivity over the yearly cycle are also zones of high whale abundance over the same long-term time scale. More detailed environmental monitoring should be a high priority for future study, to develop predictive habitat modeling for marine mammal presence in the SCORE region, as an aide to the environmental assessment process.

We have shown that acoustic methods have great potential for improving marine mammal population assessments. These methods produce significant numbers of detections, and can be conducted with lower cost and with less seasonal bias than visual methods. Additional information on whale calling statistics is needed to allow acoustic methods to make quantitative estimates of whale abundance. We have collected significant new data on blue whale calling statistics, including better understanding of the behavioral context of calling. For instance, repeated song calls are now known to be made exclusively by males, and predominantly in the fall season within SCORE. These stereotyped songs may provide an alternate means for dividing blue whales into stocks for management purposes. More research is needed on a broad range of marine mammal species to better understand how sound production is part of their behavioral repertoire.

Although we have not focused on toothed whales (odontocetes) or pinnipeds in this project, we found ample evidence for their presence in the SCORE region during our visual and acoustic surveys. For instance, California sea lions were the most commonly sighted animals in the aerial survey data. Future work should examine the acoustic behavior of these animals and also how acoustic monitoring may be used to study their seasonality and abundance in the SCORE area.

## Appendices

### Codes for marine mammal species observed

*Appendix Table 1: Codes for marine mammal species observed.*

	Species Code	Scientific Name	Common Name
Mysticetes	Ba	<i>Balaenoptera acutorostrata</i>	Minke whale
	Bb	<i>Balaenoptera borealis</i>	Sei whale
	Be	<i>Balaenoptera edeni</i>	Bryde's whale
	Bm	<i>Balaenoptera musculus</i>	Blue whale
	Bp	<i>Balaenoptera physalus</i>	Fin whale
	Er	<i>Eschrichtius robustus</i>	Gray whale
	Mn	<i>Megaptera noveaengliae</i>	Humpback whale
Odontocetes	Dd	<i>Delphinus delphis</i>	Common dolphin
	Gg	<i>Grampus griseus</i>	Risso's dolphin
	Gm	<i>Globicephala macrorhynchus</i>	Pilot whale
	Lb	<i>Lissodelphis borealis</i>	Northern Right Whale dolphin
	Lo	<i>Lagenorhynchus obliquidens</i>	Pacific White-sided dolphin
	Kb	<i>Kogia breviceps</i>	Pygmy sperm whale
	Mc	<i>Mesoplodon carlhubbsi</i>	Hubbs' beaked whale
	Md	<i>Mesoplodon densirostris</i>	Blainville's beaked whale
	Mg	<i>Mesoplodon ginkgodens</i>	Ginko-toothed beaked whale
	Mp	<i>Mesoplodon peruvianis</i>	Pygy beaked whale
	Ms	<i>Mesoplodon stejnegeri</i>	Stejneger's beaked whale
	Oo	<i>Orcinus orca</i>	Killer whale
	Pc	<i>Pseudorca crassidens</i>	False killer whale
	Pd	<i>Phocoenoides dalli</i>	Dall's porpoise
	Pm	<i>Physter macrocephalus</i>	Sperm whale
	Sc	<i>Stenella coeruleoalba</i>	Striped dolphin
Zc1	<i>Ziphius cavirostris</i>	Cuvier's beaked whale	
Pinnipeds	Cu	<i>Callorhinus ursinus</i>	Northern fur seal
	Ej	<i>Eumetopias jubatus</i>	Northern (Steller) sea lion
	Ma	<i>Mirounga angustirostris</i>	Northern elephant seal
	Zc	<i>Zalophus californianus</i>	California sea lion
Other	UD		Unidentified dolphin
	UW		Unidentified whale
	UMM		Unidentified marine mammal

**Aerial survey sightings in the SCORE region.**

*Appendix Table 2. Aerial survey sightings in the SCORE region.*

<b>Date</b>	<b>Latitude (N)</b>	<b>Longitude (W)</b>	<b>Species</b>	<b>Group Size</b>
5/14/01	32.722	-117.443	bm	1
5/14/01	32.613	-118.499	dd	3
5/14/01	32.615	-118.685	dd	19
5/14/01	32.946	-118.818	gg	29
5/14/01	32.613	-118.452	pd	1
5/14/01	32.946	-118.818	tt	29
5/14/01	32.88	-119.183	uw	1
5/14/01	32.843	-119.245	uw	1
5/14/01	32.946	-118.940	zc	1
5/14/01	32.946	-119.068	zc	1
5/14/01	32.78	-119.292	zc	1
5/14/01	32.78	-119.198	zc	1
5/14/01	32.781	-119.151	zc	1
5/14/01	32.613	-118.389	zc	2
5/14/01	32.615	-118.685	zc	1
5/14/01	32.614	-118.951	zc	1
5/14/01	32.615	-119.059	zc	2
5/14/01	32.614	-119.171	zc	1
5/14/01	32.613	-119.218	zc	1
5/14/01	32.614	-119.359	zc	1
5/14/01	32.614	-119.416	zc	1
5/14/01	32.447	-119.265	zc	1
5/14/01	32.447	-119.226	zc	35
5/14/01	32.447	-119.219	zc	3
5/14/01	32.448	-119.123	zc	1
5/14/01	32.447	-119.116	zc	1
5/14/01	32.447	-119.112	zc	1
5/14/01	32.447	-119.109	zc	1
5/14/01	32.447	-119.102	zc	3
5/14/01	32.447	-119.102	zc	6

5/14/01	32.446	-119.077	zc	2
5/14/01	32.447	-118.725	zc	1
5/14/01	32.446	-118.560	zc	1
6/11/01	32.583	-118.044	bp	2
7/13/01	32.435	-118.620	dd	12
7/13/01	32.435	-119.000	zc	1
7/20/01	32.597	-118.499	bm	2
7/20/01	32.608	-119.114	bm	2
7/20/01	32.447	-119.237	bm	1
7/20/01	32.608	-119.153	lw	1
7/20/01	32.446	-119.408	mm	1
7/20/01	32.946	-118.637	zc	1
7/20/01	32.611	-119.289	zc	3
7/20/01	32.609	-119.332	zc	2
7/20/01	32.611	-119.402	zc	1
7/20/01	32.444	-119.512	zc	1
10/29/01	32.447	-119.257	bp	2
10/29/01	32.496	-119.551	bp	1
10/29/01	32.592	-119.528	bp	4
10/29/01	32.606	-119.522	bp	1
10/29/01	32.611	-119.418	bp	2
10/29/01	32.611	-119.418	bp	1
10/29/01	32.611	-119.418	bp	1
10/29/01	32.611	-119.404	bp	1
10/29/01	32.614	-118.848	bp	1
10/29/01	32.389	-118.442	dd	550
10/29/01	32.613	-118.836	dd	15
10/29/01	32.613	-119.180	lo	2
10/29/01	32.278	-119.261	mm	2
10/29/01	32.611	-119.156	mm	1
10/29/01	32.581	-119.529	pd	2
10/29/01	32.267	-119.223	zc	1
10/29/01	32.447	-119.054	zc	40
10/29/01	32.447	-119.125	zc	4

10/29/01	32.447	-119.128	zc	1
10/29/01	32.447	-119.206	zc	1
10/29/01	32.442	-119.258	zc	2
10/29/01	32.446	-119.372	zc	1
10/29/01	32.611	-119.382	zc	1
10/29/01	32.612	-119.359	zc	1
10/29/01	32.613	-119.335	zc	4
10/29/01	32.613	-119.308	zc	2
10/29/01	32.612	-119.137	zc	1
12/18/01	32.446	-118.864	dd	525
12/18/01	32.114	-118.862	mm	7
12/18/01	32.114	-119.152	mm	2
12/18/01	32.616	-119.007	mm	4
12/18/01	32.449	-119.033	ud	10
12/18/01	32.447	-118.545	zc	1
12/18/01	32.449	-119.116	zc	80
12/18/01	32.448	-119.125	zc	2
12/18/01	32.449	-119.205	zc	5
12/18/01	32.448	-119.218	zc	1
12/18/01	32.448	-119.245	zc	2
12/18/01	32.614	-119.219	zc	1
12/19/01	32.776	-118.513	dd	550
12/19/01	32.78	-118.877	dd	12
12/19/01	32.781	-119.153	dd	300
12/19/01	32.782	-119.246	dd	1000
12/19/01	32.803	-118.247	er	1
12/19/01	32.946	-118.858	lb	4
12/19/01	32.78	-118.877	lo	12
12/19/01	32.781	-119.070	lo	2
12/19/01	32.781	-119.082	lo	32
12/19/01	32.944	-118.726	lo	1
12/19/01	32.944	-118.647	lo	1
12/19/01	32.785	-118.576	ud	6
12/19/01	32.786	-118.565	zc	1

12/19/01	32.785	-118.582	zc	1
12/19/01	32.784	-118.617	zc	1
12/19/01	32.78	-118.877	zc	12
12/19/01	32.944	-118.977	zc	1
12/19/01	32.944	-118.726	zc	13
2/10/2002	32.633	-118.333	er	2
2/10/2002	32.600	-118.633	lb	7
2/10/2002	32.600	-118.787	lb	15
2/10/2002	32.446	-119.300	zc	2
2/10/2002	32.446	-119.233	zc	1
2/10/2002	32.446	-119.233	zc	2
2/10/2002	32.446	-119.067	zc	2
2/10/2002	32.446	-119.067	zc	45
2/10/2002	32.446	-119.067	zc	10
2/10/2002	32.446	-119.067	zc	15
2/10/2002	32.446	-119.067	zc	10
2/10/2002	32.446	-119.067	zc	1
2/10/2002	32.446	-119.067	zc	45
2/10/2002	32.435	-118.883	zc	1
2/10/2002	32.600	-118.815	zc	1
4/9/2002	32.948	-119.010	bp	2
4/9/2002	32.946	-119.079	bp	1
4/9/2002	32.948	-119.010	zc	2
5/9/2002	32.782	-118.559	dd	2
5/9/2002	32.781	-118.642	dd	2
5/9/2002	32.781	-118.642	lo	7
5/9/2002	32.782	-118.559	lo	1
5/9/2002	32.781	-119.078	ud	5
5/9/2002	32.782	-118.841	zc	1
5/9/2002	32.780	-118.996	zc	1
5/9/2002	32.780	-119.004	zc	3
5/9/2002	32.781	-119.186	zc	3
5/9/2002	32.780	-119.256	zc	1
5/9/2002	32.780	-119.273	zc	1

5/9/2002	32.449	-118.541	zc	1
5/9/2002	32.449	-118.755	zc	1
5/9/2002	32.448	-118.862	zc	1
5/9/2002	32.446	-119.109	zc	2
5/9/2002	32.446	-119.111	zc	2
5/9/2002	32.447	-119.124	zc	1
5/9/2002	32.447	-119.127	zc	1
5/31/2002	32.932	-118.958	bp	2
5/31/2002	32.780	-118.880	bp	1
5/31/2002	32.781	-118.688	dd	5
5/31/2002	32.114	-118.779	zc	1
5/31/2002	32.946	-118.723	zc	1
5/31/2002	32.778	-119.116	zc	1
5/31/2002	32.780	-118.998	zc	1
5/31/2002	32.781	-118.722	zc	1
7/2/2002	32.735	-118.302	bp	1
7/2/2002	32.614	-119.017	bp	1
7/2/2002	32.614	-119.021	bp	1
7/2/2002	32.615	-119.033	bp	2
7/2/2002	32.613	-119.201	bp	1
7/2/2002	32.615	-119.207	bp	1
7/2/2002	32.613	-119.258	bp	2
7/2/2002	32.448	-118.995	bp	2
7/2/2002	32.613	-118.523	dd	10
7/2/2002	32.613	-118.560	dd	80
7/2/2002	32.613	-119.154	dd	27
7/2/2002	32.433	-119.547	oo	4
7/2/2002	32.613	-119.271	ud	7
7/2/2002	32.611	-119.363	uw	2
7/2/2002	32.614	-119.095	zc	1
7/2/2002	32.613	-119.260	zc	2
7/2/2002	32.447	-119.529	zc	1
7/2/2002	32.449	-119.163	zc	1
7/2/2002	32.449	-119.131	zc	12

