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ACOUSTIC STUDIES OF MARINE MAMMALS DURING SEVEN YEARS OF COMBINED VISUAL AND ACOUSTIC LINE-TRANSECT SURVEYS FOR CETACEANS IN THE EASTERN AND CENTRAL PACIFIC OCEAN

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U.S. DEPARTMENT OF COMMERCE
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ACOUSTIC STUDIES OF MARINE MAMMALS DURING SEVEN YEARS OF COMBINED VISUAL AND ACOUSTIC LINE-TRANSECT SURVEYS FOR CETACEANS IN THE PACIFIC OCEAN

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I. INTRODUCTION

The Southwest Fisheries Science Center has been conducting shipboard line-transect surveys of marine mammals since the 1970s. These research cruises have evolved into multi-disciplinary studies incorporating visual observations to determine distribution and abundance of cetaceans and seabirds, and oceanographic sampling to examine physical and biological aspects of the marine ecosystem. In recent years, data collection during these surveys has expanded further to include passive acoustic monitoring of cetaceans.

This report summarizes the cetacean acoustic data collected during seven years of shipboard surveys in the eastern and central Pacific Ocean. The STAR 2000 (STenella Abundance Research) project was the third in a series of three research cruises designed to study cetacean populations that have been impacted by the tuna purse-seine fishery in the eastern tropical Pacific Ocean (ETP). STAR 2003 and STAR 2006 were extensions of the STAR study, designed to update population information on cetaceans in the ETP. ORCAWALE 2001 (ORegon-CAlifornia-WAshington Line-transect Expedition) was a population survey of marine mammals in the U.S. West Coast exclusive economic zone (EEZ) waters out to a distance of approximately 300 nautical miles. HICEAS 2002 (Hawaiian Island Cetacean Ecosystem Assessment Survey) surveyed cetacean populations in the EEZ of the Hawaiian Islands. SPLASH 2004 (Structure of Populations, Levels of Abundance, and Status of Humpbacks) was a dedicated survey of humpback whales in the North Pacific. PICEAS 2005 (Pacific Islands Cetacean Ecosystem Assessment Survey) was a dedicated survey of false killer whales in the waters south of the Hawaiian Islands, including Palmyra and Johnston Atolls. The primary objective of these surveys was to determine the distribution and abundance of cetaceans using visual line-transect survey methods (Kinzey et al. 2000).

The main goals of the shipboard passive acoustic program were to evaluate the potential use of passive acoustic monitoring to improve dolphin population estimation and to collect information about acoustic detection distances for sperm whales, *Physeter macrocephalus.* Passive acoustic methods may play a role in dolphin population estimation either by increasing the number of dolphin schools detected from the survey vessel or by identifying situations in which dolphin schools may be missed by the visual observation team. In this report we seek to understand the capabilities of passive acoustic monitoring during cetacean surveys by examining the ways in which acoustic detection rates and detection distances vary in relation to oceanographic and biological factors. We also conduct a detailed comparison of visual and acoustic detections to identify situations in which the visual team and/or the acoustic team may fail to detect cetaceans.

The acoustic data collected during these surveys have provided valuable information beyond these initial goals. These surveys have provided opportunities for us to record representative samples of marine mammal vocalizations from most species within the study areas, including the first recordings of Fraser's dolphins (*Lagenodelphis* *hosei,* Oswald et al. 2007a), Bryde's whales (*Balaenoptera edeni,* Oleson et al. 2003), and sei whales (*Balaenoptera borealis,* Rankin and Barlow 2007b) in the North Pacific Ocean. In addition, we were responsible for identifying the source of a mysterious sound in the North Pacific Ocean, known as the 'boing', as produced by common minke whales (*Balaenoptera acutorostrata,* Rankin and Barlow 2005a). Analysis of archived data on these sounds has greatly increased our understanding of the distribution, population structure, and migration habits of this species in the North Pacific Ocean. Our recordings have also facilitated the creation of software for the species identification of dolphin whistles (Oswald et al. 2003; 2004a, 2007) and are providing insight into the vocal behavior of dolphins throughout the North Pacific Ocean (Rankin et al. 2008b). Summaries of ancillary acoustics projects are given as appendices to this report.

II. EQUIPMENT AND PROCEDURES

A. Shipboard Surveys

This report includes acoustic data collected during seven cruises over seven years. The primary acoustics team consisted of two acousticians using a towed hydrophone array to passively detect cetacean vocalizations. During all surveys, passive acoustic effort was conducted during daylight hours, except when interrupted as a result of inclement weather (effort was suspended in Beaufort sea states of 6 or above), equipment failure, or in order to focus on other scientific objectives. Overall, the hydrophone array was towed for a total of 46,370 km, for a total of 533 days of effort. Visual observations followed standard SWFSC protocol (Kinzey et al. 2000), using two visual observers on 25 X 150 'big eye' binoculars and one visual observer as a data-recorder and scanning the nearfield with naked eye. These three observers scanned the waters for cetaceans; when cetaceans were detected, the vessel approached the school for species identification and group size estimation.

The STAR 2000 survey included 120 sea days from July 28 to December 9, 2000 on each of two NOAA research vessels: the R/V *McArthur* and the R/V *David Starr Jordan*. The study area extended from the US/Mexico border south to the territorial waters of Peru and was bounded to the east by the continental shores of the Americas and to the west by Hawaii (roughly from 30º N to 18º S and from the coastline to 153º W). The primary acoustics team (Table 1) worked from the *McArthur* (with opportunistic sonobuoy deployments from the *Jordan*). The towed hydrophone array was deployed for 82 survey days, along 8,058 km of trackline (Fig. 1).

The ORCAWALE 2001 survey ran from July 30 to December 8, 2001 and included survey effort with the full acoustics complement on R/V *David Starr Jordan* and sonobuoys for the last survey leg on R/V *McArthur*. The study area included the EEZ off Washington, Oregon, and California and international waters out to a distance of approximately 300 nautical miles from the coast. The primary acoustics team (Table 1) worked from the R/V *Jordan* from July 30 to November 11, 2001 for a total of 57 sea days covering 4,391 km (Fig. 1).

The HICEAS 2002 survey began on July 27 and ended on December 8, 2002 and included 120 sea days on the R/V *David Starr Jordan* (with additional coverage on the R/V *McArthur* without acoustic sampling). The study area included waters within the U.S. EEZ of the Hawaiian Island Chain, with an additional survey component during transit to and from San Diego, California. The primary acoustics team (Table 1) covered 8,336 km over 107 days of survey effort (Fig. 1).

The STAR 2003 survey began on July 29 and ended on December 10, 2003, and included 120 sea days on each of the two NOAA research vessels: the R/V *McArthur II* and the R/V *David Starr Jordan*. The primary acoustics team (Table 1) worked from the *McArthur II* from October 6 to December 10, 2003, for a total of 50 days of effort, covering 4,422 km of trackline (Fig. 1). Opportunistic recordings were made from the *Jordan* using sonobuoys and the hull-mounted hydrophone.

The SPLASH 2004 survey began on June 27 and ended on November 2, 2004 on the R/V *McArthur II*. This was a focal study of humpback whales (*Megaptera noviangliae*) in the North Pacific, and passive acoustics were included as time allowed. The primary acoustics team (Table 1) surveyed approximately 4,169 km of effort over 57 days of effort during this survey (Fig. 1).

The PICEAS 2005 survey began on July 28 and ended on December 7, 2005, and included 120 sea days on the R/V *McArthur II*. This was a focal study of false killer whales (*Pseudorca crassidens*) in the central tropical Pacific Ocean, south of the Hawaiian Islands and including Palmyra and Johnston Atolls. The primary acoustics team (Table 1) surveyed from July 28 to November 29, 2005, covering 7,753 km of trackline over 80 days of survey effort (Fig. 1).

The STAR 2006 survey began on July 28 and ended on December 7, 2006, and included 120 sea days on each of the two NOAA research vessels: the R/V *McArthur II* and the R/V *David Starr Jordan*. The primary acoustics team (Table 1) worked from the *McArthur II* and covered 9,241 km of trackline over 100 days of survey effort (Fig. 1). Opportunistic recordings were made from the *Jordan* using sonobuoys and the hull-mounted hydrophone.

B. Towed Hydrophone Array

A hydrophone array (the array) was towed at a distance of approximately 200-300 m behind the ship while traveling at approximately 10 knots during daylight hours (Fig. 2b). Typical tow depth of the array was 8 – 11 m at 10 knots, with greater depths (up to 85 m) at slower ship speeds. The array was deployed 20 minutes before sunrise and retrieved about 20 minutes after sunset, when all visual observers had ended effort for the day. Two acousticians alternated 2-3 hour shifts. The acousticians monitored the array aurally via headphones and visually via a scrolling real-time spectrograph display (ISHMAEL, Mellinger 2001).

Three different hydrophone arrays were used during the course of the STAR 2000 survey, three hydrophone arrays were used during ORCAWALE, and two hydrophone arrays were used during the HICEAS survey (Table 2). All hydrophones used from 2003-2006 included various versions of the "SWFSC" hydrophones (Table 2). The SE Norris 5-element array (Sonatech, Inc., Santa Barbara), was borrowed from Southeast Fisheries Science Center. This array was essentially identical to the SW Norris array. Due to a wire mismatch between the array and our deck cable, only 4 of the 5 elements were available for monitoring and recording with the SE Norris array. The "SWFSC" arrays all consisted of a varying number of identical hydrophone elements. During SPLASH, PICEAS, and STAR 2006, an additional high-frequency hydrophone (Seiche Measurements, Ltd., UK) was spliced to the end of the SWFSC array for high-frequency recordings. Many of the individual hydrophones were calibrated; this detailed information is archived at the SWFSC acoustics lab.

The wiring diagram (Fig. 3) gives a visual representation of the flow of acoustic signals through the hardware system in the shipboard acoustics lab. Signals from the array were first sent through a Mackie CR1604-VLZ mixer for volume equalization and filtering. The Mackie equalizers were used to flatten the noise spectrum and improve the dynamic range of recordings. The signals were then recorded using a Tascam DA-38 eight-channel digital recorder (48 kHz sampling rate). The system frequency response for amplification and equalization on the Mackie and for recording and playback on the Tascam is shown in Figure 4. Signals were then re-routed through the Mackie mixer for aural (headphone) and visual (real-time scrolling spectrogram) monitoring. Select samples of single channel broadband signals were filtered through the Avens Model 4128 band pass filter and recorded directly to the computer hard disk using custom SWFSC or ISHMAEL (Mellinger 2001) software. The sampling rate for hard disk recordings varied during and between surveys.

Acoustic detections of delphinids and sperm whales were recorded to the Tascam recorder when the signal to noise ratio (S/N) of vocalizations was sufficient for localization. Recordings typically ended when the entire school was past the beam and/or the S/N decreased such that localization was no longer possible.

The hydrophone array was monitored visually using a digital signal-processing program (ISHMAEL http://www.pmel.noaa.gov/vents/acoustics/whales/ishmael/) with scrolling real-time spectrographic display and localization capabilities (Mellinger 2001). The approximate bearing angle to the signal was determined using either the beamforming or the cross-correlation (phone-pair) bearing estimation algorithm in ISHMAEL. Bearing angles were sent electronically to Whaltrak, where the angles were superimposed on the graphical mapping display (Fig. 5). The location of the vocalizing animals was determined based on the convergence of successive bearing angles for all acoustic detections. A computer log of relevant information was created using Whaltrak (providing a time, date, and GPS stamp for each entry) in addition to a paper log.

Brief high-frequency digital recordings were made for some acoustic detections, typically using a sample rate of 200 ksamples per second and a 100 kHz low-pass, anti-aliasing filter. This sampling rate allowed for recordings above the maximum high frequency sensitivity of the mid-frequency array(s). Prior to 2005, these recordings were made opportunistically during encounters with highly vocal or rare sightings. During PICEAS and STAR 2006, continuous hard disk recordings were made during all periods when the acoustics team was “on effort”.

C. Sonobuoy Deployment and Recording

All ships were equipped with a sonobuoy system for use when high-quality recordings could not be made using the hydrophone array (Fig. 2a). The towed hydrophone array was limited in its ability to record low frequency vocalizations due to ship and flow noise. For this reason, sonobuoys were primarily deployed to remotely monitor and record the low-frequency sounds of baleen whales.

Three types of sonobuoys were used: high frequency type 57 (10 Hz – 20 kHz), low frequency type 53 (10 Hz – 2.5 kHz) and type 77 (10 Hz – 2.5 kHz, vertical hydrophone array, Fig. 2b). Signals from the sonobuoys were transmitted to the ship via

VHF radio and received using a modified ICOM broadband radio receiver (ICOM IC R100) in the acoustics lab. Sonobuoy recordings were made using a portable Sony digital audio tape (DAT) recorder (Sony TCD-7 or TCD-8), or with a rack-mounted Sony PCM-R500 DAT (48 kHz sampling rate). Information regarding sonobuoy deployments and recordings were entered into a separate logbook.

D. Hull-mounted Hydrophones

A three-element hydrophone array was mounted to a plate bolted into one of the underwater ports of the 'bow bubble' of the *Jordan* (Fig. 2c). The three hydrophones were arranged in a triangular pattern, with a maximum separation of 21 cm. The frequency response of the bow hydrophone was 500 Hz to 30 kHz (± 5 dB at -155 dB re 1V/µPa). The output of the bow hydrophones was sent to the acoustics lab, where signals could be monitored independently or simultaneously with the towed hydrophone array. Due to high noise levels, the bow hydrophones have a limited acoustic detection range, and were used primarily to detect bow-riding dolphins and cetaceans located in close proximity to the bow of the ship. These were areas where the towed hydrophone array had limited detection abilities.

E. Data Analysis

In this report*, acoustic detection* will be used to refer to the presence of vocalizations attributed to a single animal or a group of cetaceans. Acoustic detections were divided into two categories: those also detected by the visual team (*matched detections*) and those that were not detected by the visual team (*exclusive acoustic detections*). Cetacean sightings in which vocalizations were not detected using our methods were considered *exclusive visual detections*. If only a few vocalizations were detected (<5), then these were not typically considered to be "vocal" groups of animals. For exclusive acoustic detections, a minimum of 5 vocalizations was required to consider the group for these analyses.

Localization was required to match an acoustic detection with a visual detection. Quantitative measurements of localizations included the time of first detection, the first angle of detection, the first distance of detection, the distance at which the group passed the beam of the ship (for exclusive acoustic detections), the acoustic detection distance (i.e. the greatest distance at which vocalizations could be localized), the time at which the group passed the beam of the ship, and the location of the group (latitude, longitude based on localization).

The *acoustic detection distance* is an estimate of the greatest distance at which vocalizations could be localized and therefore the greatest distance at which the acoustic team could confirm the detection of a particular group of animals. The distance at which non-sighted dolphin schools passed the beam of the ship (closest point of approach for passing mode) provided information on the cetacean groups missed by the visual observation team. Visual sighting data were truncated to 3 nmi to provide a more robust estimation of effective strip width, and therefore abundance. To allow for a more direct comparison of methods, acoustic schools that were not sighted by the visual observation team but were within this 3 nmi truncation distance were considered "missed" using visual sighting methods. For this analysis, acoustic detections outside of the 3 nmi beam distance were considered outside of the effective visual effort range. Likewise, sightings within 3 nmi that were not detected using acoustics methods were considered "missed" using acoustic methods. Acoustic detections and acoustic detection distances were examined in relation to physical and biological factors. To determine the effect of wind and wave noise on the acoustic detection distances of dolphin schools and sperm whales during all seven cruises, we stratified data by Beaufort sea state. The influences of thermocline depth and thermocline intensity on acoustic detections were examined for the STAR 00 cruise only.

The primary biological factors examined included species, mixed vs. single species schools, group size, and time of day. For most analyses, data were used from all research cruises. Some analyses only used a subset of data. To examine the potential benefits and limitations of acoustic techniques during dolphin abundance surveys, the numbers of acoustic detections of sighted and non-sighted dolphin schools were compared for all cruises.

III. RESULTS

A. Physical Capabilities of Towed Hydrophone Array Data

The mean acoustic detection distance varied among surveys from a low of 0.6 nmi (SD ± 0.6) for the SPLASH cruise to a high of 4.2 nmi (SD ± 2.6) for the HICEAS survey (Table 3). There was no significant relationship between the acoustic detection distance and the Beaufort sea state for the overall survey data combined ($p = 0.118$, $n = 1501$, Fig. 6); however, there was a significantly greater acoustic detection distance with increasing sea state for ORCAWALE and STAR 03 surveys ($p = 0.0004$ $n = 111$ and $p = 0.0033$, $n = 182$, respectively, Fig. 7). There were occasions when extreme noise from heavy rains lead to the decision to cease acoustic effort. Likewise, the towed array was retrieved in large seas (Beaufort sea states of 6 and above) in order to prevent physical damage to the equipment.

There was not a significant relationship between the original angle of detection versus the original detection distance ($p = 0.76$, $n = 1,527$, Fig. 8), suggesting that the sensitivity of the hydrophone array did not vary according to the orientation of the array to the sound source. Nonetheless, there was a sharp drop in the number of acoustic detections within 15° of the bow of the ship (Fig. 9). Most (96%) acoustic detections occurred before the animals had passed the beam of the ship (an original angle of 90° in Fig. 9).

The acoustic detection distance of dolphin schools was examined in comparison to sea surface temperature, thermocline intensity and thermocline depth for the STAR 00 survey. There was no significant relationship between the acoustic detection distance and sea surface temperature ($p = 0.072$, $n = 347$, Fig. 10). There was a significant increase in acoustic detection distances with an increase in thermocline strength ($p = 0.001$; $n = 347$, Fig. 11); however, this relationship was not significant for the thermocline depth ($p = 0.144$, $n = 347$, Fig. 12).

B. Towed Hydrophone Array: Sperm whales

Sperm whales were detected during all surveys, with large numbers detected during the SPLASH and HICEAS surveys (Table 4). There were a total of 481 detections of sperm whales for the combined visual and acoustic methods (Fig. 13). The majority of these detections (96%) were made exclusively by the acoustics team (Table 5). The acoustic detection distance of sperm whales ranged from 0.7 to 21 nmi, with a mean acoustic detection distance of 5.9 nmi (SD ± 4.2, Table 5). There were 211 sperm whale visual and/or acoustic detections within 3 nmi of the trackline; the visual observation team missed 39% of these sperm whales, while the acoustic detection team missed 8.5%.

C. Towed Hydrophone Array: Minke whales

Minke whales were detected during most surveys, with visual detections occurring primarily in the temperate study areas and acoustic detections occurring exclusively in the tropical study areas (Fig. 14). There were a total of 94 minke whale detections for the combined cruises, of which 85 (90%) were exclusive acoustic detections (Table 6). The acoustic detection distance of minke whales ranged from 0.5 to 8 nmi, with a mean acoustic detection distance of 3.9 nmi (SD ± 1.7, Table 7). There were 47 minke whale detections within 3 nmi of the trackline; the visual observation team missed 80% of these minke whales, and the acoustic detection team missed 19% (Table 6). None of the minke whales were detected by both the visual and acoustic teams.