7/2/2002	32.449	-119.108	zc	6
7/2/2002	32.449	-119.106	zc	2
7/2/2002	32.449	-119.105	zc	2
7/2/2002	32.449	-119.099	zc	1
7/2/2002	32.449	-119.076	zc	2
7/2/2002	32.448	-119.069	zc	1
7/2/2002	32.448	-119.054	zc	1
7/2/2002	32.613	-119.154	zc	1
8/15/2002	32.279	-119.312	bm	2
8/15/2002	32.445	-119.037	zc	1
8/15/2002	32.447	-119.037	zc	1
8/15/2002	32.447	-119.037	zc	1
8/15/2002	32.446	-119.037	zc	1
8/15/2002	32.445	-119.037	zc	1
8/15/2002	32.444	-119.037	zc	1
8/15/2002	32.443	-119.122	zc	1
8/15/2002	32.443	-119.130	zc	1
12/6/2002	32.614	-118.543	dd	3
12/6/2002	32.614	-118.836	dd	2
12/6/2002	32.614	-118.867	dd	10
12/6/2002	32.280	-119.042	dd	220
12/6/2002	32.281	-119.114	dd	1
12/6/2002	32.614	-118.756	lo	3
12/6/2002	32.614	-119.160	lo	17
12/6/2002	32.615	-119.210	lo	2
12/6/2002	32.613	-119.276	lo	15
12/6/2002	32.447	-118.821	lo	25
12/6/2002	32.615	-119.209	ud	17
12/6/2002	32.616	-119.240	ud	20
12/6/2002	32.446	-118.984	ud	16
12/6/2002	32.446	-118.902	ud	5
12/6/2002	32.447	-118.875	ud	2
12/6/2002	32.280	-118.877	ud	5
12/6/2002	32.614	-118.465	zc	1

12/6/2002	32.614	-119.054	zc	2
12/6/2002	32.615	-119.367	zc	3
12/6/2002	32.447	-119.409	zc	1
12/6/2002	32.446	-119.349	zc	1
12/6/2002	32.446	-119.347	zc	1
12/6/2002	32.446	-119.311	zc	1
12/6/2002	32.447	-119.128	zc	1
12/6/2002	32.447	-119.101	zc	1
12/6/2002	32.446	-119.074	zc	1
12/6/2002	32.446	-118.899	zc	1
12/6/2002	32.446	-118.839	zc	1
12/6/2002	32.447	-118.481	zc	1
12/6/2002	32.114	-119.159	zc	1
12/23/2002	32.787	-119.094	bp	2
12/23/2002	32.782	-118.505	dd	75
12/23/2002	32.782	-118.666	ud	5
12/23/2002	32.945	-118.644	zc	1
3/3/2003	32.780	-118.615	dd, zc	160
3/3/2003	32.947	-118.870	lb, ud	8
3/3/2003	32.938	-118.933	ud	15
3/3/2003	32.450	-119.072	ud	2
3/3/2003	32.447	-119.470	uw	2
3/3/2003	32.947	-118.745	zc	4
3/3/2003	32.947	-118.762	zc	1
3/3/2003	32.780	-118.660	zc	1
3/3/2003	32.780	-118.623	zc	2
3/3/2003	32.610	-118.373	zc	1
3/3/2003	32.613	-119.337	zc	1
3/3/2003	32.613	-119.368	zc	1
3/3/2003	32.448	-119.130	zc	1

**Shipboard survey sightings in the SCORE region**

*Table 3. Shipboard survey sightings in the SCORE region*

<b>Date</b>	<b>Time</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Species</b>	<b>N</b>
8/20/00	1023	32.45	119.22	Zc	1
8/20/00	1203	32.57	119.33	Zc	1
8/20/00	1400	32.70	119.29	Bm	1
8/20/00	1405	32.71	119.29	Bm	1
8/20/00	1409	32.72	119.29	UD	2
8/20/00	1409	32.72	119.29	UW	1
8/20/00	1501	32.54	119.32	Bp	1
8/20/00	1611	32.74	119.17	Zc	1
8/21/00	640	32.85	118.34	UW	1
8/21/00	654	32.85	118.34	Zc	1
8/21/00	736	32.84	118.36	Zc	1
8/21/00	745	32.84	118.36	Zc	1
8/21/00	833	32.84	118.33	Tt	12
8/21/00	837	32.84	118.33	UD	15
8/21/00	1455	32.36	118.22	Bm	1
8/21/00	1509	32.34	118.24	Bm	2
8/21/00	1653	32.34	118.26	Bm	2
8/21/00	1731	32.33	118.26	Bm	2
8/21/00	1744	32.33	118.25	Bm	1
8/21/00	1804	32.32	118.25	Bm	1
8/21/00	1804	32.32	118.25	Bm	1
8/21/00	1818	32.32	118.25	Bm	1
8/21/00	1821	32.34	118.26	Bm	2
8/21/00	1844	32.35	118.27	Bm	1
8/21/00	1856	32.35	118.26	Bm	1
8/21/00	1902	32.35	118.26	Bm	1
8/21/00	1903	32.35	118.26	Bm	1
8/22/00	753	32.97	118.65	UD	2
8/22/00	814	32.94	118.62	Dd	12
8/22/00	915	32.83	118.56	Dd	60
8/22/00	921	32.81	118.55	Dd	50
8/22/00	1123	32.58	118.40	Bm	2
8/22/00	1539	32.46	118.33	Bm	1
8/22/00	1543	32.45	118.33	Bm	1
8/22/00	1703	32.43	118.34	Bm	1
8/22/00	1726	32.42	118.31	Bm	1
8/22/00	1752	32.42	118.31	Bm	1
8/22/00	1803	32.42	118.32	Bm	1
8/22/00	1836	32.40	118.32	Bm	1
8/23/00	645	32.74	119.14	Bm	2
8/23/00	945	32.62	119.13	UW	1
8/23/00	1117	32.64	119.21	Bm	1

8/23/00	1210	32.63	119.20	Bm	1
8/23/00	1415	32.69	119.26	Bm	8
8/24/00	814	32.45	119.24	Bm	1
8/24/00	1002	32.40	118.96	Dd	5
8/24/00	1501	32.25	118.12	Bm	1
8/24/00	1640	32.23	118.25	Bm	1
8/24/01	1854	32.25	118.12	Bm	1
10/15/00	759	32.40	119.04	UD	1
10/15/00	1233	32.64	119.34	Zc	1
10/15/00	1234	32.64	119.33	Zc	1
10/16/00	1044	32.73	118.50	UD	10
10/16/00	1100	32.76	118.53	Zc	1
10/16/00	1100	32.78	118.56	Zc	1
10/16/00	1127	32.81	118.59	Dd	300
10/16/00	1243	32.95	118.68	UD	7
10/16/00	1406	32.12	118.80	Dd	175
10/16/00	1431	32.17	118.85	Dd	200
10/17/00	1215	34.38	121.20	UD	75
10/17/00	1250	34.46	121.20	Cv	1
10/17/00	1315	34.52	121.20	Zc	1
10/17/00	1337	34.57	121.20	Bp	2
10/17/00	1527	34.59	121.00	UP	1
10/17/00	1530	34.60	120.99	Gg?	5
10/17/00	1623	34.62	120.90	Pd	2
10/17/00	1703	34.57	120.94	Mn	1
10/17/00	1754	34.70	121.00	Gg	10
10/17/00	1820	34.63	120.99	UW	1
10/17/00	744	33.25	119.76	UD	10
10/17/00	807	33.20	119.73	Bp	1
10/17/00	815	33.20	119.72	UW	1
10/18/00	1021	33.01	119.63	Bp?	1
10/18/00	1110	32.98	119.67	Bm	1
10/19/00	832	32.72	119.26	Zc	1
10/19/00	918	32.77	119.22	Zc	1
10/19/00	940	32.76	119.21	Zc	150
10/19/00	1008	32.74	119.13	Zc	1
10/19/00	1024	32.72	119.08	Zc	1
4/29/01	652	32.38	118.95	Lo	1
4/29/01	1206	32.46	119.02	Zc	1
4/29/01	1248	32.53	119.09	Lo	4
4/29/01	1600	32.71	119.09	Zc	1
4/29/01	1623	32.73	119.15	Zc	2
4/29/01	1631	32.74	119.17	UW	1
4/29/01	1816	32.75	119.25	Zc	4
4/30/01	629	33.00	118.71	Zc	1
4/30/01	643	32.99	118.70	Lo	12
4/30/01	718	33.00	118.71	Zc	2
4/30/01	801	33.00	118.71	Lb	40

4/30/01	801	33.00	118.71	Zc	35
4/30/01	946	33.02	118.74	Zc	1
4/30/01	950	33.01	118.72	Zc	1
4/30/01	1001	32.99	118.71	Zc	10
4/30/01	1009	32.99	118.69	Lo	50
4/30/01	1017	32.97	118.68	Lo	30
4/30/01	1017	32.97	118.68	Zc	80
4/30/01	1027	32.96	118.66	Zc	2
4/30/01	1032	32.95	118.65	Dd	300
4/30/01	1054	32.93	118.61	Zc	1
4/30/01	1111	32.90	118.58	Zc	1
4/30/01	1141	32.85	118.54	Zc	1
4/30/01	1200	32.81	118.51	Zc	1
4/30/01	1214	32.79	118.48	Zc	1
4/30/01	1248	32.78	118.40	Zc	1
4/30/01	1253	32.78	118.38	Pv	1
4/30/01	1300	32.78	118.36	Zc	1
4/30/01	1307	32.79	118.34	Gg	40
4/30/01	1358	32.83	118.33	Tt,Gg	40/20
4/30/01	1448	32.84	118.33	Tt	5
4/30/01	1509	32.88	118.37	Zc	1
4/30/01	1535	33.07	118.60	Dd	175
4/30/01	1630	32.94	118.44	Lo	5
4/30/01	1644	32.97	118.46	Ba?	1
4/30/01	1733	32.98	118.47	Lo	25
4/30/01	1825	32.03	118.51	U	1
4/30/01	1845	33.06	118.53	Dd	20
4/30/01	1845	33.06	118.53	Zc	1
4/30/01	1916	33.07	118.59	Zc	25
4/30/01	1918	33.07	118.59	Dd	225
5/1/01	841	32.66	119.07	Zc	1
5/1/01	856	32.69	119.04	Zc	4
5/1/01	944	32.73	119.13	Zc	1
5/1/01	1010	32.75	119.19	Zc	1
5/1/01	1026	32.76	119.22	Zc	1
5/1/01	1045	32.73	119.27	Bp	2
5/1/01	1209	32.72	119.27	Lb	100
5/1/01	1209	32.72	119.27	Gg	25
5/1/01	1209	32.72	119.27	Lo	8
5/1/01	1339	32.62	119.32	Zc	1
5/1/01	1347	32.60	119.32	Zc	90
5/1/01	1622	32.39	119.11	Zc	1
5/1/01	1645	32.39	119.05	Zc	1
5/1/01	1655	32.39	119.02	Gg	50
5/1/01	1655	32.39	119.02	Lb	30
5/1/01	1755	32.53	118.98	Zc	1
5/1/01	1801	32.38	118.97	Zc	1
5/1/01	1830	32.39	118.91	Gg	15
5/1/01	1848	32.39	118.90	Zc	1

6/19/01	842	32.62	119.12	Dd	4
6/19/01	956	32.70	119.05	Zc	5
6/19/01	1002	32.70	119.05	Zc	1
6/19/01	1038	32.70	119.06	Zc	1
6/19/01	1049	32.71	119.09	Zc	1
6/19/01	1113	32.74	119.16	UMM	6
6/19/01	1124	32.75	119.19	Zc	1
6/19/01	1156	32.72	119.26	Zc	1
6/19/01	1159	32.72	119.22	Bm	1
6/19/01	1227	32.71	119.23	Zc	6
6/19/01	1250	32.70	119.21	Zc	1
6/19/01	1458	32.60	119.35	UD	4
6/19/01	1518	32.60	119.35	Zc	2
6/19/01	1531	32.57	119.33	Zc	1
6/19/01	1542	32.55	119.31	UD	1
6/19/01	1604	32.49	119.25	Zc	1
6/19/01	1630	32.45	119.18	Zc	2
6/19/01	1637	32.39	118.98	Zc	2
6/19/01	1745	32.47	119.21	Zc	1
6/20/01	550	33.37	119.42	Lo	1
6/20/01	627	33.44	119.49	Zc	1
6/20/01	635	33.45	119.51	Lo	1
6/20/01	639	33.45	119.52	Zc	1
6/20/01	641	33.45	119.52	Zc	1
6/20/01	650	33.46	119.55	Lo	7
6/20/01	654	33.47	119.56	Zc	1
6/20/01	702	33.47	119.42	Lb	7
6/20/01	703	33.47	119.58	Zc	1
6/20/01	714	33.48	119.62	Zc	1
6/20/01	727	33.49	119.65	Zc	2
6/20/01	735	33.50	119.67	Bp	1
6/20/01	751	33.50	119.68	Zc	4
6/20/01	816	33.51	119.70	Zc	2
6/20/01	819	33.51	119.70	Zc	1
6/20/01	820	33.51	119.70	Lo	35
6/20/01	826	33.52	119.72	Zc	1
6/20/01	833	33.52	119.73	UD	2
6/20/01	835	33.53	119.74	Zc	1
6/20/01	842	33.53	119.76	Zc	2
6/20/01	859	33.56	119.78	Ma	1
6/20/01	909	33.59	119.79	Zc	3
6/20/01	933	33.63	119.81	Lo	1
6/20/01	952	33.67	119.82	Zc	2
6/20/01	1004	33.69	119.83	Zc	1
6/20/01	1006	33.70	119.83	Zc	4
6/20/01	1015	33.72	119.84	Zc	1
6/20/01	1021	33.73	119.84	Zc	2
6/20/01	1029	33.75	119.85	Zc	1
6/20/01	1116	33.87	119.90	Zc	1

6/20/01	1120	33.88	119.90	Tt	35
6/20/01	1133	33.91	119.91	Zc	1
6/20/01	1135	33.91	119.91	Zc	1
6/20/01	1210	34.00	119.94	Zc	1
6/20/01	1253	34.08	120.00	UD	2
6/20/01	1350	34.10	120.11	Bm	1
6/20/01	1356	34.11	120.09	Zc	1
6/20/01	1436	34.11	120.12	Bm	1
6/20/01	1441	34.11	120.13	Bm	1
6/20/01	1503	34.12	120.14	Dd	5
6/20/01	1545	34.12	120.12	Dd	7
6/20/01	1626	34.12	120.16	Zc	6
6/20/01	1648	34.13	120.21	Zc	14
6/20/01	1704	34.14	120.25	Gg	15
6/20/01	1704	34.14	120.25	Zc	15
6/20/01	1707	34.14	120.26	Bm	1
6/20/01	1716	34.14	120.27	Bm	1
6/20/01	1822	34.14	120.24	Zc	1
6/20/01	1837	34.14	120.23	Zc	1
6/20/01	1855	34.12	120.14	Bm	1
6/20/01	1857	34.12	120.14	Bm	1
6/20/01	1900	34.12	120.14	ud	2
6/20/01	1948	34.13	120.06	Bm	1
6/20/01	2000	34.11	120.05	Bm	1
6/21/01	556	34.75	120.87	Zc	1
6/21/01	603	34.76	120.87	Mn	1
6/21/01	629	34.77	120.80	Pv	1
6/21/01	640	34.77	120.78	Zc	1
6/21/01	649	34.75	120.79	Zc	1
6/21/01	708	34.71	120.82	Bm	1
6/21/01	710	34.70	120.80	Lo	5
6/21/01	819	34.72	120.87	Zc	2
6/21/01	915	34.63	120.80	Zc	1
6/21/01	956	34.58	120.77	Zc	1
6/21/01	1004	34.57	120.77	Zc	1
6/21/01	1230	34.48	120.70	Zc	1
6/21/01	1244	34.48	120.71	UD	12
6/21/01	1246	34.48	120.72	Zc	1
6/21/01	1342	34.53	120.81	Zc	1
6/21/01	1351	34.55	120.81	Zc	1
6/21/01	1359	34.56	120.81	Oo	3
6/21/01	1400	34.56	120.81	Bm	1
6/21/01	1403	34.56	120.81	Bm	1
6/21/01	1404	34.56	120.81	Bm	1
6/21/01	1413	34.56	120.81	Bm	1
6/21/01	1434	34.58	120.82	Bm	1
6/21/01	1524	34.61	120.83	Pd	4
6/21/01	1558	34.62	120.82	Bm?	1
6/21/01	1610	34.63	120.82	Bm?	1

6/21/01	1721	34.72	120.83	Bm?	1
6/21/01	1727	34.73	120.83	Bm?	1
6/21/01	1728	34.73	120.83	Bm?	1
6/21/01	1734	34.73	120.83	Bm?	1
6/21/01	1741	34.73	120.85	Bm?	1
6/21/01	1753	34.74	120.86	Bm	1
6/21/01	1757	34.75	120.87	Bm	1
6/21/01	1758	34.75	120.87	Bm	1
6/21/01	1759	34.75	120.87	Bm	1
6/21/01	1800	34.75	120.87	Bm	1
6/21/01	1807	34.75	120.87	Bm	1
6/21/01	1827	34.75	120.87	Bm	1
6/21/01	2020	34.75	120.87	Dd	5
6/22/01	1038	34.15	120.03	Zc	3
6/22/01	1119	34.14	120.11	Zc	1
6/22/01	1151	34.13	120.18	Zc	1
6/22/01	1206	34.13	120.21	Bm	1
6/22/01	1216	34.13	120.21	Mn	1
6/22/01	1407	34.13	120.20	Bm	1
6/22/01	1521	34.13	120.23	Bm	1
6/22/01	1521	34.13	120.23	Bm	1
6/22/01	1521	34.13	120.23	Bm	1
6/22/01	1610	34.14	120.23	Bm	1
6/22/01	1613	34.14	120.24	Bm	1
6/22/01	1614	34.14	120.26	Bm	1
6/22/01	1625	34.14	120.26	Bm	1
6/22/01	1627	34.14	120.26	Bm	1
6/23/01	1759	34.22	120.36	Mn	1
6/23/01	1855	34.24	120.29	Bm	1
6/23/01	1907	34.25	120.28	Pd	5
6/23/01	1935	34.26	120.24	ULW	1
6/23/01	1941	34.25	120.23	Zc	1
6/23/01	725	34.40	120.23	Zc	1
6/23/01	759	34.38	120.33	Zc	1
6/23/01	800	34.38	120.28	Ej	1
6/23/01	911	34.40	120.53	Zc	1
6/23/01	919	34.40	120.55	Zc	1
6/23/01	940	34.41	120.60	Mn	1
6/23/01	1032	34.45	120.70	Bm	1
6/23/01	1235	34.56	120.78	Ej	1
6/23/01	1500	34.72	121.10	Bp	1
6/23/01	1627	34.75	121.17	Zc	1
6/23/01	1730	34.82	121.29	Zc	1
6/23/01	1836	34.88	121.36	Zc	1
6/23/01	1838	34.88	121.36	Fish	1
6/23/01	1839	34.91	121.23	Bp	1
6/23/01	1940	34.92	121.22	Bp?	2
6/23/01	1940	34.92	121.22	Bp	2
6/23/01	1943	34.92	121.23	Bp	1

6/23/01	2005	34.93	121.23	ULW	3
6/23/01	2014	34.94	121.21	Bp	1
6/23/01	2017	34.94	121.21	Bp	1
6/23/01	2019	34.44	121.20	Bp	1
6/23/01	2026	34.44	121.19	Bp	2
6/23/01	2028	34.94	121.20	ULW	1
6/23/01	2029	34.94	121.18	Mn	3
6/23/01	2036	34.95	121.17	ULW	1
6/24/01	554	34.24	120.96	Mn	2
6/24/01	602	35.25	120.96	Zc	1
6/24/01	613	35.27	120.95	Mn	1
6/24/01	620	35.27	120.96	Lo	10
6/24/01	628	35.27	120.98	Mn	2
6/24/01	648	35.27	120.99	Mn	1
6/24/01	708	35.26	120.99	Mn	1
6/24/01	722	35.24	120.96	Mn	1
6/24/01	857	35.20	120.93	Zc	2
6/24/01	906	35.18	120.93	Mn	13
6/24/01	1024	35.10	120.87	Zc	1
6/24/01	1028	35.09	120.87	Mn	1
6/24/01	1034	35.07	120.86	Bm	1
6/24/01	1041	35.07	120.87	Bm	1
6/24/01	1109	35.08	120.88	Bm	1
6/24/01	1431	35.99	120.95	Zc	1
6/24/01	1450	35.95	120.95	Zc	1
6/24/01	1506	35.91	120.94	Mn	2
6/24/01	1508	34.91	120.94	Lo	22
6/24/01	1541	34.87	120.96	Mn	1
6/24/01	1603	34.82	120.96	Bm	2
6/24/01	1629	34.79	120.96	Mn	2
6/24/01	1650	34.80	120.96	Mn	1
6/24/01	1730	34.74	120.96	Mn	4
6/24/01	1752	34.72	120.97	ULW	1
6/24/01	1756	34.71	120.97	Zc	1
6/24/01	1828	34.65	120.92	Bm	1
6/24/01	1904	34.41	120.88	Mn	1
6/24/01	1907	34.41	120.87	ULW	1
6/24/01	1912	34.57	120.86	Mn	1
6/24/01	1920	34.57	120.84	Mn	4
6/24/01	1925	34.56	120.83	Bm	1
6/24/01	1939	34.52	120.77	Bm	25
6/24/01	2001	34.52	120.77	ULW	2
6/24/01	2007	34.51	120.76	ULW	2
6/24/01	2011	34.50	120.75	ULW	2
6/24/01	2018	34.50	120.74	ULW	12
6/25/01	559	35.55	119.65	Zc	1
6/25/01	610	33.64	119.64	Lb	3
6/25/01	610	33.64	119.64	Dd	8
6/25/01	628	33.49	120.61	UW	1