D. Towed Hydrophone Array: Dolphins

There were a total of 1,527 acoustic detections of dolphin schools during the combined cruises; 779 (51%) were detected by both the acoustic team and the visual team, and 748 (49%) were exclusive acoustic detections (Table 8, Fig. 15). The proportion of dolphin schools missed by the acoustic team varied from a low of 7.7% for the STAR 06 survey, to a high of 29.7% for ORCAWALE (Fig. 15). The proportion of dolphin schools missed by the visual observation team ranged from a low of 0% for the SPLASH survey, to a high of 58.5% for HICEAS (Fig. 14). The overall mean acoustic detection distance for dolphin schools was 3.19 nmi (SD ± 2.0, Table 8). The detection distances of exclusive acoustic detections were consistently greater than those of combined visual/acoustic detections (Table 8). The mean acoustic detection distance for combined visual/acoustic dolphin schools was 2.34 nmi (SD ±1.74), while the mean acoustic detection distance for acoustic (only) dolphin schools was 4.08 (SD ± 1.98, Table 8).

All dolphin schools detected exclusively by the acoustics team (49% of acoustic detections) were considered “unidentified dolphins”, and information on these detections is limited (Fig. 16, 17). Information collected on visually detected dolphin schools includes species identity, estimated group size, and general behavioral information. This information was used to examine the vocal behavior of various dolphin species. Information on vocal behavior is discussed for each species, in order of decreasing vocal activity.

Pseudorca crassidens, the false killer whale, was detected only in the tropical waters of the Pacific Ocean (Fig. 18). There were a total of 19 visual detections of *P. crassidens* during the combined surveys, of which 100% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 2.93 nmi (SD ± 1.5), with a maximum detection distance of 6 nmi (Table 10). *P. crassidens* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). All acoustic detections of *P. crassidens* included whistles, and 94% of detections included echolocation clicks (Table 11). The average group size for groups of *P. crassidens* was 10.7 animals (Table 12).

Lagenorhynchus obscurus, the dusky dolphin, was encountered off the coast of Peru during the STAR surveys (Fig. 21.). There were a total of three visual detections of *L. obscurus* during the combined surveys, of which 100% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 0.98 nmi (SD ± 1.32), with a maximum detection distance of 2.5 nmi (Table 10). *L. obscurus* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). All acoustic detections of *L. obscurus* included echolocation clicks and burst pulses, and one detection included whistles (Table 11). The average group size for groups of *L. obscurus* was 280.2 animals (Table 12).

Lagenodelphis hosei, the Fraser's dolphin, was encountered in the tropical waters of the Pacific Ocean (Fig. 22). There were a total of two visual detections of *L. hosei* during the combined surveys, both of which produced vocalizations detected by the acoustics team (Table 9, Fig. 19). An acoustic detection distance of 2 nmi was determined for one of the two dolphin schools (Table 10). Whistles (only) were detected during these recordings (Fig. 20). The group sizes for *L. hosei* were 183 and 27 animals (Table 12).

Peponocephala electra, the melon-headed whale was detected in the tropical waters of the Pacific Ocean (Fig. 23). There was a single visual detection of *P. electra* during the combined surveys, which produced vocalizations detected by the acoustics team (Table 9, Fig. 19). Acoustic detection distances were not measured for this group. *P. electra* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). The group size for this single school of *P. electra* was 101 animals (Table 12).

Steno bredanensis, the rough-toothed dolphin, was encountered in the tropical waters of the Pacific Ocean (Fig. 24). There were a total of 31 visual detections of *S. bredanensis* during the combined surveys, of which 96.8% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 1.53 nmi (SD ± 1.19), with a maximum detection distance of 4.5 nmi (Table 10). *S. bredanensis* was found to produce whistles, echolocation clicks, and burst pulses (Table 11). Most (93%) acoustic detections of *S. bredanensis* included echolocation clicks and/or burst pulses, and 90% of detections included whistles (Fig. 20). The mean group size for vocal schools of *S. bredanensis* was 15.3 animals, which was larger (but not significantly: Mann-Whitney test, U= 8, p=0.434) than the mean group size of 7.3 for visual (only) dolphin schools (Table 12).

Delphinus delphis and *Delphinus capensis*, the short- and long-beaked common dolphins, were encountered throughout most of the eastern warm-temperate and tropical Pacific Ocean (Fig. 25). There were a total of 157 visual detections of the combined *Delphinus* spp. during the combined surveys, of which 87.3% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 2.22 nmi (SD ±1.6), with a maximum detection distance of 6 nmi (Table 10). *Delphinus spp.* were found to produce whistles, echolocation clicks, and burst pulses (Table 11). Nearly all (98.5%) acoustic detections of *Delphinus spp.* included whistles, and 68% of detections included echolocation clicks and/or burst pulses (Fig. 20). The mean group size for vocal schools of *Delphinus spp.* was 193.4 animals, which was significantly larger than the mean group size of 69.7 for visual (only) dolphin schools (Mann-Whitney test, U=774, p=0.006, Table 12).

Tursiops truncatus, the common bottlenose dolphin, was encountered throughout much of the temperate and tropical survey area south of central California (Fig. 26). There were a total of 75 visual detections of *T. truncatus* during the combined surveys, of which 82.7% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 1.79 nmi (SD ± 1.33), with a maximum detection distance of 6 nmi (Table 10). *T. truncatus* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). Nearly all (96.7%) of acoustic detections of *T. truncatus* included whistles, and 77% of detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *T. truncatus* was 78.1 animals, which was significantly larger than the mean group size of 10.1 for visual (only) dolphin schools (Mann-Whitney test, U=237.5, p=0.02, Table 12).

Stenella longirostris, the spinner dolphin, was encountered in the tropical waters of the Pacific Ocean (Fig. 27). There were a total of 46 visual detections of *S. longirostris* during the combined surveys, of which 80.4% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 2.61 nmi (SD ± 1.55), with a maximum detection distance of 6 nmi (Table 10). *S. longirostris* was found to produce whistles, echolocation clicks, and burst pulses (Table 11). All acoustic detections of *S. longirostris* included whistles, and 37.8% of detections included echolocation clicks and/or burst pulses (Fig. 20). The mean group size for vocal schools of *S. longirostris* was 116.4 animals, which was significantly larger than the mean group size of 38.1 for visual (only) dolphin schools (Mann-Whitney test, U=71, p=0.008, Table 12).

Stenella coeruleoalba, the striped dolphin, was encountered throughout most of the warm-temperate and tropical Pacific Ocean (Fig. 28). There were a total of 192 visual detections of *S. coeruleoalba* during the combined surveys, of which 79.2% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 2.63 nmi (SD ± 1.84), with a maximum detection distance of 10 nmi (Table 10). *S. coeruleoalba* were found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). All acoustic detections of *S. coeruleoalba* included whistles, and 25% of detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *S. coeruleoalba* was 60.5 animals, which was significantly larger than the mean group size of 48.3 for visual (only) dolphin schools (Mann-Whitney test, U=2175, p=0.047, Table 12).

Stenella attenuata, the pantropical spotted dolphin, was encountered in the tropical waters of the Pacific Ocean (Fig. 29). There were a total of 105 visual detections of *S. attenuata* during the combined surveys, of which 77.1% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 1.85 nmi (SD ± 1.53), with a maximum detection distance of 6 nmi (Table 10). *S. attenuata* was found to produce whistles, echolocation clicks, and burst pulses (Table 11). Nearly all (97.5%) of acoustic detections of *S. attenuata* included whistles, and 58% of detections included echolocation clicks and/or burst pulses (Fig. 20). The mean group size for vocal schools of *S. attenuata* was 93.2 animals, which was significantly larger than the mean group size of 41 for visual (only) dolphin schools (Mann-Whitney test, U=293.5, p=0.011, Table 12).

Globicephala macrorhynchus and *Globicephala melas*, the pilot whales, were encountered in the tropical waters of the Pacific Ocean and in the southern temperate study areas (Fig. 30). There were a total of 78 visual detections of the combined *Globicephala* spp. during the combined surveys, of which 73.1% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 2.56 nmi (SD ± 1.77), with a maximum detection distance of 8.5 nmi (Table 10). *Globicephala* spp. were found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). Most (92.9%) acoustic detections of *Globicephala* spp. included whistles, and 78.9% of detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *Globicephala* spp. was 21 animals, which was larger (but not significantly) than the mean group size of 14.2 for visual (only) groups (Mann-Whitney test, U=426.5, p=0.065, Table 12).

Grampus griseus, the Risso's dolphin, was encountered throughout much of the temperate and tropical study areas (Fig. 31). There were a total of 62 visual detections of *G. griseus* during the combined surveys, of which 45.2% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 0.95 nmi (SD ± 0.7), with a maximum detection distance of 2.3 nmi (Table 10). *G. griseus* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). Less than half (44.8%) of acoustic detections of *G. griseus* included whistles, and most (96.5%) of detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *G. griseus* was 21.8 animals, which was significantly larger than the mean group size of 9.9 for visual (only) dolphin schools (Mann-Whitney test, U=284.5, p=0.015, Table 12).

Orcinus orca, the killer whale, was encountered throughout the temperate and tropical Pacific Ocean (Fig. 32). There were a total of 52 visual detections of *O. orca* during the combined surveys, of which 44.2% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 0.73 nmi (SD ± 0.71), with a maximum detection distance of 2.3 nmi (Table 10). *O. orca* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). Less than half (47.8%) of acoustic detections of *O. orca* included whistles, and all detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *O. orca* was 11.9 animals, which was significantly larger than the mean group size of 5.6 for visual (only) groups (Mann-Whitney test, U=168.5, p=0.011, Table 12).

Lagenorhynchus obliquidens, the Pacific white-sided dolphin, was encountered off the west coast of the United States and Canada (Fig. 33). There were a total of ten visual detections of *L. obliquidens* during the combined surveys, of which 40% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 0.71 nmi (SD ± 0.87), with a maximum detection distance of 2 nmi (Table 10). *L. obliquidens* was found to produce echolocation clicks and burst pulses (Fig. 20). Whistles were not detected in any of the four acoustic detections of *L. obliquidens* (Table 11). The mean group size for vocal schools of *L. obliquidens* was 19.6 animals, which was larger (but not significantly) than the mean group size of 11.5 for visual (only) dolphin schools (Mann-Whitney test, U=8.5, p=0.713, Table 12).

Lissodelphis borealis, the northern right-whale dolphin, was encountered off the west coast of the United States and Canada (Fig. 34). There were a total of 20 visual detections of *L. borealis* during the combined surveys, of which 35% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 0.58 nmi (SD ± 0.67), with a maximum detection distance of 1.5 nmi (Table 10). *L. borealis* was found to produce echolocation clicks and burst pulses (Fig. 20). Whistles were not detected in any of the seven acoustic detections of *L. borealis* (Table 11). The mean group size for vocal schools of *L. borealis* was 27.3 animals, which was significantly larger than the mean group size of 7.8 for visual (only) dolphin schools (Mann-Whitney test, U=16.5, p=0.021, Table 12).

Feresa attenuata, the pygmy killer whale, was encountered in the tropical waters of the Pacific Ocean (Fig. 35). There were a total of six visual detections of *F. attenuata* during the combined surveys, of which 33.3% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 1.0 nmi (SD ± 1.0), with a maximum detection distance of 1.75 nmi (Table 10). *F. attenuata* was found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). Both acoustic detections of *F. attenuata* included all three vocalization types (Table 11). The mean group size for vocal schools of *F. attenuata* was 24 animals, which was larger (but not significantly) than the mean group size of 7.9 for visual (only) groups (Mann-Whitney test, U=0, p=0.064, Table 12).

Berardius bairdii, the Baird's beaked whale, was encountered in the temperate waters of the Pacific Ocean (Fig. 36). There were a total of seven visual detections of *B. bairdii* during the combined surveys, of which 28.6% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 1.1 nmi (SD ± 0.84), with a maximum detection distance of 1.7 nmi (Table 10). *B. bairdii* was found to produce echolocation clicks and burst pulses (Fig. 20). Whistles were not detected during either of the two acoustic detections *B. bairdii* (Table 11). The mean group size for vocal schools of *B. bairdii* was 16 animals, which was larger (but not significantly) than the mean group size of 7.6 for visual (only) groups (Mann-Whitney test, U=2, p=0.245, Table 12).

Mixed species groups of *Stenella attenuata* and *S. longirostris* were included as a separate category due to the large number of schools encountered and the importance of these dolphin schools in relation to the tuna purse-seining industry. Mixed schools of *S. attenuata* and *S. longirostris* were encountered in the tropical waters of the Pacific Ocean (Fig. 37). There were a total of 76 visual detections of *S. attenuata/S. longirostris* during the combined surveys, of which 94.7% produced vocalizations detected by the acoustics team (Table 9, Fig. 19). The mean acoustic detection distance was 3.02 nmi (SD ± 1.55), with a maximum detection distance of 6.4 nmi (Table 10). *S. attenuata/S. longirostris* were found to produce whistles, echolocation clicks, and burst pulses (Fig. 20). All acoustic detections of *S. attenuata/S. longirostris* included whistles, and 25.1% of detections included echolocation clicks and/or burst pulses (Table 11). The mean group size for vocal schools of *S. attenuata/S. longirostris* was 347.9 animals, which was larger (but not significantly) than the mean group size of 131.5 for visual (only) dolphin schools (Mann-Whitney test, U=76.5, p=0.128, Table 12).

For the combined single-species dolphin schools, 77.9% were vocal (Table 12). Group size of vocal dolphin schools was significantly greater than group size for non-vocal dolphin schools (Mann-Whitney test, U=55990, $p<0.0001$, Table 12). There was also a significant increase in the acoustic detection distance with an increase in group size ($p < 0.0001$, n=727, Fig. 38).

E. Sonobuoy Detections

Opportunistic deployments of sonobuoys were made during each survey, for a total of 236 sonobuoy deployments (Table 13). Sonobuoys were deployed on thirteen species including: blue whale (*Balaenoptera musculus*), Bryde's whale (*B. edeni*), killer whale (*Orcinus orca*), right whale (*Eubalaena japonica*), fin whale (*B. physalus*), sei whale (*B. borealis*), minke whale (*B. acutorostrata*), false killer whale (*Pseudorca crassidens*), short-finned pilot whale (*Globicephala macrorhynchus*), bottlenose dolphin (*Tursiops truncatus*), Fraser's dolphin (*Lagenodelphis hosei*), and sperm whales (*Physeter macrocephalus*) (Fig. 39).

Most recordings have not been reviewed or analyzed; some recordings may not contain vocalizations from the target species, and some recordings may contain vocalizations from species other than the target species. Vocalizations of select recordings of *B. edeni*, *B. borealis*, *E. japonica*, and *L. hosei* were analyzed to provide descriptive information on the vocal repertoire of these species (Oleson et al. 2003, Rankin and Barlow 2007b, Oswald et al. 2007a, Munger 2008,).

F. Hull-mounted Hydrophone Detections

The hull-mounted hydrophone fitted to the bow of the *Jordan* provided opportunistic recordings of bow-riding dolphins and close approaches to sperm whales (*Physeter macrocephalus*), Blainsville's beaked whales (*Mesoplodon densirostris*), common minke whales (*Balaenoptera acutorostrata*) and killer whales (*O. orca*). Most of these recordings have not been reviewed or analyzed. Vocalizations from *B. acutorostrata* and *M. densirostris* were analyzed to provide descriptive information on the vocal repertoire of these species (Rankin and Barlow 2005a, Rankin and Barlow 2007a).

IV. DISCUSSION

The future role of acoustics in line-transect surveys will depend on the ability to consistently detect cetacean schools and provide insight into cetaceans missed by the visual team. Detection can be categorized in terms of a variant on a 2x2 matrix containing four possible scenarios: (1) both acoustic and visual detection of cetaceans, (2) visual detection only, (3) acoustic detection only, and (4) animals that go undetected (Fig. 40). The information gathered from exclusive acoustic detections will provide information about the cetaceans missed by the primary visual observation team. The data provided by sighted marine mammals can be used to identify situations in which the acoustics team is likely to miss the detection of cetaceans during line-transect surveys.

There is a fundamental difference in the methods used for visually sighted dolphin schools and exclusive acoustic dolphin schools. For non-sighted schools, acoustic effort remains in 'passing mode', where the course of the vessel is not altered in response to the detection. We are unable to confirm species identity on these detections, so information regarding these exclusive acoustic detections is limited. Sighted schools, on the other hand, are typically pursued in 'closing mode'. During closing mode, the vessel is oriented towards the animals, typically keeping the animals within 20 degrees of the bow of the ship. This has significant implications on the effectiveness of acoustic methods. Dolphin schools directly in front of the ship, including animals directly on the trackline, were less likely to be detected by the acoustic team (Fig. 9). Localization of a sound source, which is critical for matching of independent visual and acoustic detections, has been determined to be imprecise within <15 degrees of the ships' heading (Rankin et al. 2008a). In these cases, propeller cavitation and the hull of the ship may act as physical barriers to sounds directly ahead of the ship. Another complicating factor is that several studies have shown that animals respond to survey vessels, which may complicate our ability to understand the acoustic behavior of these animals (Au and Perryman 1982, Hewitt 1985).

Despite these problems, the large dataset collected during these surveys allows us to examine some of the physical capabilities a towed hydrophone array may have for detection of cetacean vocalizations. We will examine the vocal behavior of animals in this study area to better understand the role of acoustics during shipboard surveys. We also discuss two alternative, but effective, methods for detection cetacean vocalizations using Navy surplus sonobuoys and a bow-mounted hydrophone.

A. Physical Capabilities of Towed Hydrophone Array

Several physical factors related to sound propagation in the ocean were examined for their potential impact on the acoustic detection of cetaceans. An increase in sea state leads to an increase in background noise (Medwin and Clay 1998), and it is suspected that this may mask cetacean vocalizations. Contrary to these expectations, we observed no significant difference in detection distances of dolphin schools based on sea state for the combined surveys (Table 3, Fig. 6). When we examined this relationship for each survey separately, we did find a significant *increase* in detection distance with an increase in sea state for ORCAWALE and STAR 03 (Fig. 7). Given that sea state adversely affects the visual observation team (Barlow et al. 2001), the general lack of sea-state effect on acoustic detection distances make them even more valuable. The acoustic component of cetacean population surveys can provide information about dolphin schools missed by the primary visual team in increased sea states, as well as provide estimates of cetacean occurrence and distribution in areas with poor weather conditions.