6/25/01	636	33.47	119.60	Bm	1
6/25/01	648	33.45	119.60	Bm	1
6/25/01	653	33.44	119.60	Bm	1
6/25/01	709	33.45	119.60	Bm	1
6/25/01	709	33.45	119.60	Bm	1
6/25/01	753	33.44	119.59	Lo	12
6/25/01	757	33.45	119.59	Mn	1
6/25/01	803	33.45	119.64	Bm	1
6/25/01	930	33.44	119.59	Bm	1
6/25/01	940	33.42	119.57	Bm	1
6/25/01	940	33.42	119.57	Bm	1
6/25/01	942	33.42	119.57	Bm	2
6/25/01	947	33.42	119.56	Bm	1
6/25/01	1000	33.42	119.56	Bm	1
6/25/01	1018	33.40	119.54	Bm	2
6/25/01	1045	33.38	119.51	Bm	2
6/25/01	1047	33.38	119.51	Bm	1
6/25/01	1050	33.38	119.51	Bm	2
6/25/01	1050	33.38	119.51	Bm	1
6/25/01	1052	33.38	119.51	Bm	1
6/25/01	1201	33.36	119.50	Bm	1
6/25/01	1206	33.37	119.50	ULW	1
6/25/01	1211	33.37	119.51	ULW	1
6/25/01	1225	33.39	119.53	UW	1
6/25/01	1230	33.39	119.53	UW	1
6/25/01	1234	33.39	119.53	Bm	2
6/25/01	1241	33.39	119.53	Bm	2
6/25/01	1246	33.40	119.54	ULW	1
6/25/01	1256	33.40	119.55	UW	1
6/25/01	1337	33.42	119.57	Bm	1
6/25/01	1338	33.42	119.57	Bm	1
6/25/01	1346	33.41	119.57	Bm	1
6/25/01	1358	33.39	119.54	Bm	2
6/25/01	1407	33.38	119.52	Bm	7
6/25/01	1414	33.38	119.50	Bm	1
6/25/01	1418	33.38	119.49	Bm	1
6/25/01	1553	33.38	119.22	Bm	1
6/25/01	1846	33.35	119.00	Zc	35
6/26/01	550	33.61	119.36	UW	1
6/26/01	617	32.60	119.33	Bm	5
6/26/01	637	32.62	119.34	Dd	35
6/26/01	659	32.64	119.35	UW	1
6/26/01	717	32.66	119.34	UW	1?
6/26/01	832	32.69	119.29	ULW	1
6/26/01	841	32.68	119.28	Bp	1
6/26/01	842	32.68	119.28	Bp	1
6/26/01	846	32.68	119.27	Bp	4
6/26/01	854	32.68	119.26	ULW	1
6/26/01	904	32.67	119.25	Bp	1

6/26/01	1040	32.64	119.25	Bm	2
6/26/01	1052	32.63	119.26	Bm?	1
6/26/01	1124	32.61	119.27	ULW	2
6/26/01	1226	32.63	119.26	ULW	1
6/26/01	1255	32.63	119.26	ULW	2
6/26/01	1337	32.63	119.29	ULW	2
6/26/01	1409	32.64	119.31	ULW	1
6/26/01	1409	32.64	119.31	ULW	1
6/26/01	1418	32.63	119.30	Zc	2
6/26/01	1434	32.60	119.29	ULW	1
6/26/01	1434	32.60	119.29	ULW	1
6/26/01	1524	32.57	119.28	Zc	2
6/26/01	1601	32.64	119.27	ULW	1
6/26/01	1613	32.67	119.26	ULW	1
6/26/01	1614	32.67	119.26	ULW	1
6/26/01	1621	32.67	119.26	UD	2
6/26/01	1920	32.71	118.99	UW	1
8/21/01	1149	32.70	117.34	Bm	1
8/21/01	1403	32.76	117.44	Bm	1
8/21/01	1408	32.76	117.43	Bm	1
8/21/01	1522	32.82	117.51	Dd	6
8/22/01	647	32.91	119.59	Dd	20
8/22/01	723	33.91	119.70	Dd	4
8/22/01	743	33.91	119.75	Dd	12
8/22/01	745	33.91	119.75	Dd	75
8/22/01	746	33.91	119.77	Dd	150
8/22/01	813	33.91	119.84	Dd	100
8/22/01	838	33.95	119.89	Dd	25
8/22/01	1420	33.13	120.02	Pp	1
8/22/01	1930	35.00	120.40	Bm	2
8/22/01	1931	34.00	120.40	Bm	2
8/22/01	1935	33.99	120.41	Bm	1
8/22/01	1940	33.99	120.49	Bm	1
8/22/01	1941	33.99	120.49	Bm	1
8/23/01	644	34.00	120.43	Bm	2
8/23/01	644	34.00	120.43	Bm	2
8/23/01	646	34.00	120.44	Bm	1
8/23/01	652	33.99	120.45	Bm	2
8/23/01	655	33.99	120.45	Bm	2
8/23/01	658	33.99	120.46	Bm	1
8/23/01	706	33.98	120.44	Bm	5
8/23/01	706	33.98	120.44	Bm	1
8/23/01	715	33.98	120.48	Bm	1
8/23/01	725	33.98	120.48	Bm	1
8/23/01	730	33.98	120.48	Bm	1
8/23/01	732	33.98	120.48	Bm	1
8/23/01	733	33.98	120.48	Bm	3
8/23/01	737	33.97	120.47	Bm	2
8/23/01	746	33.96	120.45	Bm	1

8/23/01	747	33.96	120.45	Bm	1
8/23/01	748	33.96	120.45	Bm	2
8/23/01	751	33.96	120.44	Bm	4
8/23/01	751	33.96	120.44	Bm	5
8/23/01	753	33.96	120.44	Bm	1
8/23/01	759	33.95	120.45	Bm	2
8/23/01	824	33.95	120.44	Bm	1
8/23/01	832	33.94	120.43	Bm	2
8/23/01	836	33.94	120.42	Bm	1
8/23/01	839	33.93	120.42	Bm	1
8/23/01	841	33.93	120.41	Bm	1
8/23/01	847	33.93	120.41	Bm	1
8/23/01	925	33.89	120.33	UW	1
8/23/01	927	33.88	120.33	UW	2
8/23/01	929	33.88	120.32	Bm	1
8/23/01	939	33.87	120.30	Bm	1
8/23/01	942	33.87	120.29	Bm	1
8/23/01	946	33.86	120.29	Bm	1
8/23/01	954	33.85	120.27	Bm	1
8/23/01	958	33.85	120.26	Bm	3
8/23/01	1007	33.84	120.24	Bm	1
8/23/01	1012	33.83	120.23	Bm	1
8/23/01	1016	33.82	120.22	Bm	1
8/23/01	1026	33.81	120.20	Bm	2
8/23/01	1028	33.81	120.20	Bm	2
8/23/01	1032	33.73	120.19	Bm	2
8/23/01	1032	33.81	120.19	Bm	1
8/23/01	1040	33.80	120.17	Bm	1
8/23/01	1044	33.79	120.16	Bm	1
8/23/01	1047	33.79	120.16	Bm	1
8/23/01	1051	33.79	120.16	Bm	1
8/23/01	1051	33.79	120.16	Bm	2
8/23/01	1052	33.79	120.16	Bm	1
8/23/01	1111	33.76	120.15	Bm	1
8/23/01	1114	33.76	120.15	Bm	1
8/23/01	1114	33.76	120.15	Bm	1
8/23/01	1116	33.76	120.15	Bm	1
8/23/01	1126	33.75	120.14	Bm	1
8/23/01	1150	33.75	120.15	Bm	1
8/23/01	1205	33.76	120.17	Bm	1
8/23/01	1331	33.75	120.17	Bm	1
8/23/01	1348	33.73	120.17	Bm	1
8/23/01	1352	33.73	120.17	Bm	1
8/23/01	1404	33.74	120.15	Bm	1
8/23/01	1658	33.79	119.91	Dd	100
8/23/01	1709	33.78	119.89	Dd	15
8/23/01	1830	33.66	119.76	Dd	2
8/24/01	737	33.41	119.56	Bm	1
8/24/01	746	33.40	119.53	Bm	2

8/24/01	747	33.40	119.53	Bm	1
8/24/01	748	33.40	119.53	Bm	1
8/24/01	754	33.40	119.52	Bm	1
8/24/01	910	33.38	119.48	Bm	1
8/24/01	927	33.38	119.45	Bm	1
8/24/01	1027	33.37	119.44	Bm	2
8/24/01	1028	33.37	119.44	Bm	1
8/24/01	1029	33.37	119.44	Bm	1
8/24/01	1030	33.36	119.43	Bm	1
8/24/01	1035	33.36	119.43	Bm	1
8/24/01	1036	33.36	119.43	Bm	1
8/24/01	1141	33.35	119.40	Bm	1
8/24/01	1331	33.37	119.41	UW	1
8/25/01	620	32.69	119.00	Bp	1
8/25/01	635	32.69	119.02	Bp	1
8/25/01	640	32.70	119.03	Bp	3
8/25/01	645	32.70	119.05	Bp	1
8/25/01	649	32.70	119.05	Bp	1
8/25/01	649	32.70	119.05	Bp	1
8/25/01	653	32.70	119.05	Bp	1
8/25/01	717	32.70	119.05	Bp	1
8/25/01	730	32.70	119.05	Bp	1
8/25/01	751	32.71	119.08	Bp	1
8/25/01	815	32.73	119.12	Bp	1
8/25/01	816	32.74	119.13	Dd	1
8/25/01	832	32.75	119.16	UW	1
8/25/01	837	32.75	119.17	Bp	1
8/25/01	839	32.76	119.17	Bp	1
8/25/01	911	32.76	119.23	UW	1
8/25/01	918	32.76	119.23	Bp	1
8/25/01	920	32.75	119.24	Bp	1
8/25/01	926	32.74	119.24	Bp	1
8/25/01	936	32.74	119.26	Bp	1
8/25/01	940	32.75	119.26	UW	1
8/25/01	1001	32.72	119.28	Lo	2
8/25/01	1020	32.67	119.30	Bp	2
8/25/01	1238	32.65	119.27	Dd	20
8/25/01	1557	32.52	119.07	Dd	75
8/25/01	1608	32.50	119.05	Bm	1
8/25/01	1622	32.49	119.07	Bm	1
8/25/01	1629	32.49	119.07	Bm	1
8/25/01	1713	32.50	119.09	Bm	1
8/25/01	1725	32.51	119.10	Bm	1
8/25/01	1737	32.51	119.10	Bm	1
8/25/01	1740	32.51	119.10	Bm	1
8/25/01	1758	32.52	119.12	Bm	1
8/25/01	1800	32.52	119.12	Dd	50
8/25/01	1825	32.52	119.13	Dd	50
8/26/01	627	32.39	118.95	Bm	1

8/26/01	757	32.40	118.96	Bp	1
8/26/01	814	32.38	118.96	Bp	1
8/26/01	1006	32.42	119.19	Dd	2
8/26/01	1242	32.43	119.23	Dd	75
8/26/01	1417	32.50	119.05	Bp	1
8/26/01	1420	32.50	119.05	Bm	1
8/26/01	1506	32.50	119.06	Bp	2
8/26/01	1522	32.50	119.07	Bm	1
8/27/01	646	32.72	119.26	Bp	1
8/27/01	652	32.71	119.24	Bp	2
8/27/01	653	32.71	119.24	Dd	10
8/27/01	659	32.70	119.22	Bp	1
8/27/01	702	32.70	119.22	Bp	2
8/27/01	705	32.71	119.21	Bp	2
8/27/01	713	32.68	119.19	Bp	2
8/27/01	715	32.68	119.18	Bm	2
8/27/01	858	32.65	119.31	Dd	25
8/27/01	913	32.65	119.34	Bp	1
8/27/01	937	32.65	119.36	Bp	2
8/27/01	941	32.65	119.35	Bp	1
8/27/01	953	32.63	119.33	Ma	1
8/27/01	1306	32.64	119.17	Dd	12
8/27/01	1456	32.66	119.20	Bp	1
8/27/01	1858	32.62	119.16	Bm	1
8/28/01	644	32.64	119.19	Bp	1
8/28/01	700	32.65	119.20	Bp	1
8/28/01	752	32.65	119.22	Lo	1
8/28/01	946	32.64	119.21	Dd	2
8/28/01	1041	32.63	119.20	Dd	5
8/28/01	1352	32.65	119.19	Bm	1
8/28/01	1414	32.18	119.20	Bm	2
8/28/01	1414	32.68	119.20	Bm	1
8/28/01	1450	32.69	119.20	Bm	2
8/28/01	1600	32.71	119.24	Bm	1
8/28/01	1629	32.71	119.24	UW	1
8/28/01	1656	32.70	119.23	Bm	1
8/28/01	1713	32.69	119.21	Bm	1
8/28/01	1738	32.68	119.20	Bm	1
8/28/01	1814	32.67	119.19	Bm	2
8/28/01	1826	32.66	119.18	Bm	1
8/29/01	744	32.72	119.26	Dd	40
8/29/01	801	32.70	119.23	Dd	20
8/29/01	803	32.70	119.23	Dd	70
8/29/01	809	32.69	119.22	Dd	75
8/29/01	847	32.68	119.19	Bp	2
8/29/01	852	32.68	119.18	Bp	2
8/29/01	1314	32.62	119.21	Bm	2
8/29/01	1414	32.64	119.19	Bm	1
8/29/01	1417	32.64	119.19	Bm	1