Location for most vocalizing dolphins is likely to be in relatively shallow waters, above the thermocline. Sounds produced in these surface waters are typically refracted upwards by the thermocline, which creates a physical impedance boundary for propagation paths of most moderate- to high-frequency sounds (Medwin and Clay 1998). The depth of the array was typically less than 6 m at a towing speed of 10 kts. This depth is well above the thermocline depth and within the likely range of dolphin sound production. Sea surface temperature and thermocline depth did not impact the detection distance of dolphin schools (Fig. 10, 12). There was a positive relationship between the thermocline intensity and the detection distance, suggesting that a large thermocline gradient increased the propagation of dolphin vocalizations by an increase in reflection and refraction (Fig. 11). Given that most groups of deep-diving sperm whales are detected using acoustic methods, it is unlikely that their detection range is greatly influenced by thermocline depth.

Physical oceanographic features such as surface ducts may influence the ability of to detect dolphins using passive acoustic methods. Indeed, results obtained from this dataset have demonstrated that geographic differences exist in the detection rates of dolphin vocalizations (Rankin et al. 2008b). However, a preliminary examination of these features using sound propagation modeling found no significant impact on our detection of delphinid vocalizations (Oswald et al. 2004b). While there are likely conditions in which oceanographic features negatively impact sound propagation to a degree that affects the detection of cetacean vocalizations using a towed hydrophone array, our cursory examination suggests little or no effect within the 3 nmi effort range used during SWFSC line-transect surveys.

B. Towed Hydrophone Array: Sperm whales

Barlow and Taylor (2005) recommended that line-transect surveys for sperm whales should include detection by both visual and acoustic methods. Nearly all sperm whales were detected by the acoustics team, and many of these groups were missed by the visual team (Table 4). Sperm whales can be easily identified to species, and estimates of group size can be made for small and moderate group sizes based on their vocalizations. Information gathered on sperm whale detections during these cruises has been collected in a way to allow for independent population estimates using acoustic detections. Protocols for future line-transect cruises will incorporate acoustic detections into normal operations (Barlow and Rankin 2004). Additionally, passive acoustics allowed for tracking of diving animals and estimation of surfacing times during these surveys, which facilitated maneuvering of the vessel to allow for more effective photographic and biopsy sampling of the whales during their relatively brief surface intervals.

C. Towed Hydrophone Array: Minke whale

Prior to our HICEAS 2002 survey, common minke whales were considered infrequent ‘visitors’ to the subtropical and tropical waters of the Pacific Ocean. During this survey, we used our passive towed hydrophone array to localize the mysterious “boing” sound, and assist the visual observation team in the detection and identification of this sound source: the minke whale (Rankin and Barlow 2005a). Due to this simple match of a sound to a whale, we have been able to vastly improve our understanding of the population structure of minke whales in the Pacific Ocean. All acoustic detections of minke whales occurred in tropical and subtropical waters, while all visual detections occurred in the temperate study areas (Fig. 14). Visual detection of this species is difficult due to its dive and surface behavior, and our results suggest that winter shipboard surveys of minke whales *must* include passive acoustic detection.

D. Towed Hydrophone Array: Dolphins

The total numbers of acoustic detections of dolphin schools were nearly evenly divided between sighted and non-sighted detections; however, a large number of these detections were beyond the range of the visual detection team (Table 8). Unfortunately, there is little or no information on the identity, group size, and behavior of dolphin schools missed by the visual observation team. On a few occasions, the acoustics team was allowed to lead the pursuit of acoustic detections that were missed by the visual team. When these were successful, the visual team was able to identify the species and estimate group sizes. These acoustic “chases” included a wide range of species: false killer whale (n = 5), striped dolphin (n = 5), rough-toothed dolphin (n = 5), short-finned pilot whale (n = 4), common bottlenose dolphin (n = 1), and spotted dolphin (n = 1). Tentative acoustic identifications by an experienced acoustician (S. Rankin) suggest that false killer whales and rough-toothed dolphins are two species that frequently escape detection by the visual team. In time, improved acoustic identification of these exclusive acoustic detections will allow us to examine the species that the visual observation team often misses during shipboard surveys.

Greater than two-thirds of sighted dolphin schools were detected by the acoustics team; however, acoustic detection rates varied by species (Table 9). Examination of the acoustic behavior of these sighted dolphin schools has suggested that dolphin schools generally can be grouped into two types (Rankin et al. 2008b). The first type is typically found in larger group sizes in tropical and subtropical waters, is detected at greater ranges, commonly produce whistles, and is easily detected using the passive acoustics methods in this study. Examples of species in this group include *S. coeruleoalba*, *S. longirostris*, and *S. attenuata*. The second type is typically found in smaller group sizes in temperate waters, is detected at shorter ranges, does not commonly produce whistles, and is not easily detected using these methods (Rankin et al. 2008b). This second type includes species such as *L. borealis*, *L. obliquidens*, and *B. bairdii*. These general patterns have important implications for the use of passive acoustics for population and mitigation purposes.

There was a strong relationship between group size and vocal activity (detection of vocalizations) of dolphins. Dolphin schools detected using these acoustic methods were consistently larger than non-vocal dolphin schools for each species, and for the combined detections (Table 12). This does *not* suggest that the vocal rate, or the number of calls per unit of time, was related to group size. In fact, anecdotal observations suggest that this is not the case for most species (S. Rankin, pers. comm.). The positive relationship between the acoustic detection distance and group size is likely influenced by the large group sizes of whistling dolphins, which can be heard at great distances, compared to the smaller group size that is characteristic of species that only click, which have a limited detection range (Fig. 38, Rankin et al. 2008b).

Overall, 23.7% of dolphin schools went undetected by the acoustics. Again, the acoustic detection rate was not equal for all species. For whistling species (such as *Stenella longirostris, S. attenuata, and Tursiops truncatus*), group size had the greatest effect on acoustic detection rates, with smaller schools most likely being undetected by the acoustics team (Rankin and Barlow 2005b). The methods presented here were particularly poor at detecting species that appear primarily (or entirely) to produce clicks or burst-pulses, such as *Lissodelphis borealis* (Rankin et al. 2008). In fact, there were no known acoustic detections of *Phocoenidae*, *Kogiidae,* and *Ziphiidae* using these towed array methods. There are many reasons to explain the poor detection rates of these species, including: the narrow beam-pattern of echolocation clicks leads to decreased detection range, the peak frequencies and bandwidth of many of these click sounds are above the frequency response range of our system (e.g. frequencies are too high), and high-frequency clicks have greater transmission loss so are detected at shorter ranges than whistles.

In summary, we have found a strong relationship between group size and vocal behavior. Also, dolphin schools that primarily produce clicks are found in smaller group sizes than dolphins that produce whistles (Rankin et al. 2008, Oswald et al. *in press*).

While it is possible that these species have a lower vocal rate (and therefore a decreased acoustic detection rate), we are unable to test this with our data. In fact, we wish to clarify that the low detection of these species in our study may be a significant bias of our study methods, and does *not* imply that they vocalize at a lower rate.

Overall, our results suggest that passive acoustic detection methods can play an important role in shipboard population and mitigation and monitoring surveys of tropical and sub-tropical dolphins. Passive acoustic surveys will require information on the vocal behaviors and rates of each species, acoustic detection of these vocalizations, species identification based on vocalizations, and group size information. The data presented here will provide valuable baseline information on both the vocal behavior and acoustic detection of many cetacean species in the eastern and central Pacific Ocean.

Data on dolphin vocalizations from these surveys has been used to create a whistle-based acoustic species classification program that allows for real-time species identification that has been used successfully in real-time in the field (ROCCA, Oswald et al. 2007b). The high correct classification scores provided by ROCCA for acoustic species identification of *P. crassidens* (80%, Oswald et al. 2007b) allowed for incorporation of passive acoustics during the PICEAS cruise. The addition of passive acoustic methods to line-transect surveys more than doubled the overall detections of *P. crassidens* using visual methods alone (Barlow and Rankin 2007). In addition, acoustic detection provided a means of estimating the fraction of schools missed by the visual observers. Future improvement on acoustic species identification algorithms for other species will allow passive acoustics to play an increasingly important role in cetacean surveys. Independent estimation of abundance using acoustic methods will require a means of determining group size, which has not yet been accomplished. Nonetheless, the results from these surveys have demonstrated that passive acoustics detection using a towed hydrophone array can provide considerable contributions to ship-based cetacean surveys.

E. Sonobuoy Detections

These SWFSC cetacean surveys have provided numerous opportunities to obtain sonobuoy recordings of baleen whale and dolphin species in remote regions of the Pacific Ocean. Only a fraction of the recordings have been analyzed; this subset of data has resulted in characterizations of calls from several species including *B. borealis* (Rankin and Barlow 2007b), *B. edeni* (Oleson et al. 2003), *L. hosei* (Oswald et al. 2007a), *B. musculus* (Rankin et al. 2006), and *E. japonica* (Munger 2008). Analysis of the remainder of these recordings will provide additional information on the vocal repertoire of these species. For example, there are at least three recordings of a previously undescribed pulsed vocalization recorded in the presence of *B. edeni* that have yet to be analyzed.

In addition to providing a means of recording low frequency sounds, some types of sonobuoys can provide bearing information to the sound source (e.g. type 53D, 77B). During the SPLASH survey, sonobuoys were used successfully to detect, localize, and approach groups of the endangered *E. japonica* in the Bering Sea (Wade et al. 2006). While these methods are not typically used during most surveys due to limited personnel and funding; they can provide a means of detecting, localizing and tracking certain species over long ranges, at night, and in poor weather conditions where visual observations may be of little use.

F. Hull-mounted Hydrophone Detections

The hull-mounted hydrophones provided a simple means of obtaining recordings of bow-riding dolphins, and other species in close proximity to the bow of the ship. At full speed, there was increased noise from bow waves, and from the anchor hitting the hull of the ship. Nonetheless, we now have numerous high-quality recordings of many species recorded using the bow hydrophone. Recordings from the bow hydrophone played an important role in analysis of the initial *B. acutorostrata* 'boing' detection (Rankin and Barlow 2005a). Likewise, opportunistic recordings of a group of *M. densirostris* which dove 100 m off the bow provided a previously undescribed mid-frequency vocalization produced by these animals (Rankin and Barlow 2007a). These are the only two hull-hydrophone recordings that have been analyzed. This hydrophone can provide some information on vocalizing animals ahead of the ship that we are unable to detect using the towed hydrophone array. While this hydrophone can provide high-quality opportunistic recordings, it appears to have a low range of detection at survey speeds. At slow speeds, the hull hydrophones may be useful for acoustic detections and mitigation using passive acoustic methods.

V. CONCLUSION

The basic goals of this study were to determine the potential role that passive acoustic detection methods may play in future line-transect cetacean surveys, and to obtain additional information regarding the acoustic detection of sperm whales. The preliminary results presented here, as well as the numerous publications, reports, and presentations given in the Appendix, indicate the great effectiveness of acoustic methods for ship-board surveys. There are still innumerable questions regarding the variability in the acoustic detection of cetaceans, but there is no doubt that ship-based surveys of cetaceans greatly benefit from the use of passive acoustics. This is especially true in tropical waters, where highly vocal whistling dolphin species are common.. Sufficient information on the acoustic detection of sperm whales, *P. macrocephalus*, has been obtained for passive acoustics to be incorporated into the standard protocols for line-transect surveys run by SWFSC. Results from these surveys suggest that the passive acoustic detection of minke whales, *B. acutorostrata*, may be essential for estimating population size in tropical and sub-tropical waters.

Patterns in passive acoustic detection of delphinids are more complicated. Passive acoustic monitoring *must* include precise localization to estimate the position of vocalizing groups. There were many occasions in which acoustic localization of vocalizations indicated that the sounds were produced from a different group than those sighted by the visual observers. Likewise, localization allowed for detection of additional subgroups within a sighting that were not detected by the visual observation team.

Passive acoustic monitoring should allow for detection of high frequency vocalizations, especially in temperate waters.

There are two critical limitations in this dataset. First, the methods for monitoring were limited to frequencies below 24 kHz. In many cases recordings of higher frequencies were made, but these higher frequencies were not included in this analysis.

This limitation severely affects our ability to detect sounds from delphinids in temperate study areas, and we have no ability to detect sounds from any *Phoceonids* or from *Kogia*. We are currently modifying our equipment and methods to address this limitation.

The second limitation of this dataset is the lack of detailed information on the exclusive acoustic detections. For most of these detections, we have been able to determine the location, time the animals passed the beam of the ship, beam distance, acoustic detection distance, and call types detected. With the exception of the few acoustic detections that were "chased", we have no information about species identity, group size, or behavioral information. These exclusive acoustic detections provide valuable information about the detections missed by the visual observation team. In order for acoustics to be used as a primary detection method on future surveys, non-sighted acoustic detections within the visual effort range (3 nmi) must be routinely approached and identified as is done for visual detections. There are several logistic impediments to implementing this protocol. Acoustic chases are typically longer than visual chases. In high-density areas, acoustic detections are often so common that search time would be impeded. In many cases, if groups cease vocalizing, acoustic chases end before the animals are seen.

Passive acoustic detection of cetaceans has proven effective for assisting the visual team during high sea states, rain, and fog. Current work on real-time species identification of delphinids will allow for independent acoustic monitoring during times when visual observation is compromised. The data presented in this report provide a baseline for the understanding of the acoustic detection of sounds produced by cetaceans as well as the vocal behavior of many cetacean species. This, combined with more accurate acoustic species identification, will provide the necessary information for passive acoustics using a towed hydrophone array to be incorporated into line-transect population surveys, as has been done for sperm whales.

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VIII. TABLES

Table 1. Acoustics personnel and affiliation for all cruises. SIO = Scripps Institution of Oceanography, CofC = College of Charleston, SAIC = Science Applications International Corporation, SDSU = San Diego State University, OSU = Oregon State University, and SEFSC = Southeast Fisheries Science Center.

Cruise	Ship	Leg	Acoustics Personnel	Affiliation
STAR 00	*McArthur*	1	Shannon Rankin, Jay Barlow, Julie Oswald	SWFSC, SIO
STAR 00	*McArthur*	2	Shannon Rankin, Megan Furguson	SWFSC, SIO
STAR 00	*McArthur*	3	Shannon Rankin, Ann Chen	SWFSC, CofC
STAR 00	*McArthur*	4	Shannon Rankin, Tom Norris	SWFSC, SAIC
STAR 00	*McArthur*	5	Shannon Rankin, Xenia Brobeil	SWFSC, SDSU
ORCAWALE	*Jordan*	1	Shannon Rankin, Megan Furguson	SWFSC, SIO
ORCAWALE	*Jordan*	2	Shannon Rankin, Julie Oswald	SWFSC, SIO
ORCAWALE	*Jordan*	3	Shannon Rankin, Julie Oswald	SWFSC, SIO
ORCAWALE	*Jordan*	4	Shannon Rankin, Tony Martinez	SWFSC, SEFSC
ORCAWALE	*Jordan*	5	Shannon Rankin, Jessica Burtenshaw	SWFSC, SIO
ORCAWALE	*McArthur*	6	Shannon Rankin	SWFSC
HICEAS	*McArthur*	1	Shannon Rankin, Alison Walker	SWFSC
HICEAS	*McArthur*	2	Shannon Rankin, Julie Oswald	SWFSC, SIO
HICEAS	*McArthur*	3	Shannon Rankin, Tom Norris	SWFSC, SAIC
HICEAS	*McArthur*	4	Shannon Rankin, Jenna Borberg	SWFSC
HICEAS	*McArthur*	5	Shannon Rankin, Tony Martinez	SWFSC, SEFSC
HICEAS	*McArthur*	6	Shannon Rankin, Katie Cramer	SWFSC
STAR 03	*McArthur II*	3	Shannon Rankin, Megan Furguson	SWFSC, SIO
STAR 03	*McArthur II*	4	Shannon Rankin, Jenna Borberg	SWFSC
STAR 03	*McArthur II*	5	Julie Oswald, Carolina Bonin	SIO, SWFSC
SPLASH	*McArthur II*	1	Shannon Rankin, Julie Oswald	SWFSC, SIO
SPLASH	*McArthur II*	2	Shannon Rankin, Kate Stafford	SWFSC, PMEL
SPLASH	*McArthur II*	3	Shannon Rankin, Liz Zele, Lisa Munger	SWFSC, SIO
SPLASH	*McArthur II*	4	Shannon Rankin, Julie Oswald	SWFSC, SIO
PICEAS	*McArthur II*	1	Shannon Rankin, Julie Oswald	SWFSC, SIO
PICEAS	*McArthur II*	2	Shannon Rankin, Julie Oswald	SWFSC, SIO
PICEAS	*McArthur II*	3	Shannon Rankin, Sara Heimlich	SWFSC, OSU
PICEAS	*McArthur II*	4	Shannon Rankin, Jen Pettis	SWFSC
STAR 06	*McArthur II*	1	Shannon Rankin, Liz Zele	SWFSC
STAR 06	*McArthur II*	2	Shannon Rankin, Liz Zele	SWFSC
STAR 06	*McArthur II*	3	Shannon Rankin, Liz Zele	SWFSC
STAR 06	*McArthur II*	4	Shannon Rankin, Liz Zele	SWFSC

Table 2. Hydrophone array characteristics and dates used during SWFSC research cruises. Hydrophones with a "*" included a single high-frequency hydrophone with a flat frequency range from 1 kHz to 150 kHz (± 2 dB at -166 dB *re* 1 V/mPa) in addition to the other elements listed. The 'SW Norris' and 'SE Norris' arrays were built by Don Norris of Sonatech, Inc. Due to a design problem, only four of the five hydrophone elements on the SW Norris and SE Norris arrays were operational (shown in parentheses).

Cruise	Array Name	Elements	Array Frequency Response	Dates Used
STAR 00	SW Norris	5 (4)	2 - 45 kHz ± 4 dB at -132 dB re 1 V/mPa	7/30-8/06, 8/09-8/21, 8/24, 8/31-9/03
STAR 00	high frequency	3	2 - 120 kHz ± 3 dB at -164 dB re 1 V/mPa	8/07-8/09, 8/22-8/23; 10/06-10/19
STAR 00	SE Norris	5 (4)	2 - 45 kHz ± 4 dB at -132 dB re 1 V/mPa	10/20-12/09
ORCAWALE	SW Norris	5 (4)	2 - 45 kHz ± 4 dB at -132 dB re 1 V/mPa	8/04; 9/03, 9/10-10/19, 10/24-12/08
ORCAWALE	high frequency	3	2 - 120 kHz ± 3 dB at -164 dB re 1 V/mPa	7/30-8/02, 8/05-9/02, 9/04-9/09
ORCAWALE	SE Norris	5 (4)	2 - 45 kHz ± 4 dB at -132 dB re 1 V/mPa	10/20-10/23
HICEAS	SWFSC	3	500 Hz - 30 kHz ± 5 dB at -155 dB re 1 V/mPa	all
STAR 03	SWFSC	3	500 Hz - 30 kHz ± 5 dB at -155 dB re 1 V/mPa	all
SPLASH	SWFSC	4*	500 Hz - 30 kHz ± 5 dB at -155 dB re 1 V/mPa	all
PICEAS	SWFSC	2-5*	500 Hz - 40 kHz ± 5 dB at -150 dB *re* 1 V/mPa	all
STAR 06	SWFSC	2-4*	500 Hz - 40 kHz ± 5 dB at -150 dB *re* 1 V/mPa	all

Table 3. Mean acoustic detection distances of dolphin schools stratified by Beaufort sea state for each survey. Distance is given in nautical miles (nmi). Overall mean acoustic detection distance for all detections on each cruise is also given. Standard deviations are shown in parenthesis. Beaufort 0 and 1 were combined due to small sample size.

	Sample Size	Overall	Beaufort Sea State				
			0-1	2	3	4	5+
STAR 00	362	3.5 (1.8)	3.7 (1.5)	3.5 (1.6)	3.5 (1.9)	3.1 (1.8)	3.9 (1.9)
ORCAWALE	111	2.1 (1.7)	1.1 (1.2)	0.4 (0.2)	1.9 (1.6)	2.4 (1.9)	2.5 (1.5)
HICEAS	205	4.2 (2.6)	2.7 (2.5)	5.6 (2.6)	4.6 (2.3)	4.0 (2.6)	4.0 (2.5)
STAR 03	182	2.1 (1.7)	0.8 (0.9)	1.7 (1.5)	1.7 (1.6)	2.5 (1.9)	2.4 (1.8)
SPLASH	21	0.6 (0.6)	1.1 (0.8)	0.5 (0.3)	1.6 (0.6)	0.4 (0.6)	0.5 (0.7)
PICEAS	121	2.5 (1.5)	0.6 (0.8)	2.0 (1.5)	2.6 (1.7)	2.8 (1.5)	2.3 (1.2)
STAR 06	499	3.4 (1.8)	3.3 (1.9)	3.5 (2.2)	3.6 (1.9)	3.3 (1.9)	3.2 (1.6)
Overall	1501	3.1 (2.0)	2.6 (2.0)	3.0 (2.2)	3.2 (2.0)	3.2 (2.0)	3.2 (1.9)

Table 4. Number and percentage of sperm whales detected by acoustic methods, visual methods, and both methods for each survey. For acoustic methods, the number of detections within 3 nmi of the ship is given in parentheses.

	Acoustic		Visual		Both		
Cruise	n	%	n	%	n	%	Total
STAR 00	23 (5)	76% (10%)	0	0%	7	23%	30
ORCAWALE	24 (9)	72% (27%)	2	6%	7	21%	33
HICEAS	109 (16)	73% (11%)	8	5%	31	21%	148
STAR 03	16(2)	69% (9%)	0	0%	7	30%	23
SPLASH	127 (39)	75% (23%)	4	2%	37	22%	168
PICEAS	27 (2)	71 (5%)	1	3%	10	26%	38
STAR 06	28 (11)	68 (27%)	3	7%	10	24%	41
Total	354 (84)	73% (17%)	18	4%	109	23%	481

Table 5. Summary statistics for acoustic detection distances of sperm whales for each survey, and for the total of the combined surveys.

Cruise	Sample Size	Detection Distance (nmi)		
		Mean	St. Deviation	Range
STAR 00	19	6.5	3.2	2.3 - 15
ORCAWALE	21	6.4	4.6	1.4 - 19
HICEAS	78	8.4	4.6	1.7 - 20
STAR 03	12	4.2	2.3	1 - 8
SPLASH	72	3.3	2	0.7 - 10
PICEAS	10	8.8	5.3	3 - 21
STAR 06	19	4.3	3	0.8 - 12.7
Combined	231	5.9	4.2	0.7 - 21

Table 6. Number of minke whales detected using acoustic methods, visual methods, and both methods for each survey. For acoustic methods, the number of detections within 3 nmi of the ship is given in parentheses.

Cruise	Acoustic	Visual	Both	Total
STAR 00	0	0	0	0
ORCAWALE	0	3	0	3
HICEAS	47(25)	0	0	47
STAR 03	27(11)	0	0	27
SPLASH	0	6	0	6
PICEAS	2(0)	0	0	2
STAR 06	9(2)	0	0	9
Total	85(38)	9	0	94

Table 7. Summary statistics for the acoustic detection distances of minke whales for each survey, and for the total of the combined surveys.

Cruise	Sample Size	Detection Distance (nmi)		
		Mean	St. Deviation	Range
STAR 00	0	-	-	-
ORCAWALE	0	-	-	-
HICEAS	35	3.7	1.8	0.5 - 8
STAR 03	16	4.3	1.5	1.7 - 7
SPLASH	0	-	-	-
PICEAS	1	6.3	-	-
STAR 06	3	3.9	2.6	2 - 7
Combined	55	3.9	1.7	0.5 - 8

Table 8. Acoustic detection distances for dolphin schools detected (1) both visually and acoustically, and (2) by the acoustics team (only) for each research survey.

			Detection Distance (nmi)		
Cruise	Detection Type	Sample Size	Mean	St. Deviation	Range
STAR 00	Visual/Acoustic	187	2.74	1.66	0.1 - 7
	Acoustic (only)	184	4.35	1.67	1 - 9
ORCAWALE	Visual/Acoustic	71	1.35	1.37	0.1 - 6
	Acoustic (only)	40	3.43	1.65	0.5 - 8
HICEAS	Visual/Acoustic	54	2.48	2.15	0.05 - 10
	Acoustic (only)	151	4.87	2.43	0.3 - 12
STAR 03	Visual/Acoustic	170	2.06	1.71	0.01 - 8
	Acoustic (only)	13	3.22	1.94	1 - 7
SPLASH	Visual/Acoustic	20	0.64	0.65	0.05 - 2.1
	Acoustic (only)	1	1.50	-	-
PICEAS	Visual/Acoustic	69	2.00	1.34	0.01 - 5
	Acoustic (only)	56	3.13	1.49	0.6 - 7
STAR06	Visual/Acoustic	208	2.78	1.74	0.01 - 9
	Acoustic (only)	302	3.83	1.87	0.3 - 10
Combined	Visual/Acoustic	779	2.34	1.74	0.01 - 10
	Acoustic (only)	748	4.08	1.98	0.3 - 12
	Overall	1527	3.19	2.05	0.01 - 12

Table 9. Number of sightings and the presence of vocalizations for each species/stock for the combined research survey. The total percentage of schools from which vocalizations were detected is given. With the exception of mixed schools of *S. attenuata*/*S. longirostris*, only single-species schools with visual confirmation of species identity are included.

Species	Total	Number of Schools Vocal	Not Vocal	% Vocal
P. crassidens	19	19	0	100.0%
L. obscurus	3	3	0	100.0%
L. hosei	2	2	0	100.0%
P. electra	1	1	0	100.0%
S. bredanensis	31	30	1	96.8%
S.attenuata/S.longirostris	76	72	4	94.7%
Delphinus spp.	157	137	20	87.3%
T. truncatus	75	62	13	82.7%
S. longirostris	46	37	9	80.4%
S. coeruleoalba	192	152	40	79.2%
S. attenuata	105	81	24	77.1%
Globicephala spp.	78	57	21	73.1%
G. griseus	62	28	34	45.2%
O. orca	52	23	29	44.2%
L. obliquidens	10	4	6	40.0%
L. borealis	20	7	13	35.0%
F. attenuata	6	2	4	33.3%
B. bairdii	7	2	5	28.6%
Overall	942	719	223	76.3%

Table 10. Mean acoustic detection distances for single species dolphin schools for the combined research surveys.

Species	Sample Size	Detection Distance (nmi) Mean	St. Deviation	Range
L. borealis	5	0.58	0.67	0.1 - 1.5
L. obliquidens	4	0.71	0.87	0.1 - 2
O. orca	19	0.73	0.71	0.1 - 2.3
G. griseus	24	0.95	0.7	0.026 - 2.3
L. obscurus	3	0.98	1.32	0.01 - 2.5
F. attenuata	2	1.00	1.05	0.26 - 1.75
B. bairdii	2	1.10	0.84	0.5 - 1.7
S. bredanensis	28	1.53	1.19	0.01 - 4.5
T. truncatus	53	1.79	1.33	0.08 - 6
S. attenuata	71	1.85	1.53	0.01 - 6
L. hosei	1	2.00	-	-
Delphinus spp.	112	2.22	1.6	0.1 - 6
Globicephala spp.	48	2.56	1.77	0.1 - 8.5
S. longirostris	35	2.61	1.55	0.1 - 6
S. coeruleoalba	136	2.63	1.84	0.1 - 10
P. crassidens	14	2.93	1.52	1 - 6
S. attenuata, S. longirostris	70	3.02	1.55	0.2 - 6.4
Overall	627	2.22	1.66	0.01 - 10

Table 11. Number of schools from which each call type was detected for each species. Call types include: B = burst pulses, E = echolocation clicks, and W = whistles. All combinations of call types are given.

		Call Type						
	Sample Size	B	E	EB	W	WB	WE	WEB
B. bairdii	2	0	1	1	0	0	0	0
L. borealis	7	1	1	5	0	0	0	0
L. obliquidens	4	1	0	3	0	0	0	0
L. obscurus	3	0	0	2	0	0	0	1
P. electra	1	0	0	0	0	0	0	1
O. orca	23	1	4	7	0	2	3	6
F. attenuata	2	0	0	0	0	0	0	2
G. griseus	29	2	3	11	1	3	1	8
P. crassidens	19	0	0	0	1	0	10	8
L. hosei	1	0	0	0	1	0	0	0
S. bredanensis	30	0	1	2	2	0	11	14
Globicephala spp.	57	0	1	3	12	5	11	25
T. truncatus	62	0	0	2	14	2	14	30
S. longirostris	37	0	0	0	23	4	3	7
S. attenuata, S. longirostris	72	0	0	0	33	8	11	20
S. attenuata	81	0	2	0	34	3	14	28
Delphinus spp.	137	0	2	0	43	12	26	54
S. coeruleoalba	151	0	0	0	113	11	16	11
Overall	718	5	15	36	277	50	120	215

Table 12. Mean group size for dolphin schools detected (1) both visually and acoustically, and (2) only visually. A statistical comparison was made of the group sizes for acoustic/visual detections vs. visual-only detections (Mann-Whitney U test).

		Visual/Acoustic Detections		Visual (only) Detections		%	Mann-Whitney Test	
Species	Total	# schools	Mean Group Size	# schools	Mean Group Size	Vocal	U	p
P. electra	1	1	101.0	0	n/a	100.0%	-	-
P. crassidens	19	19	10.7	0	n/a	100.0%	-	-
L. obscurus	3	3	280.2	0	n/a	100.0%	-	-
L. hosei	2	2	105.0	0	n/a	100.0%	-	-
S. bredanensis	31	30	15.3	1	7.3	96.8%	8	0.434
S.attenuata/S.longirostris	76	72	347.9	4	131.5	94.7%	77	0.128
Delphinus spp.	154	135	193.4	19	69.7	87.7%	774	0.006
T. truncatus	75	62	78.1	13	10.1	82.7%	237.5	0.020
S. longirostris	46	37	116.4	9	38.1	80.4%	71	0.008
S. coeruleoalba	186	149	60.5	37	48.3	80.1%	2175	0.047
S. attenuata	94	81	93.2	13	41.0	86.2%	293.5	0.011
Globicephala spp.	77	56	21.0	21	14.2	72.7%	426.5	0.065
G. griseus	60	29	21.8	31	9.9	48.3%	284.5	0.015
O. orca	49	21	11.9	28	5.6	42.9%	168.5	0.011
L. obliquidens	9	4	19.6	5	11.5	44.4%	8.5	0.713
L. borealis	19	7	27.3	12	7.8	36.8%	16.5	0.021
F. attenuata	6	2	24.0	4	7.9	33.3%	0	0.064
B. bairdii	7	2	16.0	5	7.6	28.6%	2	0.245
Overall	914	712	85.7	202	29.3	77.9%	55990	<0.0001

Table 13. Number of sonobuoys deployed during each survey by species. Opportunistic sonobuoys were not deployed on a specific sighting but were deployed in an attempt to detect vocalizing whales.

Species	STAR 00	ORCAWALE	HICEAS	STAR 03	SPLASH	PICEAS	STAR 06	Total
Opportunistic sonobuoys	-	-	-	-	30	-	9	39
Balaenoptera musculus	6	11	-	18	10	-	22	67
Balaenoptera edeni	9	-	7	9	-	4	17	46
Orcinus orca	-	2	-	4	10	-	7	23
Eubalaena japonica	-	-	-	-	20	-	-	20
Megaptera noviangliae	1	5	-	1	-	-	1	8
Balaenoptera physalus	-	2	1	3	2	-	-	8
Balaenoptera edeni/borealis	-	-	-	4	-	-	3	7
Balaenoptera borealis	-	-	3	2	-	-	-	5
Balaenoptera acutorostrata	-	-	-	-	2	-	1	3
Unid Whale	-	-	-	-	-	1	2	3
Psuedorca crassidens	2	-	-	-	-	-	-	2
Globicephala macrorhynchus, Tursiops truncatus	1	-	-	-	-	-	1	2
Lagenodelphis hosei	-	-	-	1	-	-	-	1
Physeter macrorhynchus	-	-	-	1	-	-	-	1
Globicephala spp.	-	-	-	1	-	-	-	1
Total	19	20	11	44	74	5	63	236

IX. FIGURES

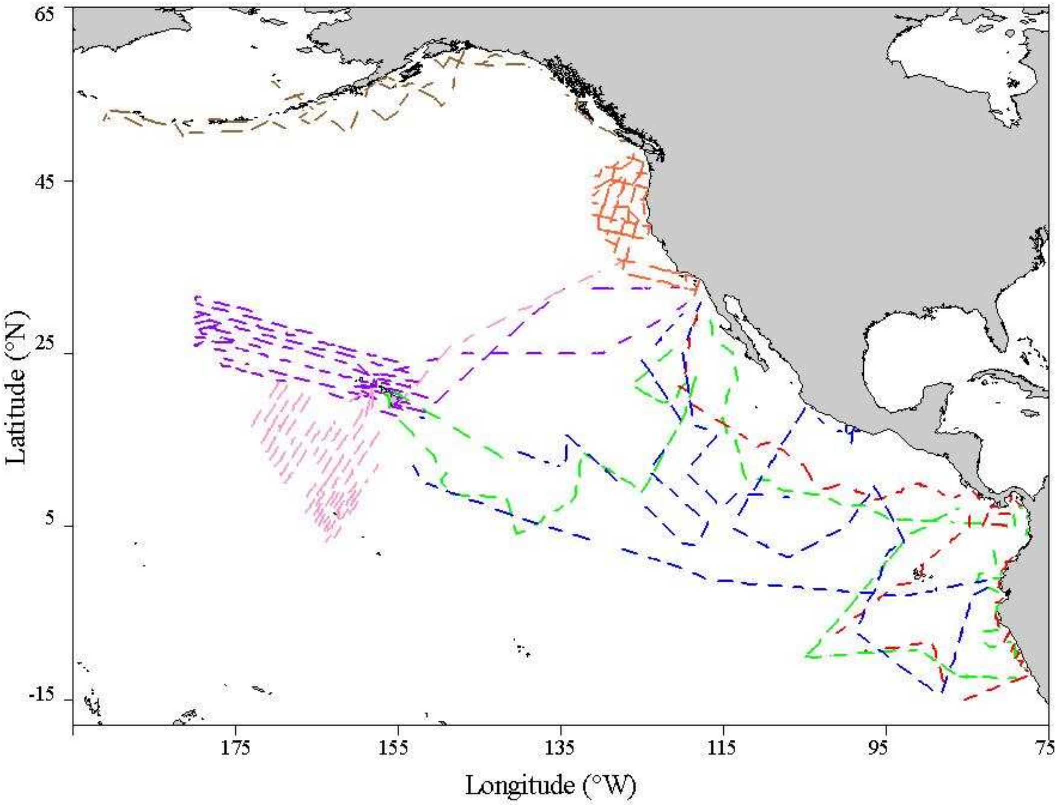


Figure 1. Map of study area for seven shipboard cetacean surveys including passive acoustic monitoring tracklines. STAR 2000 tracklines are shown in green, ORCAWALE 2001 are shown in orange, HICEAS 2002 are shown in purple, STAR 2003 are shown in red, SPLASH 2004 is shown in brown, PICEAS 2005 is shown in pink, and STAR 2006 are shown in blue.

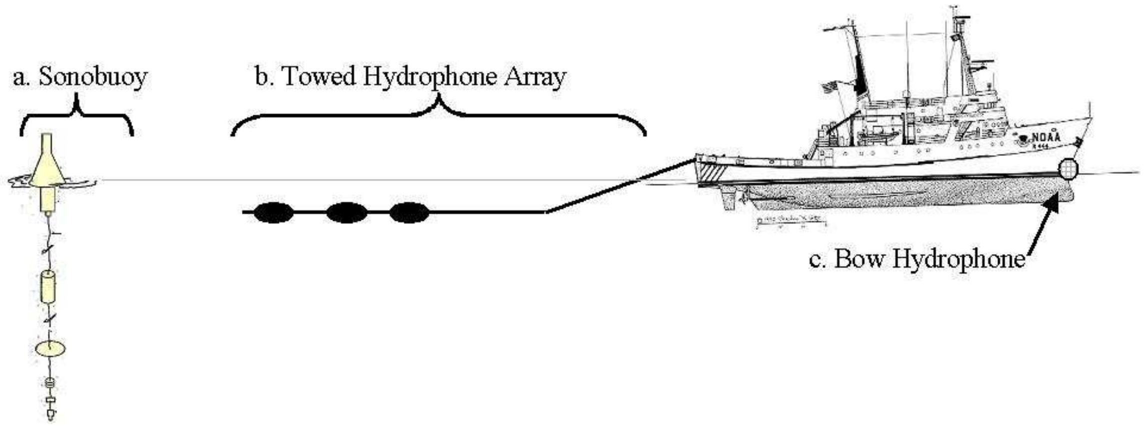


Figure 2. Diagrams of a) sonobuoy, b) towed hydrophone array and c) bow-mounted hydrophone.