8/29/01	1425	32.64	119.19	UW	1
8/29/01	1431	32.66	119.19	Bm	1
8/29/01	1504	32.66	119.16	Bm	1
8/29/01	1520	32.66	119.17	Bm	1
8/29/01	1607	32.66	119.21	Bm	2
8/29/01	1613	32.66	119.21	Bm	1
8/29/01	1641	32.67	119.22	Bp	2
8/29/01	1653	32.68	119.22	Bm	1
8/29/01	1655	32.69	119.22	Bm	2
8/29/01	1705	32.69	119.21	Bm	2
8/29/01	1729	32.69	119.20	Bm	1
8/29/01	1905	32.63	119.05	USW	1
10/23/01	6:52	32.39	118.95	Dd	6
10/23/01	7:07	32.41	118.97	Zc	1
10/23/01	7:20	32.44	118.99	UBW	1
10/23/01	7:29	32.45	119.00	Bm	3
10/23/01	7:39	32.46	119.02	Lo	3
10/23/01	7:55	32.48	119.04	Lo	6
10/23/01	8:14	32.49	119.05	Bm	1
10/23/01	8:37	32.52	119.07	Bm	1
10/23/01	8:45	32.66	119.08	Zc	1
10/23/01	10:17	32.62	119.12	Dd	30
10/23/01	11:42	32.71	119.06	Zc	3
10/23/01	11:46	32.71	119.08	Zc	1
10/23/01	13:00	32.77	119.22	UBW	1
10/23/01	13:14	32.76	119.24	Dd	40
10/23/01	13:27	32.73	119.25	Zc	1
10/23/01	14:05	32.67	119.30	Zc	1
10/23/01	15:00	32.60	119.35	Bp	2
10/23/01	15:27	32.60	119.35	Bp	1
10/23/01	15:28	32.60	119.35	Bp	2
10/23/01	15:31	32.60	119.38	Bp	1
10/23/01	15:34	32.60	119.38	UBW	1
10/23/01	15:37	32.59	119.38	Bp	1
10/23/01	15:47	32.58	119.38	Bp	1
10/23/01	15:51	32.58	119.38	UBW	1
10/23/01	16:04	32.56	119.36	Bp?	3
10/23/01	16:07	32.55	119.36	Bp?	2
10/23/01	16:14	32.54	119.35	Bp	1
10/23/01	16:20	32.52	119.35	Bp	1
10/23/01	16:21	32.51	119.34	Bp	2
10/23/01	16:29	32.50	119.33	Bp?	4
10/23/01	16:38	32.49	119.32	Bp	1
10/23/01	16:38	32.49	119.32	Bp	2
10/23/01	16:45	32.49	119.32	Bp	2
10/23/01	16:48	32.49	119.32	Bp?	2
10/23/01	17:03	32.46	119.29	UBW	1
10/23/01	17:03	32.46	119.29	UBW	1
10/23/01	17:38	32.43	119.20	UBW	1

10/23/01	17:44	32.43	119.18	Bp	1
10/23/01	18:18	32.40	119.09	Lb	4
10/24/01	7:11	32.65	119.21	Dd	11
10/24/01	7:38	32.65	119.21	UBW	1
10/24/01	7:55	32.65	119.21	Bp?	2
10/24/01	8:46	32.65	119.17	Dd	16
10/24/01	9:51	32.66	119.19	Dd	20
10/24/01	10:03	32.64	119.19	Ud	30
10/24/01	10:19	32.63	119.19	UBW	1
10/24/01	10:37	32.63	119.19	Zc	1
10/24/01	11:25	32.62	119.18	Zc	1
10/24/01	11:28	32.62	119.17	Dd	70
10/24/01	11:35	32.60	119.15	Zc	1
10/24/01	12:40	32.59	119.14	Zc	1
10/24/01	15:27	32.60	119.14	Bp	3
10/24/01	16:04	32.60	119.18	Zc	1
10/24/01	16:40	32.62	119.25	UBW	1
10/24/01	16:53	32.64	119.28	Zc	1
10/24/01	17:46	32.67	119.33	Dd	60
10/24/01	18:06	32.67	119.28	Zc	1
10/24/01	18:11	32.67	119.26	Dd	30
10/24/01	18:21	32.67	119.23	Dd	10
10/25/01	7:57	32.60	117.59	Zc	1
10/25/01	8:18	32.60	117.53	Gg?	2
10/25/01	8:21	32.60	117.52	Ud	10
10/25/01	9:12	32.59	117.38	Zc	1
4/15/02	0910	32.93	118.47	GG	10
4/15/02	1030	32.96	118.48	UD	2
4/15/02	1043	32.95	118.48	TT	60
4/15/02	1157	32.86	118.38	GG	6
4/15/02	1305	32.82	118.34	TT	6
4/15/02	1320	32.81	118.34	TT	50
4/15/02	1348	32.79	118.35	ZC	1
4/16/02	1410	32.57	119.12	BP	1
4/17/02	0805	32.54	118.84	BP	1
4/17/02	0815	32.52	118.82	BP	3
4/17/02	0816	32.52	118.82	BP	1
4/17/02	0817	32.52	118.82	BP	1
4/17/02	0829	32.49	118.78	BP	1
4/17/02	0905	32.45	118.69	BP	1
4/17/02	0920	32.46	118.65	ZC	1
4/17/02	1045	32.51	118.35	UW	1
4/17/02	1130	32.49	118.41	BP	2
4/17/02	1310	32.42	118.69	UW	1
4/17/02	1446	32.40	118.92	UW	1
4/17/02	1650	32.39	119.11	UW	1
4/17/02	1800	32.38	118.96	BP	3
4/17/02	1910	32.41	118.79	ZC	1

6/24/02	0827	32.49	119.09	BM	1
6/24/02	0829	32.50	119.09	BM	1
6/24/02	1917	32.71	119.24	UW	1
6/25/02	0613	34.06	119.18	MN	1?
6/25/02	0710	34.09	119.66	DD	20-30
6/25/02	0712	34.09	119.67	DD	50-70
6/25/02	0751	34.09	119.80	DD	40-60
6/25/02	0757	34.09	119.82	MN	1?
6/25/02	0759	34.09	119.83	MN	1
6/25/02	0808	34.09	119.85	MN	2-3
6/25/02	0808	34.09	119.85	MN	2
6/25/02	0817	34.09	119.88	MN	2
6/25/02	0909	34.11	119.94	DD	15-20
6/25/02	0946	34.19	119.87	UD	5-10
6/25/02	1405	32.23	120.07	UW	1
6/25/02	1410	34.23	120.07	MN	1-2
6/25/02	1434	34.20	120.11	BM	1
6/25/02	1443	34.18	120.12	BM	1
6/25/02	1450	34.17	120.12	BM	1
6/25/02	1519	34.14	120.13	BM	2-3
6/25/02	1536	34.13	120.13	BM	2
6/25/02	1540	34.11	120.15	UW	1
6/25/02	1628	34.11	120.15	MN	1
6/25/02	1630	34.11	120.15	BM	1
6/25/02	1632	34.11	120.15	BM	2
6/25/02	1634	34.11	120.15	BM	1
6/25/02	1634	34.11	120.15	BM	1
6/25/02	1634	34.11	120.15	BM	1
6/25/02	1637	34.11	120.15	BM	1
6/25/02	1637	34.11	120.15	GG	1
6/25/02	1637	34.11	120.15	DD	12
6/26/02	0605	34.09	119.84	MN	2
6/26/02	0608	34.09	119.83	MN	1?
6/26/02	0619	34.09	119.83	MN	1?
6/26/02	0621	34.09	119.84	MN	1?
6/26/02	0628	34.09	119.86	MN	1
6/26/02	0648	34.10	119.91	BM	2
6/26/02	0653	34.11	119.93	BM	1?
6/26/02	0659	34.11	119.94	BM	2?
6/26/02	0709	34.11	119.97	LO	5-10
6/26/02	0714	34.12	119.99	BM	1
6/26/02	0714	34.12	119.99	BM	1
6/26/02	0716	34.12	119.99	BM	2
6/26/02	0732	34.11	119.99	LO	1
6/26/02	0747	34.12	120.00	BM	1?
6/26/02	0748	34.12	120.00	BM	1?
6/26/02	0748	34.12	120.00	BM	1?

6/26/02	750	34.12	120.00	BM	1
6/26/02	0838	34.13	120.01	UD	1?
6/26/02	1219	34.11	120.07	BM	2
6/26/02	1402	34.12	120.05	BM	2
6/26/02	1529	34.13	120.08	BM	2
6/26/02	1541	34.14	120.09	BM	1
6/26/02	1544	34.14	120.09	BM	3
6/26/02	1548	34.15	120.10	BM	1
6/26/02	1558	34.14	120.11	BM	1
6/26/02	1558	34.14	120.11	BM	1
6/26/02	1602	34.14	120.12	BM	2
6/26/02	1620	34.12	120.15	BM	1
6/26/02	1621	34.12	120.15	Bm	1
6/26/02	1622	34.12	120.15	Bm	1
6/26/02	1630	34.12	120.16	Bm	1
6/26/02	1634	34.12	120.17	BM	4
6/26/02	1637	34.12	120.17	BM	1
6/26/02	1638	34.12	120.18	BM	1
6/26/02	1644	34.12	120.19	BM	1
6/26/02	1645	34.12	120.19	BM	1
6/26/02	1648	34.13	120.19	BM	1
6/26/02	1651	34.13	120.20	BM	1
6/26/02	1654	34.13	120.20	BM	2
6/26/02	1700	34.13	120.21	BM	1
6/26/02	1715	34.14	120.23	BM	1
6/26/02	1720	34.14	120.24	BM	1
6/26/02	1849	34.12	120.14	GG	8-10
6/27/02	702	34.03	120.02	UD	2
6/27/02	740	34.12	120.01	BM	2
6/27/02	742	34.12	120.01	BM	1
6/27/02	743	34.12	120.02	BM	1
6/27/02	749	34.12	120.03	BM	2
6/27/02	750	34.12	120.03	BM	1
6/27/02	752	34.12	120.04	BM	1
6/27/02	758	34.12	120.05	BM	2
6/27/02	759	34.12	120.05	BM	1
6/27/02	815	34.12	120.08	BM	1
6/27/02	816	34.12	120.09	BM	1
6/27/02	821	34.12	120.10	BM	3
6/27/02	822	34.12	120.10	GG	6
6/27/02	829	34.12	120.12	BM	1
6/27/02	831	34.12	120.12	BM	1
6/27/02	835	34.12	120.14	BM	2
6/27/02	839	34.12	120.13	BM	2
6/27/02	843	34.12	120.12	BM	1
6/27/02	844	34.12	120.12	BM	1
6/27/02	848	34.12	120.11	BM	2

6/27/02	850	34.12	120.10	BM	2
6/27/02	855	34.12	120.09	BM	1
6/27/02	903	34.12	120.06	BM	2
6/27/02	903	34.12	120.06	BM	1
6/27/02	910	34.12	120.04	BM	1
6/27/02	918	34.12	120.02	BM	1
6/27/02	919	34.12	120.02	BM	1
6/27/02	924	34.12	120.00	BM	1
6/27/02	935	34.12	120.00	BM	1
6/27/02	935	34.12	120.00	BM	2
6/27/02	937	34.12	120.00	BM	1
6/27/02	938	34.12	120.01	BM	1
6/27/02	943	34.12	120.02	BM	1
6/27/02	943	34.12	120.02	BM	1
6/27/02	959	34.12	120.06	BM	1
6/27/02	1000	34.12	120.06	BM	3
6/27/02	1000	34.12	120.07	BM	1
6/27/02	1002	34.12	120.07	BM	1
6/27/02	1008	34.12	120.09	BM	1
6/27/02	1012	34.12	120.09	BM	4
6/27/02	1017	34.12	120.11	BM	1
6/27/02	1026	34.12	120.13	BM	2
6/27/02	1033	34.12	120.13	BM	1
6/27/02	1035	34.12	120.12	BM	2
6/27/02	1035	34.12	120.12	BM	1
6/27/02	1037	34.12	120.12	BM	2
6/27/02	1040	34.12	120.11	BM	1
6/27/02	1043	34.12	120.10	BM	1
6/27/02	1043	34.12	120.10	BM	2
6/27/02	1044	34.12	120.09	BM	3
6/27/02	1049	34.12	120.08	BM	1
6/27/02	1049	34.12	120.08	BM	1
6/27/02	1053	34.12	120.07	BM	2
6/27/02	1055	34.12	120.07	BM	1
6/27/02	1101	34.12	120.05	BM	2
6/27/02	1108	34.12	120.03	BM	1
6/27/02	1117	34.12	120.01	BM	1
6/27/02	1151	34.12	120.00	BM	1
6/27/02	1152	34.12	120.01	BM	1
6/27/02	1152	34.12	120.01	BM	1
6/27/02	1156	34.12	120.02	BM	1
6/27/02	1159	34.12	120.02	BM	1
6/27/02	1204	34.12	120.04	BM	1
6/27/02	1207	34.12	120.04	BM	1
6/27/02	1211	34.12	120.05	BM	1
6/27/02	1212	34.12	120.05	BM	1
6/27/02	1214	34.12	120.06	BM	1

6/27/02	1215	34.12	120.06	BM	2
6/27/02	1217	34.12	120.07	BM	3
6/27/02	1224	34.12	120.08	BM	1
6/27/02	1225	34.12	120.09	BM	1?
6/27/02	1227	34.12	120.09	BM	2
6/27/02	1236	34.12	120.11	BM	1
6/27/02	1236	34.12	120.11	BM	1
6/27/02	1237	34.12	120.11	BM	1
6/27/02	1237	34.12	120.11	BM	1
6/27/02	1239	34.12	120.11	BM	2
6/27/02	1240	34.12	120.12	BM	1
6/27/02	1241	34.12	120.12	BM	2
6/27/02	1241	34.12	120.12	BM	2
6/27/02	1243	34.12	120.12	BM	1
6/27/02	1243	34.12	120.12	BM	1
6/27/02	1246	34.12	120.13	BM	1
6/27/02	1330	34.12	120.13	BM	1
6/27/02	1330	34.12	120.13	BM	2
6/27/02	1331	34.12	120.12	BM	1
6/27/02	1332	34.12	120.12	BM	1
6/27/02	1333	34.12	120.12	BM	1
6/27/02	1333	34.12	120.12	BM	2
6/27/02	1338	34.12	120.10	BM	2
6/27/02	1341	34.12	120.09	BM	2
6/27/02	1345	34.12	120.08	BM	1
6/27/02	1346	34.12	120.08	BM	3
6/27/02	1350	34.12	120.06	BM	1
6/27/02	1351	34.12	120.06	BM	2
6/27/02	1352	34.12	120.06	BM	3
6/27/02	1353	34.12	120.05	BM	1
6/27/02	1400	34.12	120.03	BM	1
6/27/02	1403	34.12	120.02	BM	1
6/27/02	1516	34.12	120.00	BM	1
6/27/02	1520	34.12	120.01	BM	2
6/27/02	1521	34.12	120.01	BM	1
6/27/02	1525	34.12	120.02	BM	2
6/27/02	1525	34.12	120.02	BM	1
6/27/02	1529	34.12	120.03	BM	2
6/27/02	1532	34.12	120.04	BM	2
6/27/02	1535	34.12	120.04	BM	1
6/27/02	1537	34.12	120.05	BM	1
6/27/02	1538	34.12	120.05	BM	2
6/27/02	1540	34.11	120.06	BM	1
6/27/02	1542	34.11	120.06	BM	3
6/27/02	1546	34.11	120.06	BM	1
6/27/02	1605	34.14	120.02	GG	8
6/27/02	1636	34.11	120.04	MN	1

6/28/02	0738	32.61	119.10	UD	1?
6/28/02	0804	32.61	119.13	DD	2-6
6/28/02	1557	34.57	119.20	UW	1
6/28/02	1623	32.57	119.20	UW	1
6/28/02	1817	32.57	119.14	UW	1?
6/28/02	1822	32.57	119.14	UW	1?
6/28/02	1906	32.58	119.14	BP	1
6/28/02	1909	32.57	119.14	BP	2
6/28/02	1913	32.57	119.13	BP	2
6/29/02	0715	32.91	118.39	TT	100-150
6/29/02	1305	32.16	118.23	UD	10
6/29/02	1730	32.29	118.19	UD	2-50
6/29/02	1858	32.37	118.07	UD	1
6/29/02	2000	32.42	118.10	BM	1?
6/30/02	0657	32.59	118.09	DD	60-80
6/30/02	0755	32.67	118.02	BP	2
6/30/02	1120	32.60	117.45	BM	1
6/30/02	1426	32.67	117.43	BM	1
6/30/02	1633	32.82	117.38	BM	2
8/17/02	1426	32.69	119.04	UW	1
8/17/02	1437	32.71	119.07	DD	200
8/17/02	1440	32.71	119.07	UW	1
8/17/02	1548	32.76	119.23	UW	1
8/17/02	1559	32.74	119.25	BP	2
8/17/02	1611	32.72	119.26	BP	1
8/17/02	1611	32.72	119.26	BP	2
8/17/02	1611	32.72	119.26	BP	1
8/17/02	1624	32.70	119.28	BP	1
8/17/02	1642	32.68	119.31	BP	1
8/17/02	1724	32.60	119.36	BP	2
8/17/02	1746	32.57	119.36	BP	1
8/17/02	1840	32.47	119.29	BP	1
8/17/02	1852	32.45	119.26	LO	~30
8/17/02	1856	32.44	119.26	UW	1
8/17/02	1926	32.42	119.18	Zc	1
8/17/02	1940	32.41	119.15	LO	4
8/18/02	0648	32.60	119.17	UW	1
8/18/02	0758	32.60	119.19	BP	1
8/18/02	0820	32.61	119.21	UW	1
8/18/02	0820	32.61	119.21	ZC	1
8/18/02	0924	32.65	119.20	BP	1
8/18/02	1030	32.60	119.13	ZC	1
8/18/02	1038	32.58	119.12	ZC	1
8/18/02	1229	32.58	119.12	ZC	1
8/18/02	1237	32.57	119.12	ZC	1
8/18/02	1313	32.54	119.12	BM	2
8/18/02	1425	32.56	119.17	UW	1

8/18/02	1504	32.57	119.18	UW	1
8/18/02	1537	32.58	119.19	Bp	1
8/18/02	1643	32.63	119.21	UW	3
8/18/02	1653	32.64	119.21	ZC	1
8/18/02	1743	32.65	119.08	ZC	2
8/18/02	1831	32.67	118.95	BP	2
8/17/02	1926	32.42	119.18	ZC	1
8/19/02	0827	32.80	118.33	ZC	1
8/19/02	0833	32.80	118.33	ZC	1
8/19/02	0853	32.80	118.34	LO	>8
8/19/02	0951	32.83	118.31	DSP	6
8/19/02	0955	32.83	118.30	DSP	3
8/19/02	1004	32.83	118.30	UD	1
8/19/02	1142	32.74	118.20	ZC	1
8/19/02	1204	32.71	118.16	ZC	1
8/19/02	1212	32.70	118.14	DD	6
8/19/02	1220	32.69	118.12	DD	30
8/19/02	1332	32.61	117.96	UD	3
8/19/02	1452	32.53	118.00	DSP	10
8/19/02	1534	32.44	118.01	DSP	200
8/19/02	1534	32.44	118.01	LO	2
8/19/02	1602	32.38	118.02	DSP	100
8/19/02	1611	32.36	118.04	DD	5,7,10
8/19/02	1618	32.35	118.05	DSP	12
8/19/02	1625	32.33	118.06	DD	6
8/19/02	1718	32.30	118.18	UD	4
8/19/02	1816	32.28	118.17	BM	1
8/20/02	0857	32.65	119.15	ZC	1
8/20/02	0924	32.66	119.19	DD	3
8/20/02	0924	32.66	119.19	DD	2
8/20/02	0940	32.67	119.22	DSP	2
8/20/02	1148	32.60	119.22	ZC	1
8/20/02	1332	32.58	119.19	ZC	1
8/20/02	1553	32.62	119.18	ZC	1
8/20/02	1606	32.62	119.19	BP	1
8/20/02	1704	32.62	119.20	LO	3
8/20/02	1740	32.59	119.19	DD	4
8/20/02	1820	32.57	119.19	BM	1
8/21/02	0818	32.60	119.13	ZC	1
8/21/02	0833	32.60	119.14	DSP	25
8/21/02	0917	32.61	119.20	BP	1
8/21/02	1022	32.59	119.23	ZC	1
8/21/02	1120	32.58	119.15	DD	15
8/21/02	1606	32.63	119.17	BP	2
8/21/02	1633	32.62	119.17	BP	1
8/21/02	1805	32.60	119.20	BP	1
8/21/02	1825	32.61	119.21	ZC	1

8/22/02	1446	32.07	118.65	ZC	1
8/22/02	1447	33.07	118.65	UW	1
8/22/02	1610	33.18	118.65	DD	200
8/22/02	1610	33.18	118.65	ZC	2
8/22/02	1624	33.21	118.63	ZC	1
8/22/02	1706	33.29	118.58	ZC	1
8/22/02	1806	33.29	118.45	ZC	1
8/22/02	1815	33.29	118.42	ZC	1
8/22/02	1905	33.26	118.28	TT	20
11/2/02	0816	33.58	119.19	BP	1
11/2/02	1002	32.66	119.18	BP	1
11/2/02	1038	32.66	119.20	BP	2
11/2/02	1045	32.66	119.22	BP	1
11/2/02	1204	32.61	119.24	UBW	1
11/2/02	1249	32.62	119.23	UW	1
11/2/02	1708	32.49	119.07	Lo	3
11/3/02	0554	32.76	119.22	MN	3
11/3/02	0619	32.75	119.19	BP	1
11/3/02	0837	32.64	119.34	BP	2
11/3/02	0927	32.66	119.33	UW	1
11/3/02	1008	32.66	119.23	BP	3
11/3/02	1018	32.66	119.19	BP?	1
11/3/02	1044	32.66	119.20	UW	1
11/3/02	1233	32.74	119.17	PV	2
11/3/02	1248	32.76	119.21	BM	1
11/4/02	0703	32.66	119.29	UW	1
11/4/02	0715	32.66	119.26	UW	1
11/4/02	0738	32.66	119.20	BP	1
11/4/02	0826	32.66	119.18	UW	1
11/4/02	0826	32.66	119.18	UW	3
11/4/02	0914	32.66	119.21	UW	1
11/4/02	0934	32.66	119.22	UW	3
11/4/02	0945	32.66	119.22	BP	1
11/4/02	1039	32.65	119.21	UW	1
11/4/02	1042	32.65	119.21	UW	2
11/4/02	1049	32.63	119.20	BP	1
11/4/02	1059	32.62	119.18	UW	1
11/4/02	1121	32.62	119.18	UW	1
11/4/02	1132	32.62	119.18	UW	1
11/4/02	1155	32.62	119.18	UW	1
11/4/02	1232	32.61	119.24	BP	2
11/4/02	1336	32.61	119.24	UW	1
11/4/02	1404	32.62	119.27	UW	2
11/4/02	1409	32.63	119.28	UW	1
4/16/03	10:44	32.64	119.21	CU	1
4/16/03	13:05	32.49	119.05	BA	1
4/16/03	13:55	32.41	118.98	BA	1