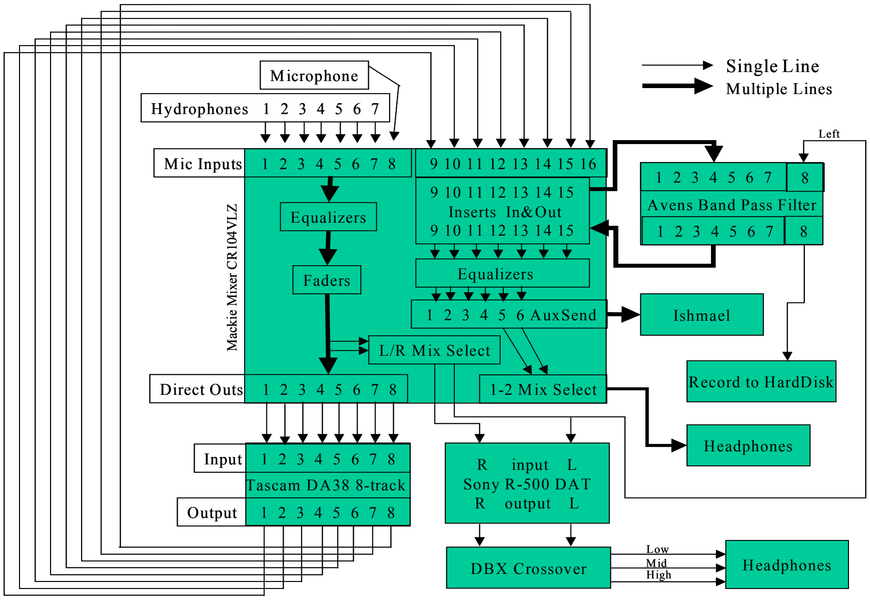


Figure 3. Hardware wiring diagram for shipboard routing and processing of acoustic signals from the towed hydrophone array. The Sony R-500 DAT recorder (shown here) was wired to a pair of sonobuoy receivers on most cruises.

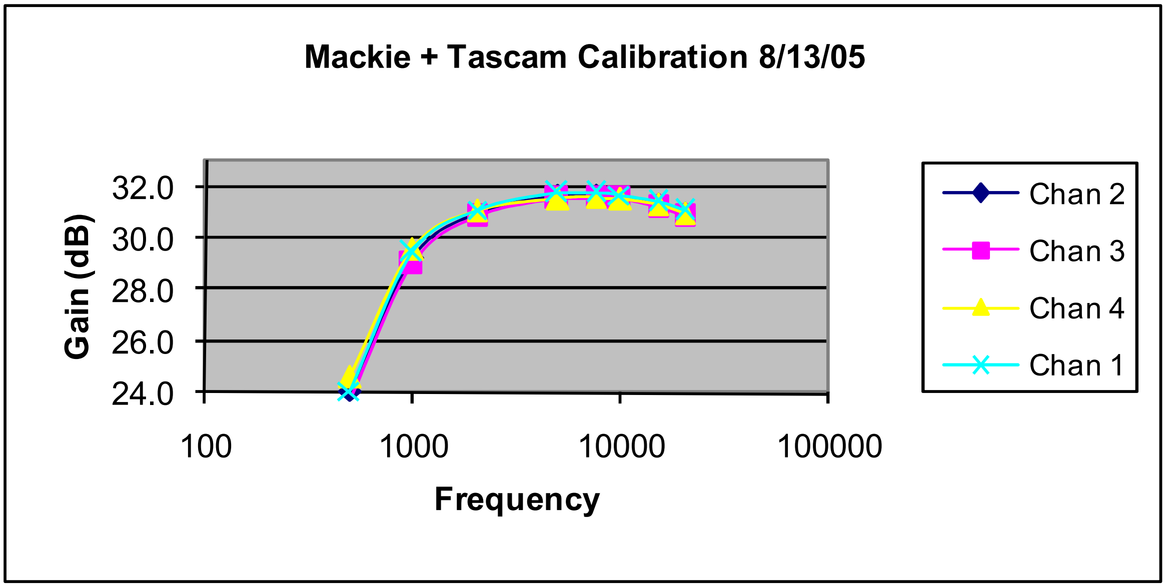


Figure 4. System frequency response for signals that pass through the Mackie CR1604-VLZ mixer, are recorded on the Tascam DA-38 digital tape recorder, and are played back on the Tascam. An AC voltage of 0.1 V RMS was sent to the Mackie over a frequency range of 500 Hz to 20 kHz, was amplified and filtered with an analog equalizer, and was recorded to tape. The output voltage was measured during playback. Equalizer settings were unity gain (high), -15dB @ 100Hz (mid), -15dB (low). Only four of eight channels were calibrated.

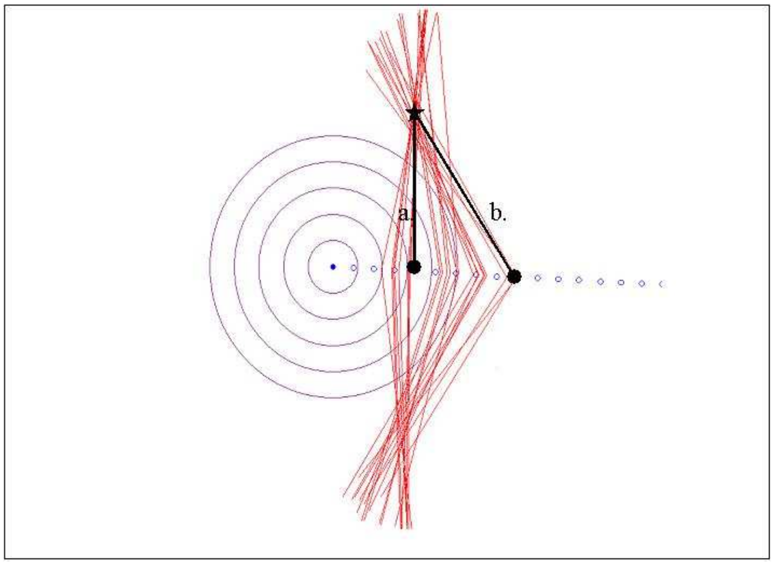


Figure 5. Whaltrak plot of beamform angles with approximated (a) closest distance of approach (nmi) and (b) greatest distance (nmi) for a non-sighted sperm whale acoustic detection. The ships track is indicated by small open circles; final position of the ship is shown as a closed blue circle surrounded by one nautical mile concentric circles as a reference for distance. The "★" indicates the position of the sound source as estimated by a bio-acoustician from the convergent beamform angles. The closest distance of approach for groups in passing mode was typically the distance of the group as it passed the hydrophone array.

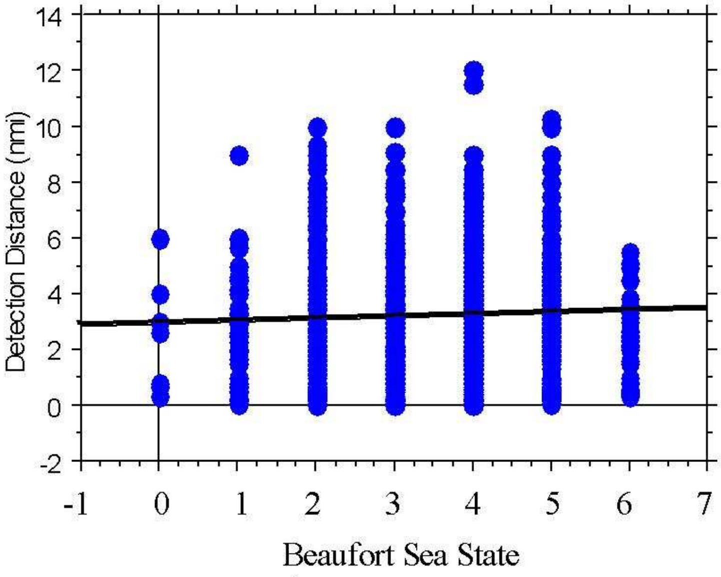


Figure 6. Regression plot of the acoustic detection distance (nmi) of dolphin schools by Beaufort Sea State for the combined surveys. Beaufort sea state explained 2% of the variation in the detection distance ($R^2 = 0.002$); this was not significant ($p = 0.118$, $n=1501$).

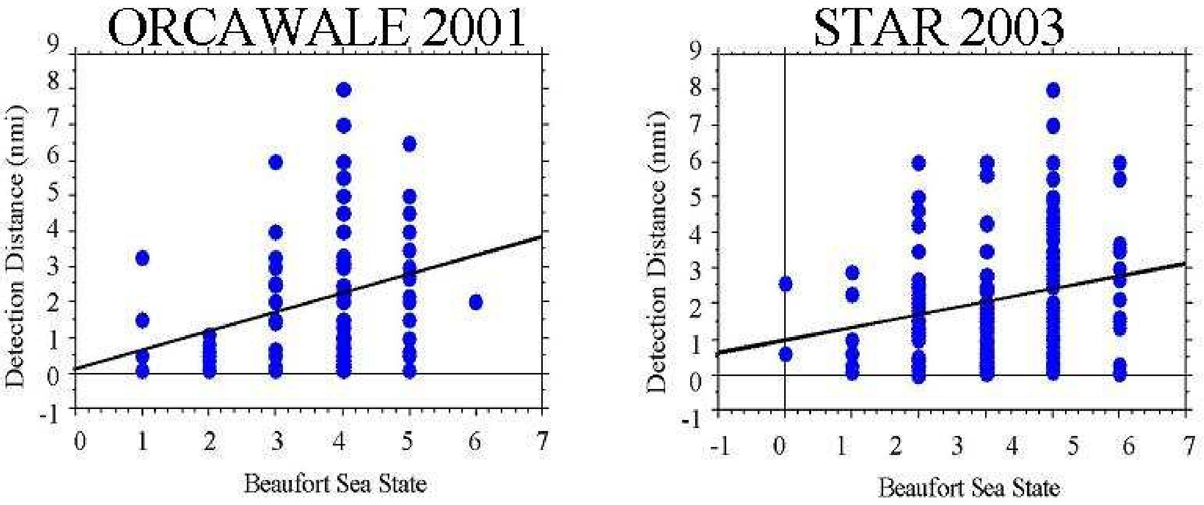


Figure 7. Regression plots of the acoustic detection distance (nmi) of dolphin schools by Beaufort Sea State for Orcawale 2001 and STAR 2003 surveys. There was an increase in the detection distance with increasing sea state during both ORCAWALE ($p = 0.0004$, $n=111$) and STAR 03 ($p = 0.0033$, $n=182$).

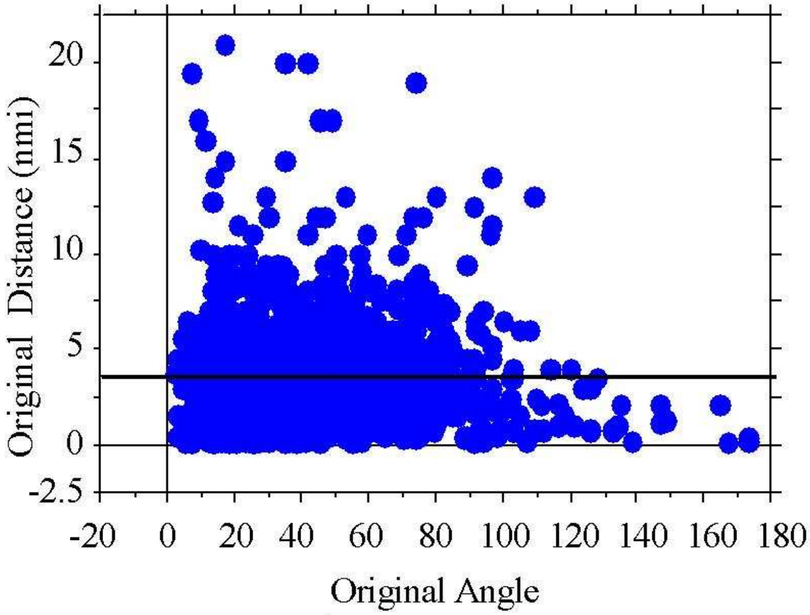


Figure 8. Regression plot of original angle vs. original distance (nmi) for all acoustic detections from the combined cruises. The regression was not significant ($p = 0.76$, $n=1,527$).

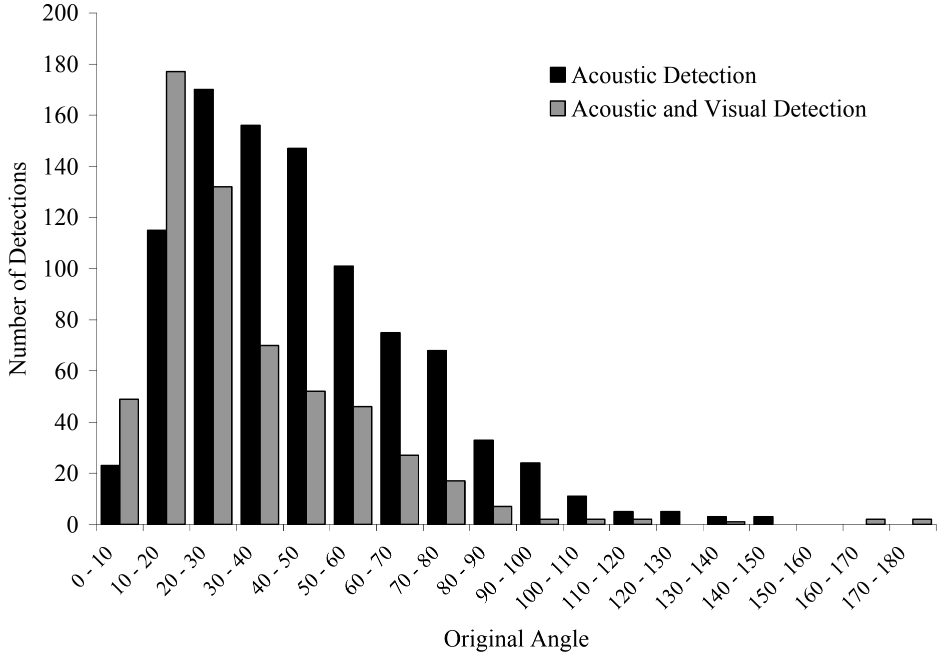


Figure 9. The number of acoustic detections within a given range of original angles for all cruises combined. Detections made by acoustic methods (only) are shown in black; detections made using both acoustic and visual methods are shown in gray.

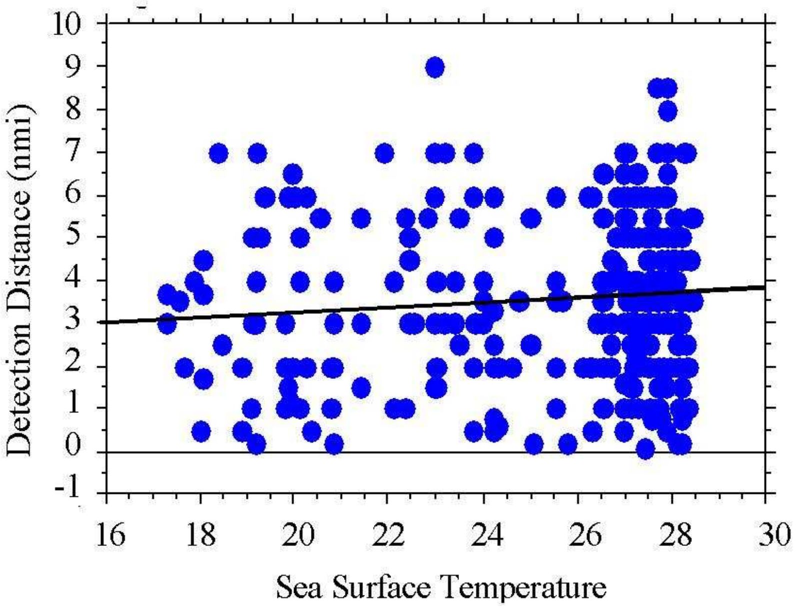


Figure 10. Regression plot of the acoustic detection distance (nmi) of dolphin schools vs. sea surface temperature (°C) for the STAR 00 survey. The thermocline depth explains 0.9% of the variation in the detection distance (R^2=0.009), which is not significant (p = 0.072, n=347).

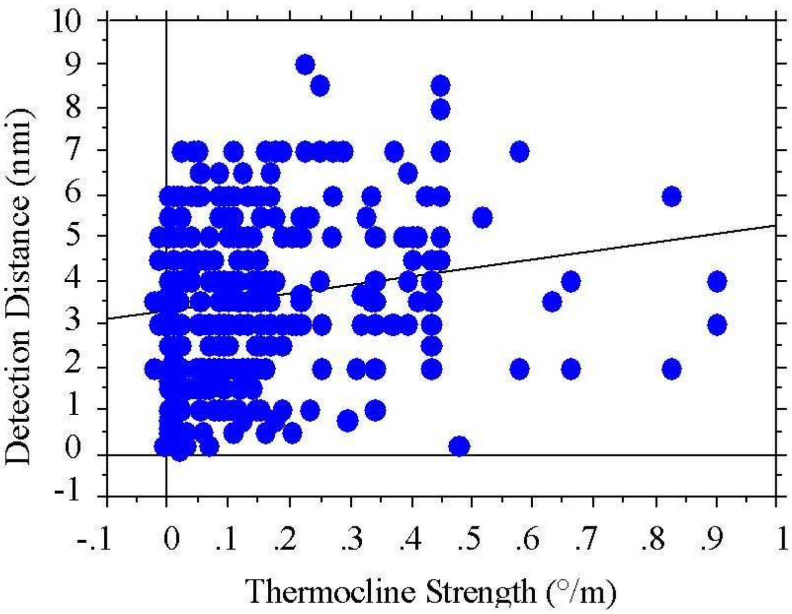


Figure 11. Regression plot for acoustic detection distance (nmi) of dolphin schools vs. thermocline strength (°/m) for the STAR 00 cruise. The thermocline strength explains 3.1% of the variation in detection distance (R^2 = 0.034); which is significant (p = 0.001, n=347).

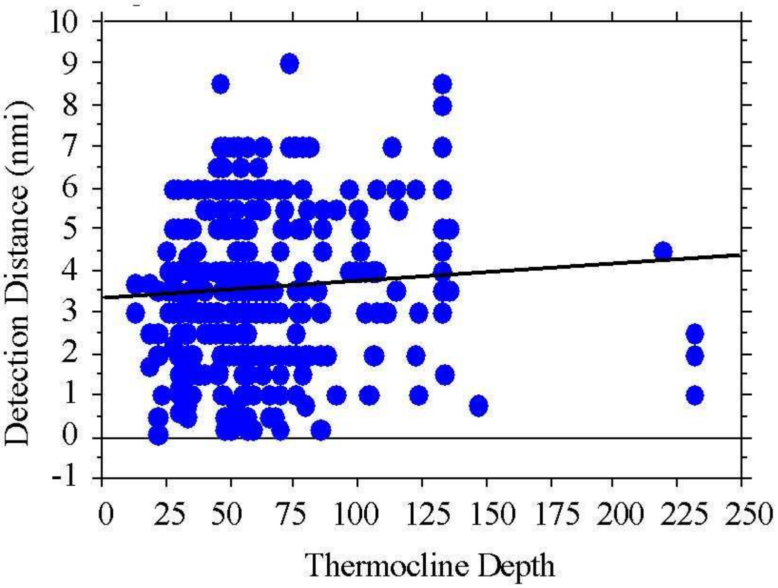


Figure 12. Regression plot for the acoustic detection distance (nmi) of dolphin schools vs. depth of the thermocline (m) for the STAR 00 cruise. The thermocline depth explains 0.6% of the variation in the detection distance ($R^2 = 0.006$), which is not significant ($p = 0.144$, n=347).

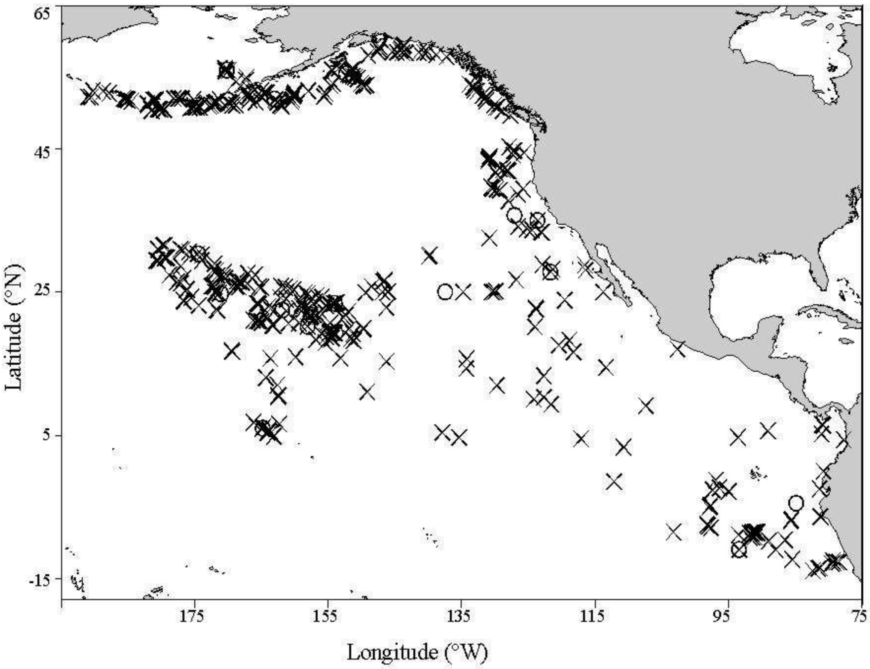


Figure 13. Map of study area and sperm whale, *Physeter macrocephalus*, detections. Vocal groups of *P. macrocephalus* are represented with an "X", non-vocal groups are represented with an "O".

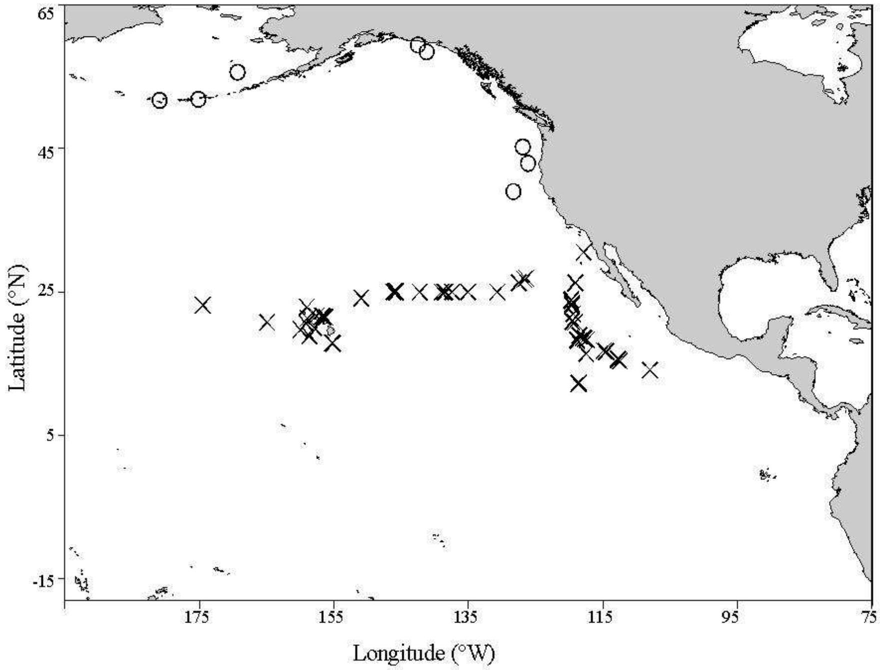


Figure 14. Map of study area and minke whale, *Balaenoptera acutorostrata*, detections. Vocal groups of *B. acutorostrata* are represented with an "X", non-vocal groups are represented with an "O".

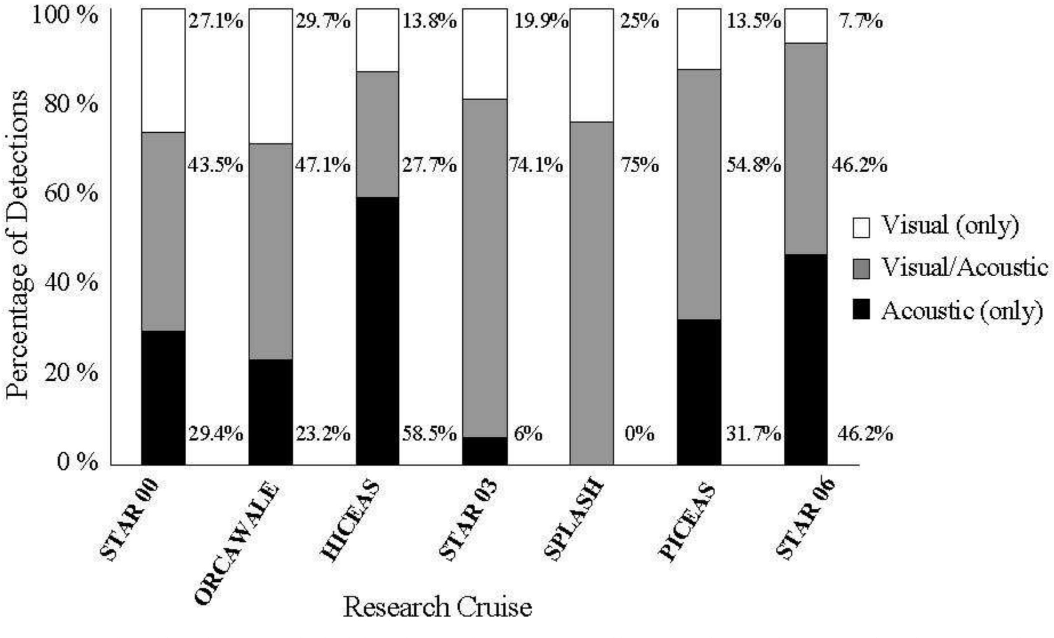


Figure 15. Distribution of dolphin detections according to detection method for each research survey. Detection of dolphin schools using visual (only) methods are shown in white, detections by combined visual and acoustic methods are shown in gray, and acoustic (only) detections are shown in black. The percentage for each detection method is shown to the right of each column.

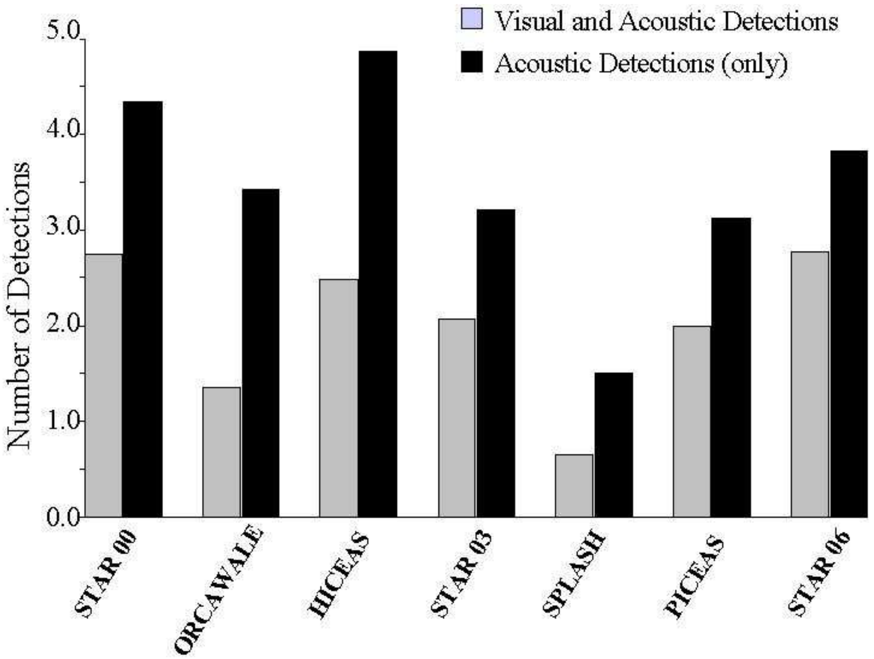


Figure 16. The number of dolphin schools detected by combined visual and acoustic methods (gray) and by acoustic methods only (black), for each research cruise.

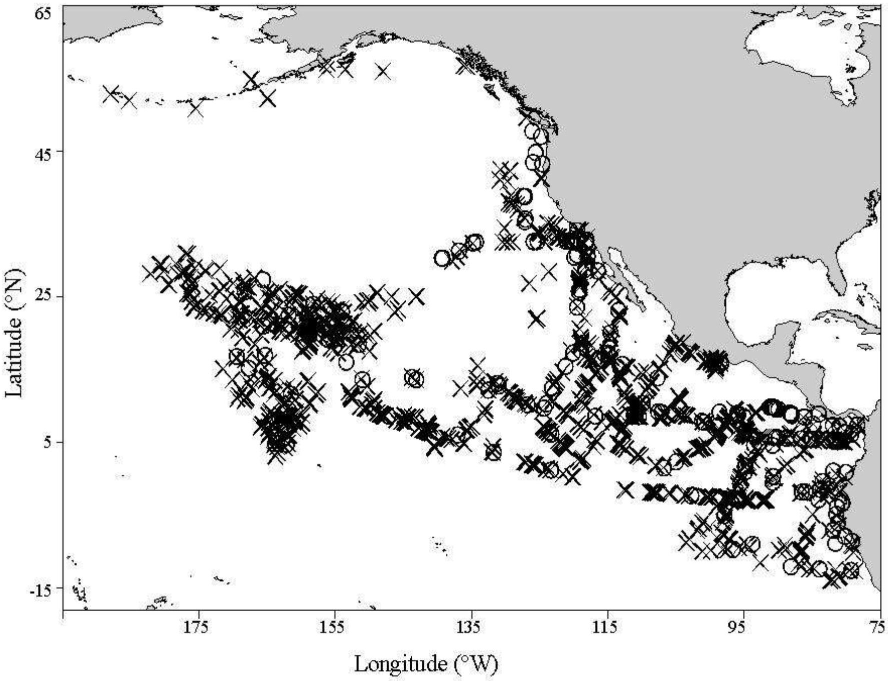


Figure 17. Map of study area and unidentified dolphin detections. Vocal groups of unidentified dolphins are represented with an "X", non-vocal groups are represented with an "O".

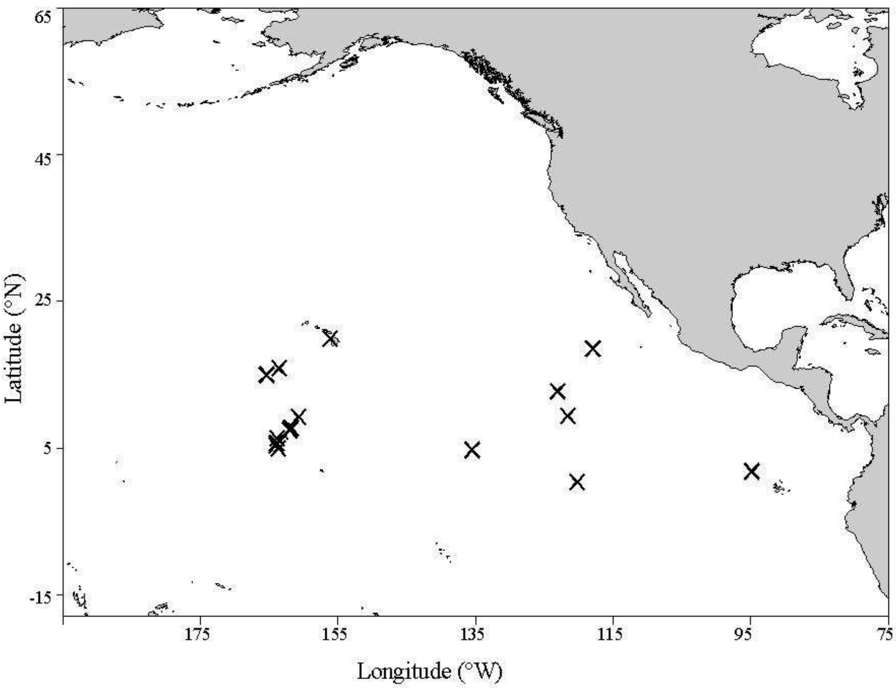


Figure 18. Map of study area and false killer whale, *Pseudorca crassidens*, detections. Vocal groups of *P. crassidens* are represented with an "X" There were no non-vocal groups of this species.

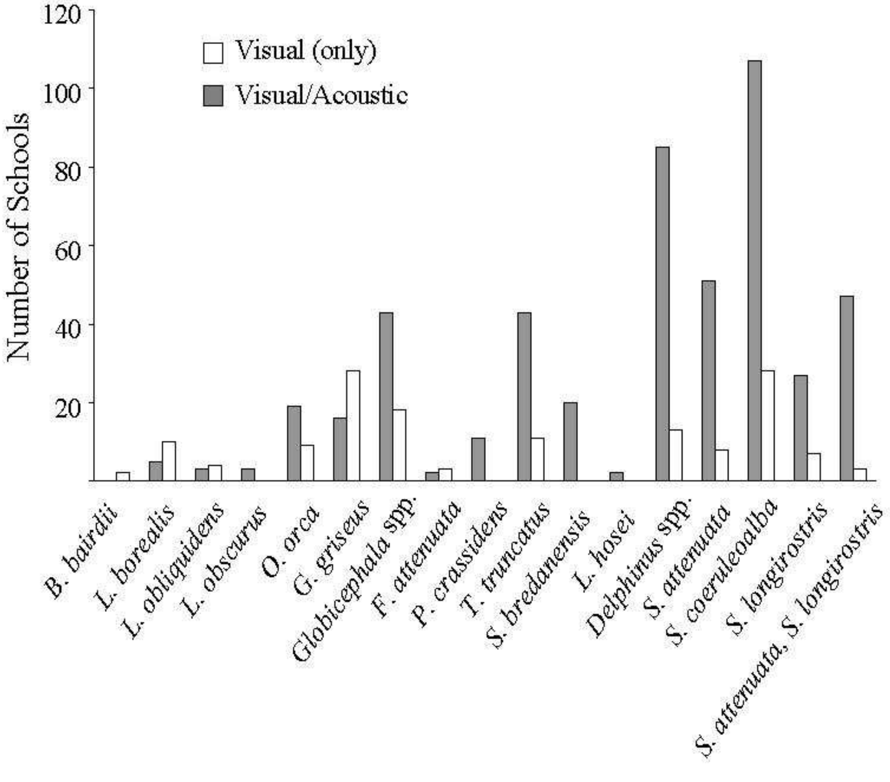


Figure 19. Number of dolphin schools for each species detected using visual (only) methods (white) and by combined visual/acoustic methods (gray).

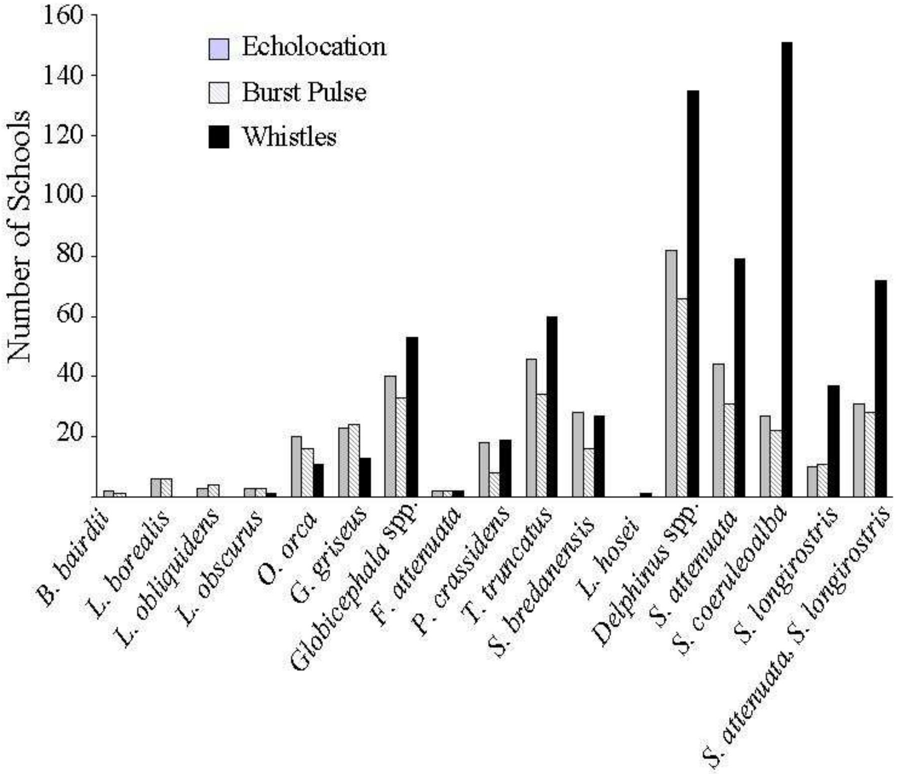


Figure 20. Number of dolphin schools, for each species, from which echolocation clicks (gray), burst pulses (white), and whistles (black) were detected.

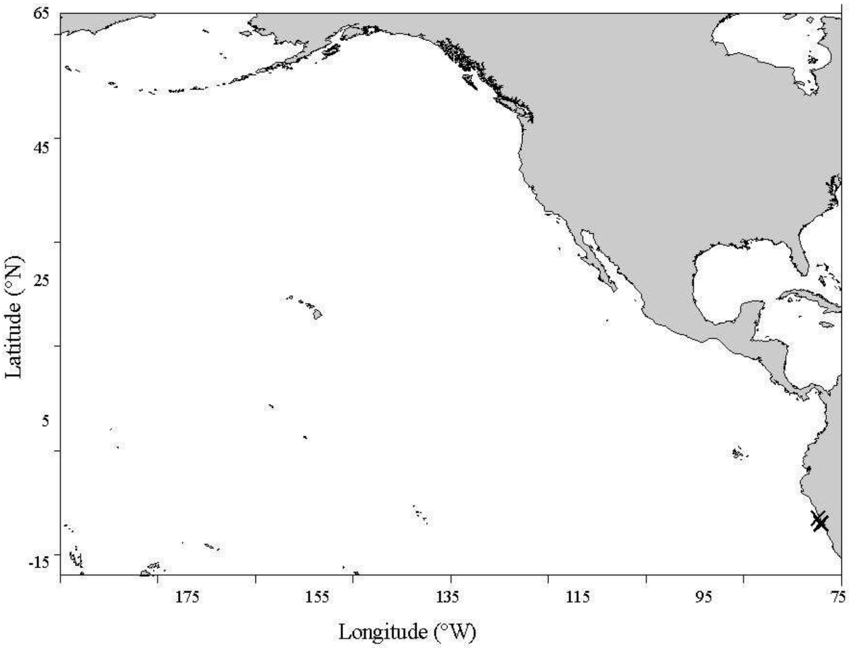


Figure 21. Map of study area and dusky dolphin, *Lagenorhynchus obscurus*, detections. Vocal groups of *L. obscurus* are represented with an "X", non-vocal groups are represented with an "O".