4/16/03	18:50	32.67	119.31	Bp	1
4/17/03	7:05	32.99	118.63	TT	456
4/17/03	9:34	32.92	118.39	TT	8
4/17/03	9:48	32.91	118.37	UD	5
4/17/03	10:13	32.86	118.33	LO	6
4/17/03	10:24	32.84	118.31	Gg	7
4/17/03	10:55	32.82	118.22	UD	4
4/17/03	12:55	32.75	117.89	Dd	20
4/17/03	13:36	32.73	117.78	Ba?	1
4/17/03	13:36	32.73	117.78	Tt	7
4/17/03	14:33	32.69	117.61	UD	175
4/17/03	14:54	32.68	117.56	Pd	1
4/17/03	15:53	32.64	117.39	Bm	1
7/22/03	7:13	32.40	119.14	Bm	1
7/22/03	7:27	32.42	119.18	Bm	1
7/22/03	7:30	32.42	119.19	Bp	1
7/22/03	7:34	32.44	119.21	Uw	1
7/22/03	7:48	32.45	119.23	Bp	1
7/22/03	8:37	32.50	119.35	DD	58
7/22/03	8:56	32.54	119.35	Uw	1
7/22/03	9:07	32.54	119.35	Bp	1
7/22/03	9:13	32.57	119.35	Bp	1
7/22/03	9:15	32.58	119.36	Bm	1
7/22/03	9:20	32.60	119.35	Bp	1
7/22/03	9:22	32.60	119.35	Bm	2
7/22/03	9:23	32.60	119.35	Uw	1
7/22/03	9:24	32.60	119.35	Bm	1
7/22/03	9:30	32.60	119.35	Bp	1
7/22/03	9:33	32.60	119.35	Uw	1
7/22/03	9:38	32.60	119.35	Bm	2
7/22/03	9:38	32.60	119.35	Uw	1
7/22/03	9:55	32.60	119.36	Bp	1-2
7/22/03	9:59	32.60	119.36	Bp	4
7/22/03	10:03	32.60	119.35	Bp	1
7/22/03	10:04	32.60	119.35	Bp	1
7/22/03	10:05	32.60	119.35	Bp	1-2
7/22/03	10:38	32.61	119.36	Uw	2
7/22/03	10:46	32.61	119.36	Bp	1
7/22/03	10:56	32.60	119.35	Bp	1-2
7/22/03	10:57	32.60	119.35	Bp	2
7/22/03	11:24	32.61	119.35	Bp	2
7/22/03	11:30	32.62	119.35	uw	1
7/22/03	11:41	32.63	119.34	Bp	1
7/22/03	11:47	32.64	119.33	Uw	2
7/22/03	11:49	32.64	119.33	bp	1
7/22/03	11:55	32.64	119.33	Uw	3
7/22/03	12:10	32.64	119.33	Bp	2?

7/22/03	12:10	32.64	119.33	Uw	1
7/22/03	12:22	32.64	119.33	Uw	1
7/22/03	12:38	32.64	119.33	Uw	1
7/22/03	12:49	32.64	119.33	Uw	3
7/22/03	12:51	32.64	119.33	bP	2
7/22/03	13:01	32.64	119.33	uW	1
7/22/03	13:06	32.64	119.33	bP	1
7/22/03	13:14	32.64	119.33	Bp	1
7/22/03	13:15	32.64	119.33	uW	2?
7/22/03	13:27	32.65	119.34	Bp	1
7/22/03	14:37	32.67	119.34	Uw	1
7/22/03	15:01	32.69	119.33	Uw	1
7/22/03	15:06	32.69	119.34	Uw	1-2
7/22/03	15:21	32.68	119.32	Uw	1
7/22/03	15:24	32.68	119.31	Uw	2-3
7/22/03	15:36	32.67	119.31	Uw	1
7/22/03	15:40	32.67	119.31	Uw	1
7/22/03	15:43	32.67	119.31	Uw	1
7/22/03	15:53	32.66	119.31	Uw	2-3
7/22/03	15:59	32.66	119.30	Uw	2
7/22/03	16:15	32.65	119.30	Uw	1
7/22/03	16:18	32.65	119.31	Uw	1
7/22/03	16:22	32.65	119.31	Bm	1
7/22/03	16:23	32.65	119.31	Uw	1
7/22/03	16:32	32.66	119.32	Uw	1
7/22/03	16:35	32.66	119.32	Bp	1
7/22/03	16:40	32.66	119.32	Bp	1
7/22/03	16:50	32.68	119.30	Bm	2
7/22/03	16:58	32.69	119.29	Uw	1?
7/22/03	17:02	32.70	119.28	Uw	1
7/22/03	17:14	32.72	119.26	Bp	1
7/22/03	18:09	32.76	119.21	Bp	1
7/22/03	18:28	32.76	119.21	Uw	1
7/22/03	19:19	32.72	119.10	Lo	25
7/23/03	10:04	32.52	119.06	Lo	100
7/23/03	12:20	32.60	119.17	Uw	1
7/23/03	12:22	32.60	119.17	Uw	1
7/23/03	12:25	32.60	119.17	Uw	1
7/23/03	12:26	32.60	119.17	Uw	1-2
7/23/03	12:28	32.60	119.18	Uw	1
7/23/03	12:36	32.60	119.18	Uw	1
7/23/03	12:38	32.60	119.18	Bp	1-2
7/23/03	12:51	32.60	119.20	Bp?	2
7/23/03	12:59	32.61	119.20	Bp	2-3
7/23/03	13:01	32.61	119.20	Uw	1
7/23/03	13:12	32.64	119.20	Uw	1
7/23/03	13:18	32.65	119.20	Bp	1

7/23/03	13:23	32.65	119.20	Bp	2
7/23/03	13:24	32.65	119.20	Bp	1
7/23/03	13:28	32.65	119.20	Bp	1
7/23/03	13:43	32.65	119.20	Bp	1
7/23/03	13:47	32.65	119.21	Bp	2
7/23/03	13:48	32.65	119.21	Bp	2
7/23/03	13:48	32.65	119.21	Uw	1
7/23/03	13:48	32.65	119.21	Uw	2-3
7/23/03	14:02	32.63	119.25	Bp	2
7/23/03	14:07	32.63	119.25	Bp	1
7/23/03	14:07	32.63	119.27	Bp	2
7/23/03	14:08	32.63	119.27	Bp	1
7/23/03	14:09	32.63	119.27	Bp	2
7/23/03	14:09	32.63	119.27	Bp	2
7/23/03	14:13	32.63	119.28	Bp?	1
7/23/03	14:21	32.62	119.32	Bp	2
7/23/03	14:29	32.61	119.33	Bp?	1
7/23/03	14:31	32.61	119.33	Bp	3
7/23/03	14:33	32.61	119.33	Bp	1
7/23/03	14:40	32.60	119.35	Bp	2
7/23/03	14:45	32.60	119.35	Bp	3
7/23/03	14:59	32.58	119.35	bp?	1
7/23/03	15:15	32.55	119.32	Mn	1
7/23/03	15:37	32.50	119.28	Bp	1
7/23/03	15:44	32.48	119.27	Ba	2
7/23/03	16:02	32.46	119.23	Bp	3
7/23/03	16:15	32.44	119.19	Bp	3
7/24/03	7:34	32.32	119.39	DD?	75-100
7/24/03	7:58	33.35	119.45	DD?	2
7/24/03	9:41	33.50	119.64	Bm	2
7/24/03	9:56	33.52	119.62	Bm	5
7/24/03	9:56	33.52	119.62	Bm	1
7/24/03	10:27	33.51	119.60	Bm	1
7/24/03	10:36	33.51	119.61	Bm	1
7/24/03	10:41	33.51	119.61	Bm	1
7/24/03	10:41	33.51	119.61	Bm	1
7/24/03	10:58	33.51	119.62	Bm	2
7/24/03	11:17	33.52	119.63	Bm	1
7/24/03	11:33	33.51	119.62	Bm	1
7/24/03	11:48	33.51	119.61	Bm	1
7/24/03	12:08	33.51	119.63	Bm	3
7/24/03	12:56	33.51	119.62	Bm	1
7/24/03	13:21	33.52	119.62	Bm	1
7/24/03	13:59	33.51	119.58	Bp	1
7/24/03	14:35	33.51	119.57	Bm	1
7/24/03	14:45	33.51	119.57	Uw	2
7/24/03	14:54	33.51	119.57	Uw	1

7/24/03	15:04	33.51	119.57	Bm	1
7/24/03	15:09	33.51	119.57	Bm	1
7/24/03	15:15	33.51	119.58	Uw	1
7/24/03	15:45	33.50	119.58	Bm	2
7/24/03	16:02	33.50	119.58	Bm	2
7/24/03	16:04	33.50	119.58	Bm	2
7/24/03	16:11	33.51	119.58	Bm	1
7/24/03	16:15	33.51	119.58	Bm	1
7/24/03	16:27	33.51	119.58	Bm	1
7/24/03	18:28	33.52	119.59	Zc	1
7/25/03	6:55	33.51	119.60	Gg	2
7/25/03	7:20	33.54	119.65	Bm	2
7/25/03	7:24	33.54	119.65	Bm	1
7/25/03	8:07	33.54	119.65	Ba	1
7/25/03	13:26	33.51	119.92	Bm?	1-2
7/25/03	13:41	33.49	119.90	Bm	2
7/25/03	13:41	33.49	119.90	Bm	2
7/25/03	13:41	33.49	119.90	Bm?	1
7/25/03	13:52	33.49	119.89	Bm	1-2
7/25/03	15:00	33.48	119.71	Bm?	1
7/25/03	15:12	33.48	119.69	Bm	1
7/25/03	15:35	33.48	119.63	Dd	150
7/25/03	16:49	33.50	119.63	Bm	1
7/25/03	17:50	33.48	119.80	Bm	2
7/25/03	17:56	33.48	119.82	Uw	2?
7/25/03	18:06	33.48	119.84	Bm	3
7/25/03	18:12	33.48	119.86	Bm	2
7/25/03	18:12	33.48	119.86	Bm	2
7/25/03	18:15	33.48	119.87	Bm	1
7/25/03	18:16	33.48	119.87	Bm	4-5
7/25/03	18:37	33.48	119.90	Bm	2
7/25/03	18:39	33.48	119.90	Bm	1
7/26/03	6:48	33.86	118.72	Dd	4
7/26/03	15:27	32.65	117.50	Pv	20
8/19/03	19:48	32.64	117.44	Bm	3+
8/20/03	6:35	32.67	119.27	Uw	1?
8/20/03	6:38	32.67	119.27	Uw	1?
8/20/03	6:40	32.67	119.28	Uw	1?
8/20/03	6:42	32.67	119.28	Bp?	1?
8/20/03	6:44	32.67	119.29	Bp?	1?
8/20/03	6:44	32.67	119.29	Uw	1?
8/20/03	6:49	32.67	119.30	Bp	1?
8/20/03	7:02	32.67	119.32	Uw	1?
8/20/03	7:15	32.67	119.32	Uw	1?
8/20/03	7:18	32.67	119.32	Bp	2
8/20/03	10:03	32.66	119.33	Bp	1
8/20/03	10:07	32.52	119.33	Bp	2