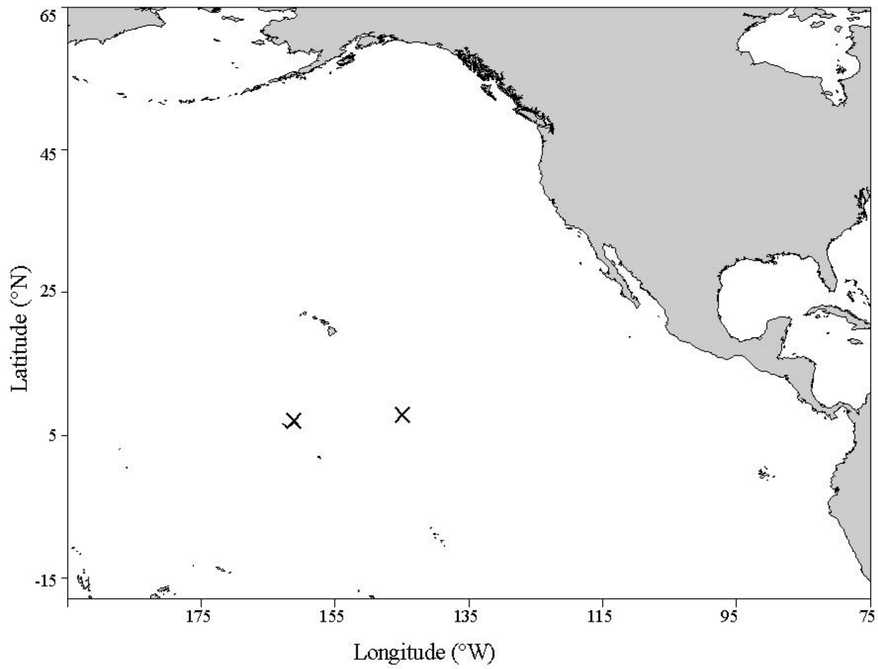


Figure 22. Map of study area and Fraser's dolphin, *Lagenodelphis hosei*, detections. Vocal groups of *L. hosei* are represented with an "X". There were no non-vocal groups of this species.

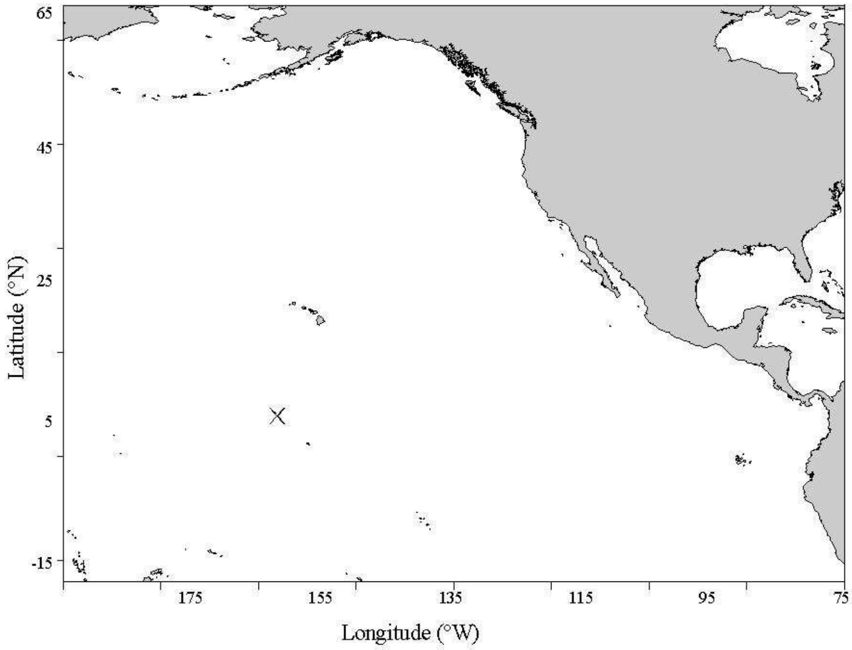


Figure 23. Map of study area and melon-headed whale, *Peponocephala electra*, detections. Vocal group of *P. electra* is represented with an "X". There were no non-vocal groups of this species.

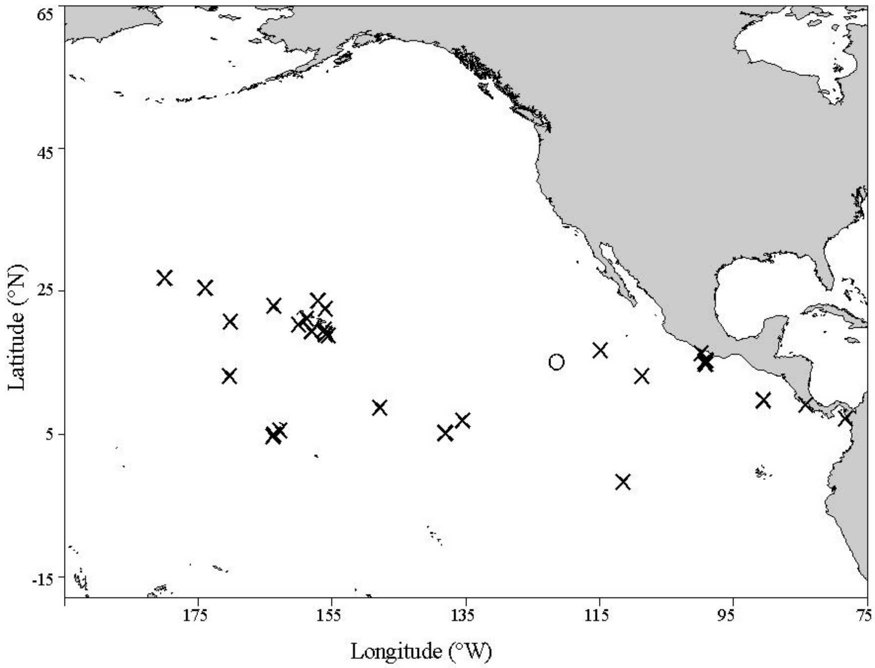


Figure 24. Map of study area and rough-toothed dolphin, *Steno bredanensis*, detections. Vocal groups of *S. bredanensis* are represented with an "X", non-vocal groups are represented with an "O".

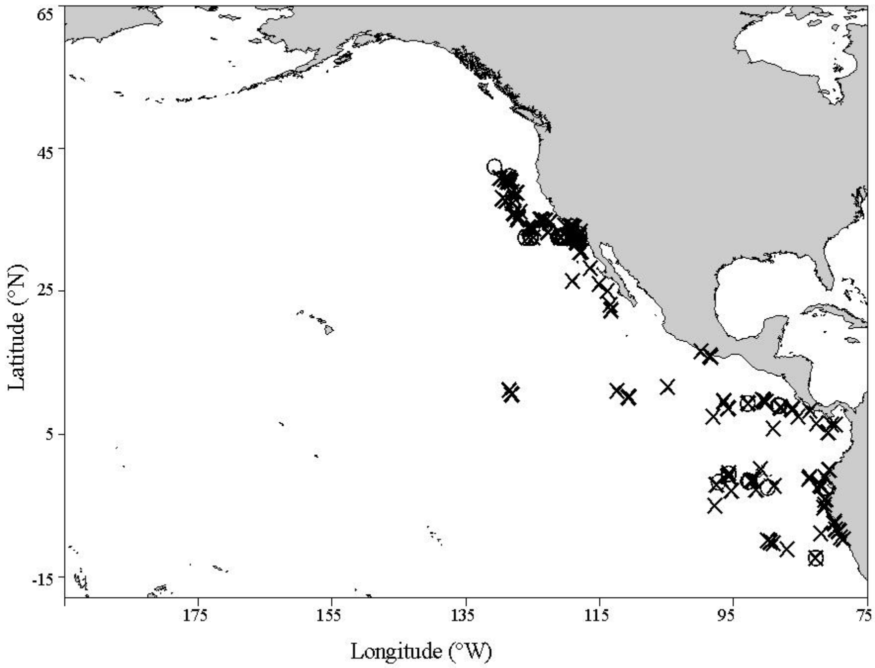


Figure 25. Map of study area and common dolphin, *Delphinus* spp., detections. Vocal groups of *Delphinus* spp. are represented with an "X", non-vocal groups are represented with an "O".

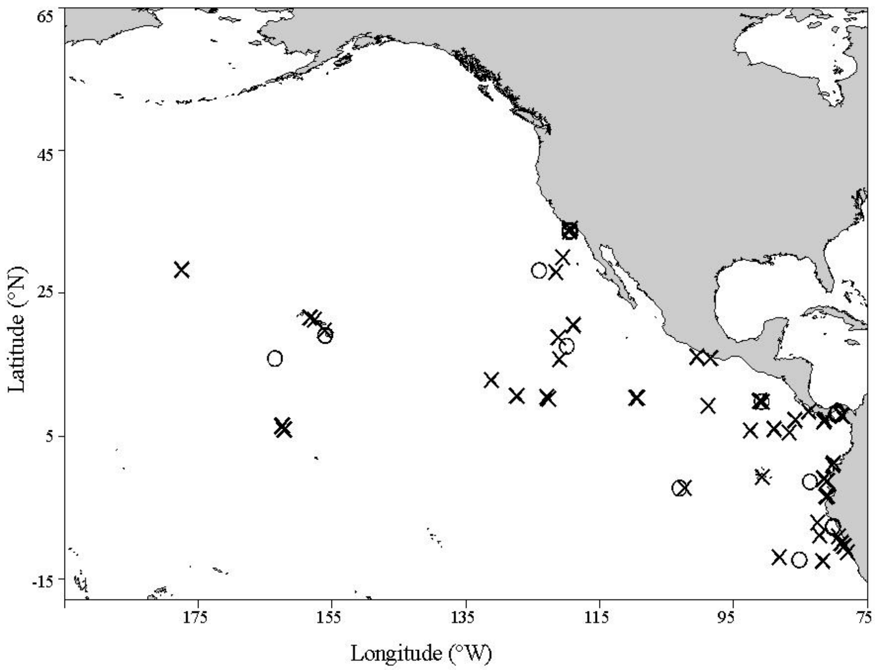


Figure 26. Map of study area and bottlenose dolphin, *Tursiops truncatus*, detections. Vocal groups of *T. truncatus* are represented with an "X", non-vocal groups are represented with an "O".

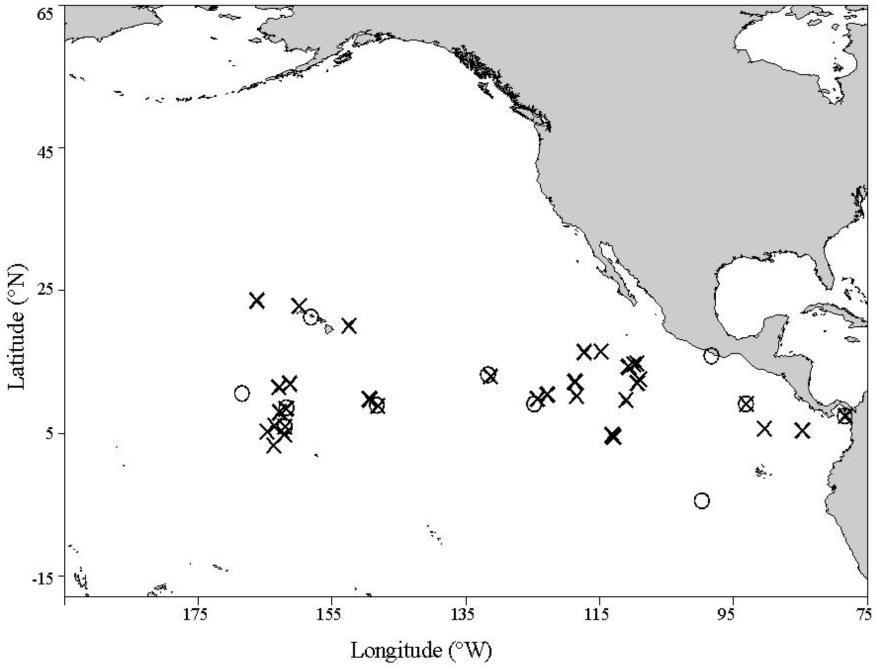


Figure 27. Map of study area and spinner dolphin, *Stenella longirostris*, detections. Vocal groups of *S. longirostris* are represented with an "X", non-vocal groups are represented with an "O".

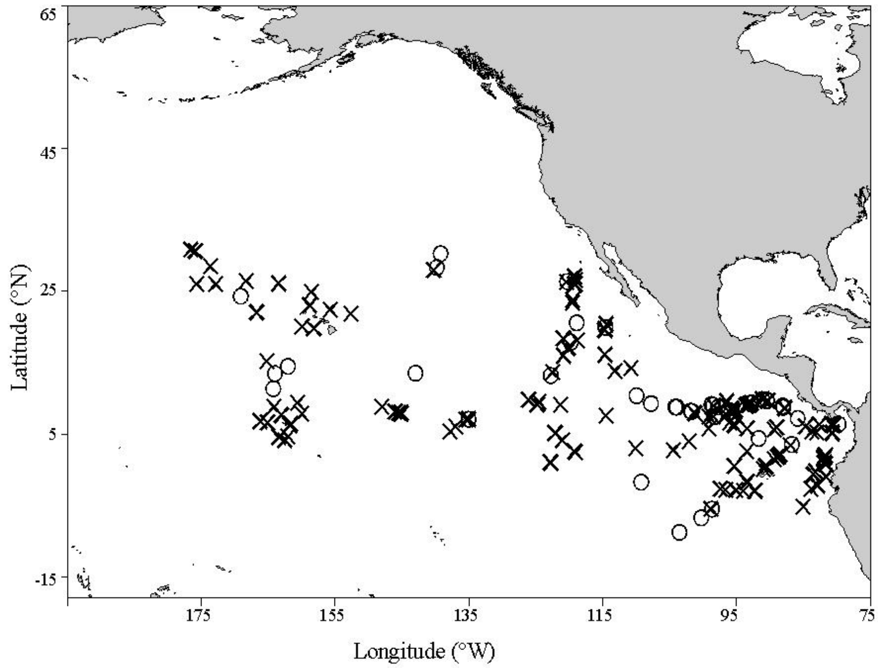


Figure 28. Map of study area and striped dolphin, *Stenella coeruleoalba*, detections. Vocal groups of *S. coeruleoalba* are represented with an "X", non-vocal groups are represented with an "O".

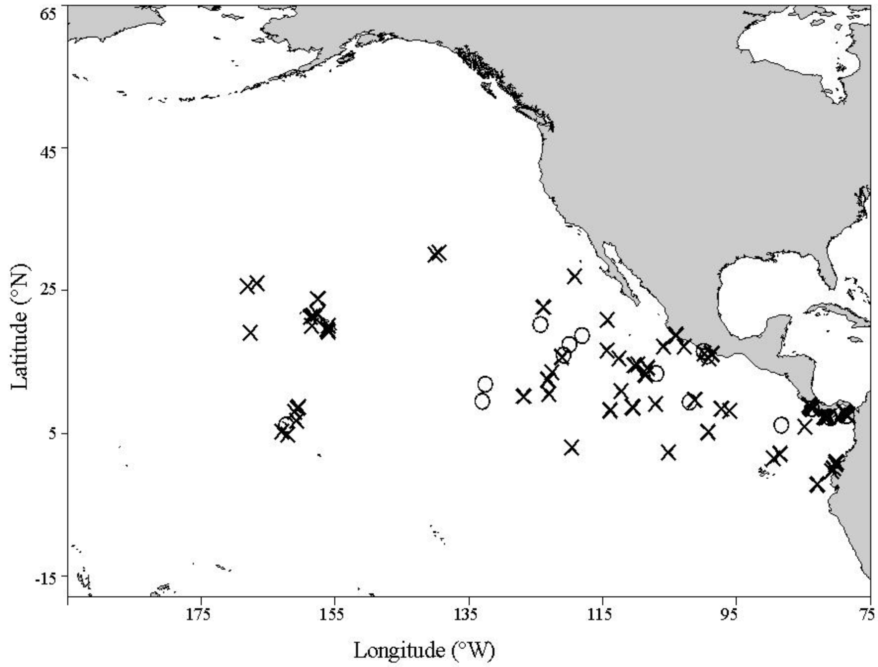


Figure 29. Map of study area and spotted dolphin, *Stenella attenuata*, detections. Vocal groups of *S. attenuata* are represented with an "X", non-vocal groups are represented with an "O".

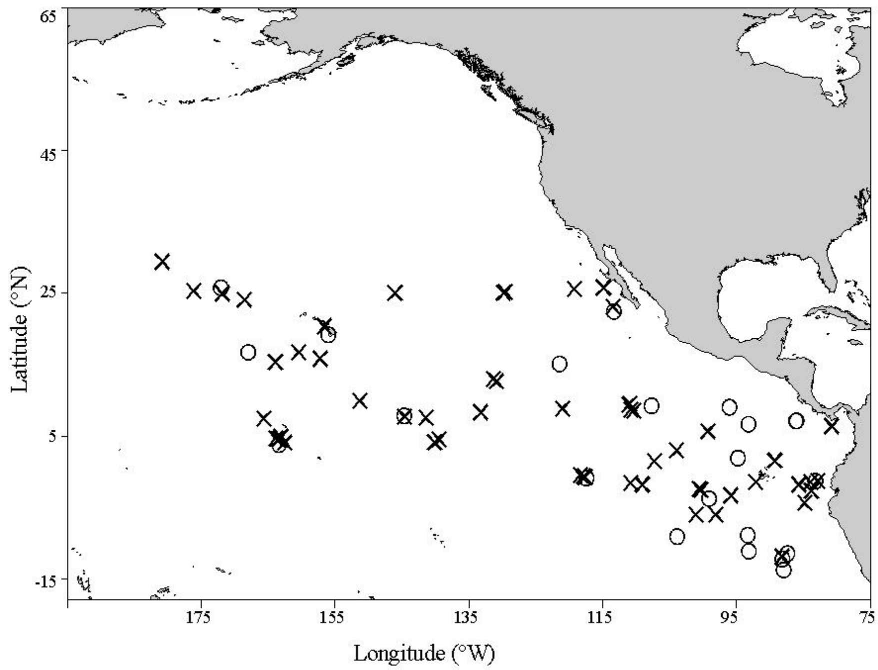


Figure 30. Map of study area and pilot whale, *Globicephala* spp., detections. Vocal groups of *Globicephala* spp. are represented with an "X", non-vocal groups are represented with an "O".