8/20/03	10:09	32.65	119.33	Bp	1
8/20/03	10:13	32.64	119.34	Bp	1
8/20/03	10:16	32.63	119.34	Bp	2
8/20/03	10:16	32.63	119.34	Bp	1
8/20/03	10:17	32.63	119.34	Bp	2
8/20/03	10:18	32.63	119.34	Bp	2
8/20/03	10:22	32.62	119.34	Bp	2
8/20/03	10:29	32.60	119.35	Bp	1
8/20/03	10:29	32.60	119.35	UD	2-10
8/20/03	10:34	32.61	119.35	Bp	1
8/20/03	10:36	32.61	119.35	Bp	3
8/20/03	10:39	32.62	119.34	Bp	2
8/20/03	10:41	32.62	119.34	Bp?	2
8/20/03	10:43	32.62	119.34	Bp	1
8/20/03	10:43	32.62	119.34	Lo	60-100
8/20/03	10:44	32.62	119.34	Bp	3
8/20/03	11:00	32.63	119.31	Bp	4
8/20/03	11:04	32.64	119.31	Bp	2
8/20/03	11:08	32.65	119.31	Bp	2
8/20/03	11:10	32.65	119.30	Bp	1
8/20/03	11:16	32.66	119.30	Bp	4
8/20/03	11:30	32.69	119.28	Bp	2
8/20/03	11:34	32.69	119.28	Bp?	1
8/20/03	11:34	32.70	119.27	Bp	1
8/20/03	11:38	32.71	119.26	Bp	1?
8/20/03	11:41	32.71	119.26	Bp	1
8/20/03	11:45	32.71	119.26	Bp	2
8/20/03	11:45	32.71	119.25	Bp	1
8/20/03	11:55	32.74	119.24	Bp	1
8/20/03	13:03	32.64	119.16	Bp	1
8/20/03	13:03	32.64	119.16	Bp	2
8/20/03	13:03	32.64	119.16	Bp	1
8/20/03	13:11	32.63	119.15	Bp	2
8/20/03	13:14	32.62	119.15	Lo	5-10
8/20/03	18:17	32.59	119.33	Bp?	1
8/20/03	18:32	32.61	119.35	Bp	3
8/20/03	18:38	32.63	119.34	Bp?	1
8/20/03	18:41	32.63	119.34	Bp	1
8/20/03	18:42	32.64	119.34	Bp	1
8/20/03	18:44	32.64	119.34	Bp	1
8/20/03	18:47	32.65	119.33	Bp	1
8/20/03	18:51	32.65	119.33	Bp	2
8/20/03	18:56	32.66	119.32	Bp	3?
8/20/03	19:00	32.67	119.31	Bp	1
8/20/03	19:02	32.67	119.31	Bp	1
8/20/03	19:04	32.67	119.31	Bp	2
8/20/03	19:05	32.67	119.31	Bp	3

8/20/03	19:07	32.68	119.30	Bp	2
8/21/03	6:47	32.72	119.42	Bp	2
8/21/03	6:51	32.71	119.41	DD	200-250
8/21/03	7:19	32.68	119.35	Bp	2
8/21/03	7:24	32.67	119.33	Bp	1
8/21/03	7:24	32.67	119.33	Bp	3
8/21/03	8:15	32.65	119.33	Lo	35-50
8/21/03	8:18	32.65	119.33	Bp	2
8/21/03	8:22	32.64	119.34	Bp	2
8/21/03	8:32	32.62	119.35	Bp	1
8/21/03	8:45	32.60	119.36	Bp	1
8/21/03	8:50	32.61	119.35	Bp	1
8/21/03	8:52	32.62	119.34	Bp	1
8/21/03	8:57	32.63	119.34	Bp	4
8/21/03	8:58	32.63	119.34	Bp	2
8/21/03	9:07	32.65	119.32	Bp	1
8/21/03	9:10	32.65	119.32	Bp	2
8/21/03	9:10	32.65	119.32	Bp	1
8/21/03	9:16	32.66	119.31	Bp	1
8/21/03	9:16	32.66	119.31	Bp	2
8/21/03	9:22	32.67	119.30	Bp	1
8/21/03	9:22	32.67	119.30	Bp	2
8/21/03	9:23	32.68	119.29	Bp	3-4
8/21/03	9:23	32.68	119.29	Bp	2-3
8/21/03	9:40	32.70	119.27	Bp	1
8/21/03	9:40	32.70	119.27	Bp	1
8/21/03	9:41	32.71	119.27	Bp	2
8/21/03	9:41	32.71	119.27	Bp	1
8/21/03	9:44	32.71	119.26	Bp	1
8/21/03	9:48	32.72	119.25	Bp	2
8/21/03	9:57	32.74	119.24	DD	80-100
8/21/03	10:22	32.79	119.20	Bp	1
8/21/03	12:07	32.63	119.13	Bp?	1
8/21/03	12:08	32.62	119.13	Bp?	3
8/21/03	12:10	32.62	119.13	Bp?	1
8/21/03	12:29	32.62	119.17	Bp	1
8/21/03	12:47	32.64	119.22	DD	20
8/21/03	13:15	32.66	119.28	Uw	1?
8/21/03	13:47	32.68	119.26	Bp	1
8/21/03	13:49	32.69	119.26	Bp	1
8/21/03	13:53	32.70	119.26	Bp	1
8/21/03	13:55	32.70	119.25	Bp	1
8/21/03	13:58	32.71	119.25	Bp	1
8/21/03	14:18	32.73	119.23	Bp	2
8/21/03	14:18	32.73	119.23	Bp	1
8/21/03	14:30	32.70	119.24	Bp	2
8/21/03	14:30	32.70	119.24	Bp	3

8/21/03	14:36	32.69	119.24	Dd	50
8/21/03	14:46	32.67	119.26	Bp	3
8/21/03	14:55	32.66	119.27	Bp	2
8/21/03	14:58	32.65	119.28	Bp	3
8/21/03	15:05	32.65	119.29	Bp	1
8/21/03	15:07	32.65	119.29	Bp	1
8/21/03	15:15	32.64	119.30	Bp	1
8/21/03	15:15	32.64	119.30	Bp	3
8/21/03	15:38	32.61	119.34	Ud	1
8/21/03	15:48	32.62	119.33	Bp	1?
8/21/03	16:33	32.61	119.28	Bp	1
8/21/03	16:37	32.62	119.27	Bp	1
8/21/03	16:41	32.62	119.26	Bm	1
8/21/03	16:44	32.63	119.26	Bp	1
8/21/03	17:15	32.61	119.27	Bm	1?
8/21/03	17:27	32.62	119.27	Bp	1?
8/21/03	18:27	32.63	119.32	Bm/Bp	1/1
8/21/03	18:30	32.64	119.33	Bp	1
8/21/03	18:40	32.64	119.34	Bp	1
8/21/03	18:48	32.65	119.34	Bp	2
8/21/03	18:48	32.65	119.34	Bp?	1
8/21/03	18:48	32.65	119.34	Bp	2
8/22/03	6:38	32.40	119.82	Bp	1
8/22/03	6:43	33.40	119.81	bm	1
8/22/03	6:51	33.38	119.80	Bp	1
8/22/03	7:04	33.35	119.78	Bp	2
8/22/03	7:40	33.28	119.73	Dd?	50
8/22/03	11:29	33.83	119.43	Bp	1
8/22/03	11:39	32.82	119.41	Bp	1
8/22/03	11:59	32.81	119.38	Bm	1
8/22/03	16:51	32.82	119.37	Bp	1
8/22/03	16:51	32.82	119.37	Bp?	1
8/22/03	16:51	32.82	119.37	Bp?	1
8/22/03	17:13	32.81	119.37	Uw	1
8/22/03	18:31	32.73	119.35	Uw	1
8/22/03	18:36	32.72	119.34	Uw	1
8/22/03	18:40	32.71	119.34	Bp	1
8/22/03	18:46	32.69	119.33	Bp	1
8/22/03	18:48	32.69	119.33	Bp	1
8/22/03	18:55	32.68	119.33	Bp	1
8/23/03	7:28	32.07	119.60	Lo/Pd	15-20
8/23/03	8:56	33.88	119.48	Bp	1
8/23/03	10:03	32.75	119.38	Bp	1
8/23/03	10:35	32.68	119.34	Dd	300-400
8/23/03	11:39	32.68	119.29	Bp	2
8/23/03	12:06	32.69	119.28	Bp	1?
8/23/03	12:19	32.69	119.28	Bm	1?

8/23/03	14:22	32.67	119.33	Bp	1
8/23/03	14:28	32.66	119.33	Bp	1
8/23/03	14:36	32.66	119.34	Bp?	1
8/23/03	14:39	32.65	119.34	Bp?	1
8/23/03	14:46	32.64	119.34	Bp	2
8/23/03	15:11	32.61	119.34	Uw	1?
8/23/03	15:20	32.62	119.34	Bp	3
8/23/03	15:33	32.63	119.32	Bp?	1
8/23/03	15:41	32.63	119.30	Bp?	2
8/23/03	15:48	32.63	119.29	Bp?	1
11/2/03	6:11	32.70	119.05	Uw	1-2
11/2/03	6:31	32.70	119.06	Uw	1
11/2/03	7:58	32.75	119.23	Uw	2-3
11/3/03	6:34	32.81	119.91	D sp.	15-20
11/3/03	7:14	32.78	119.80	Lb	3-4
11/3/03	9:39	32.70	119.42	Gg	20-25
11/3/03	12:03	32.66	119.34	Bp	2
11/3/03	12:19	32.66	119.34	Bp	1
11/3/03	14:09	32.57	119.36	Uw	5-8
11/3/03	14:24	32.54	119.36	Uw	3-4
11/3/03	14:26	32.53	119.36	Bm	2
11/3/03	14:26	32.53	119.36	Bp	2
11/3/03	14:26	32.53	119.36	Bp	1
11/3/03	14:32	32.52	119.36	Bm	1
11/3/03	14:35	32.52	119.36	Uw	2
11/3/03	14:36	32.52	119.35	Uw	1
11/3/03	14:37	32.52	119.35	Bm?	4
11/3/03	14:39	32.52	119.35	Uw	1
11/3/03	14:40	32.51	119.35	Bp	1
11/3/03	14:48	32.50	119.33	Bp	1
11/4/03	7:38	32.89	118.41	D sp.	15-20
11/4/03	7:51	32.87	118.38	UD	40-60
11/4/03	7:59	32.86	118.36	D sp.	30-50
11/4/03	8:07	32.85	118.34	D sp.	10-15
11/4/03	8:09	32.84	118.34	D sp.	6
11/4/03	8:22	32.82	118.31	D sp.	40-60
11/4/03	9:01	32.77	118.23	Uw	1
11/4/03	10:32	32.67	118.07	Bp	4-6
11/4/03	15:00	32.65	117.60	UD	50+
11/4/03	15:11	32.64	117.56	UD	20+
11/4/03	15:14	32.63	117.56	Lo	2
11/4/03	16:31	32.62	117.31	Lo	2

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