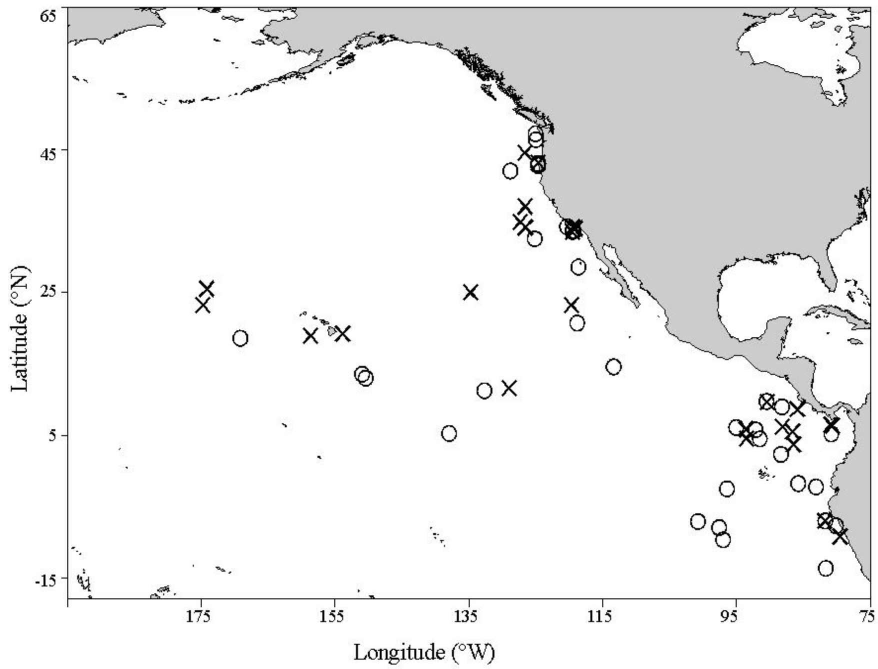


Figure 31. Map of study area and Risso's dolphin, *Grampus griseus*, detections. Vocal groups of *G. griseus* are represented with an "X", non-vocal groups are represented with an "O".

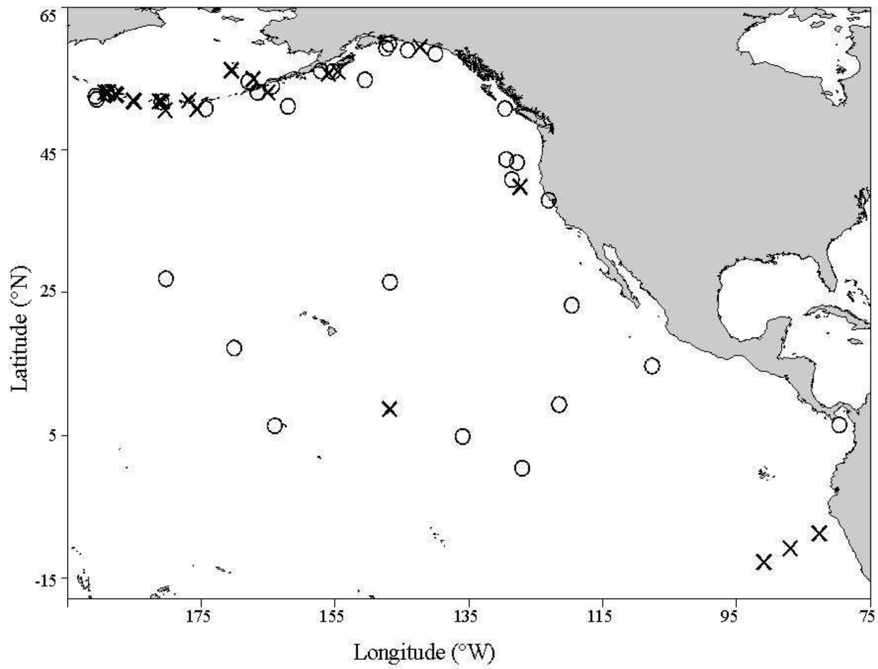


Figure 32. Map of study area and killer whale, *Orcinus orca*, detections. Vocal groups of *O. orca* are represented with an "X", non-vocal groups are represented with an "O".

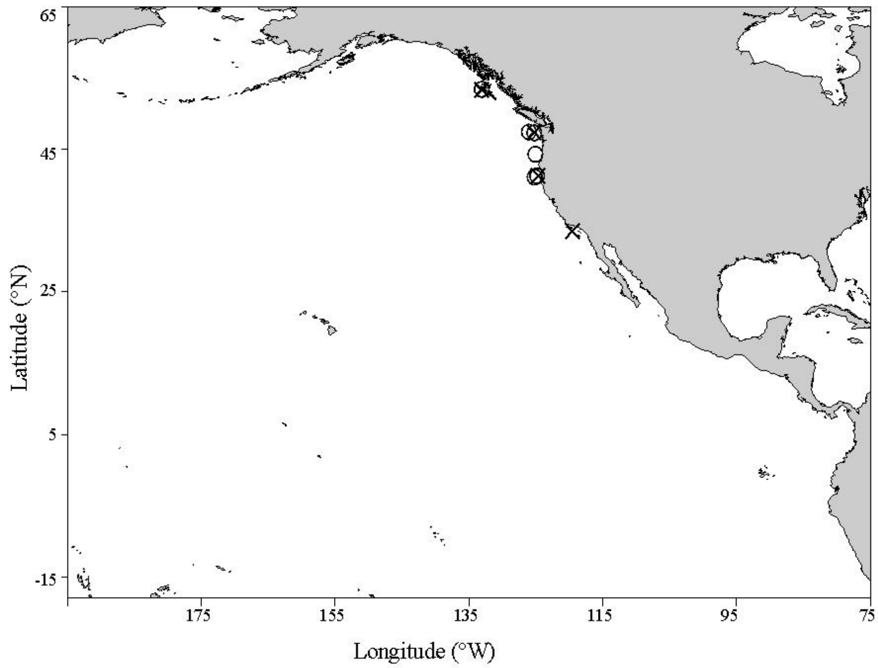


Figure 33. Map of study area and Pacific white-sided dolphin, *Lagenorhynchus obliquidens*, detections. Vocal groups of *L. obliquidens* are represented with an "X", non-vocal groups are represented with an "O".

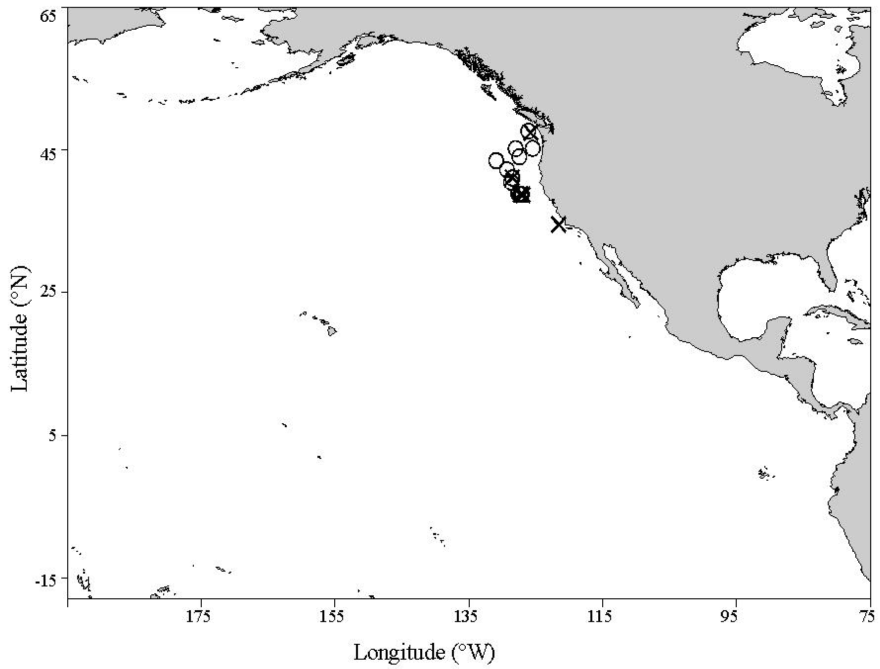


Figure 34. Map of study area and northern right whale dolphin, *Lissodelphis borealis*, detections. Vocal groups of *L. borealis* are represented with an "X", non-vocal groups are represented with an "O".

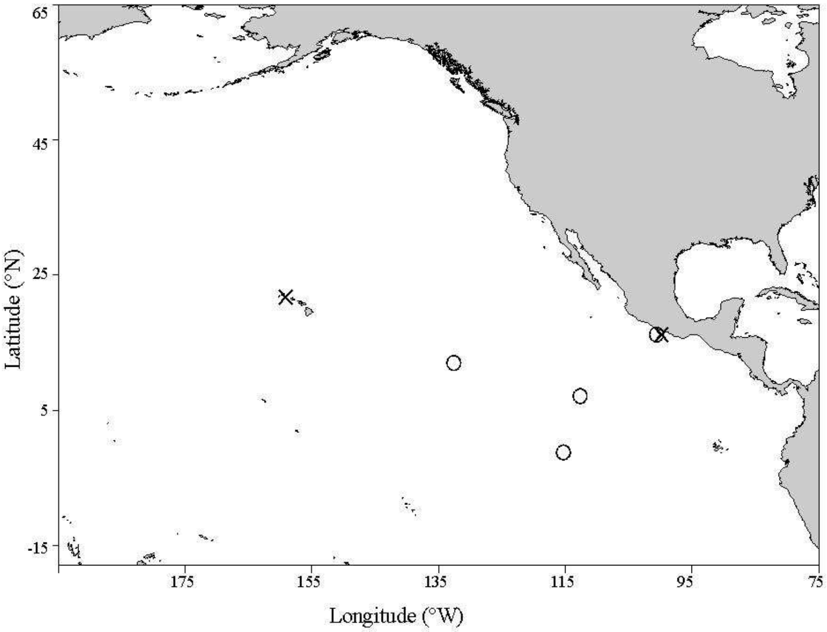


Figure 35. Map of study area and pygmy killer whale, *Feresa attenuata*, detections. Vocal groups of *F. attenuata* are represented with an "X", non-vocal groups are represented with an "O".

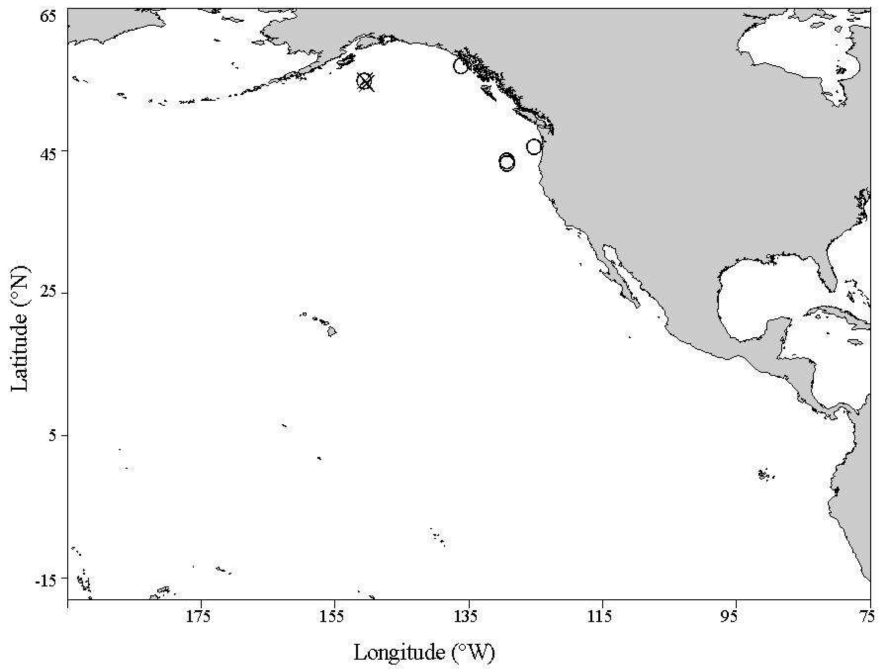


Figure 36. Map of study area and Baird's beaked whale, *Berardius bairdii*, detections. Vocal groups of *B. bairdii* are represented with an "X", non-vocal groups are represented with an "O".

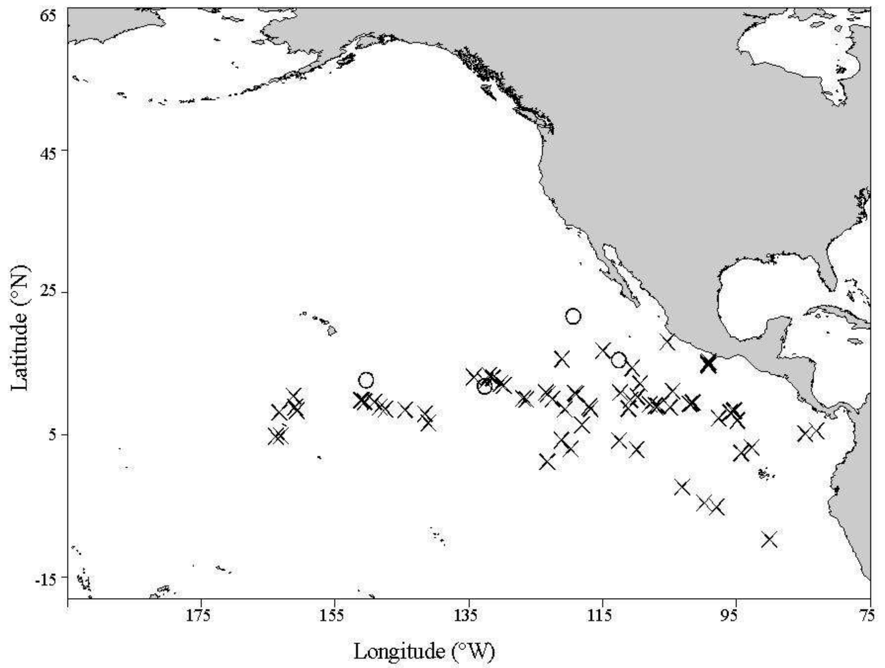


Figure 37. Map of study area and combined spotted and spinner dolphin, *Stenella attenuata* and *S. longirostris*, detections. Vocal groups of *S. attenuata/S. longirostris* are represented with an "X", non-vocal groups are represented with an "O".

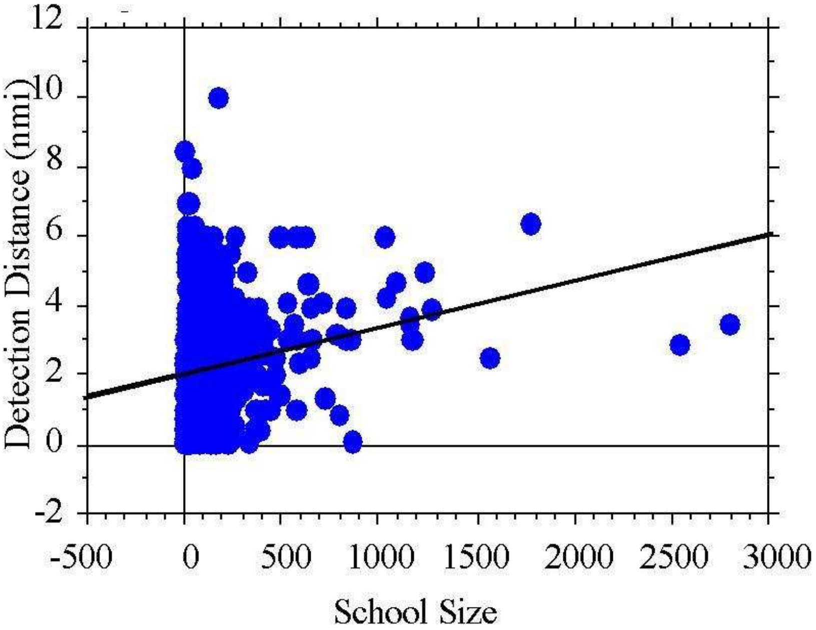


Figure 38. Regression plot of the relationship between acoustic detection distance (nmi) and school size for dolphin schools. School size explains 3.4% of the variation in detection distance (R2= 0.034); this was significant ($p < 0.0001$, n=727).

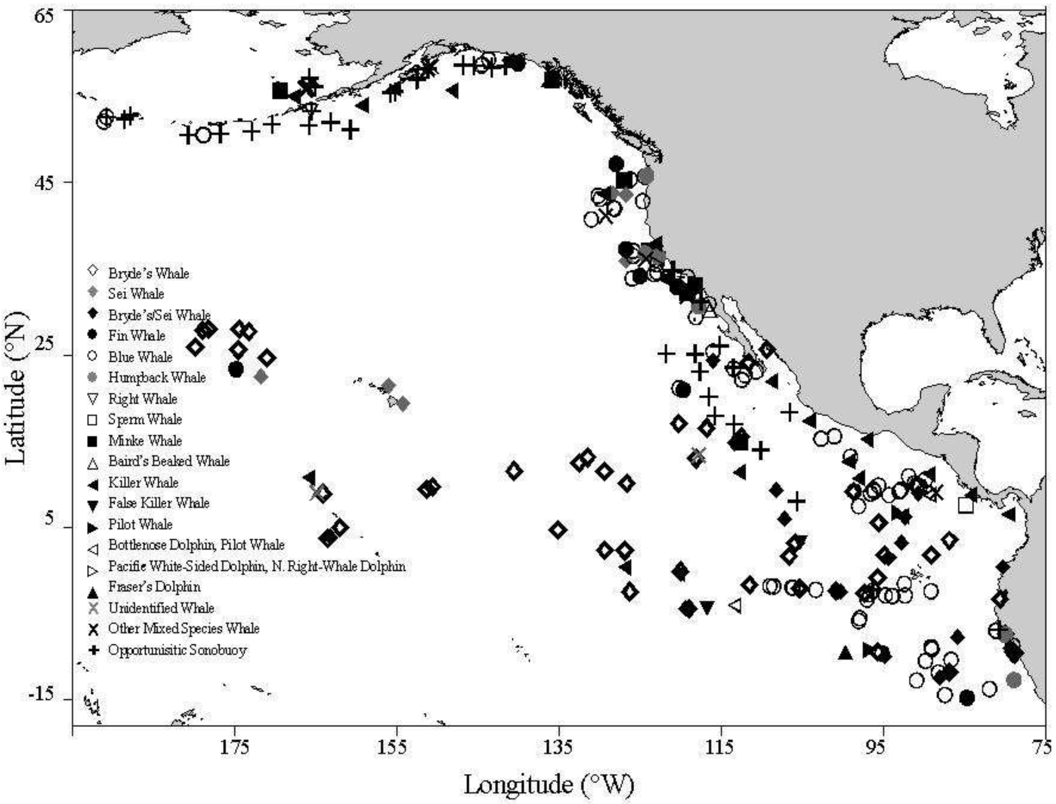
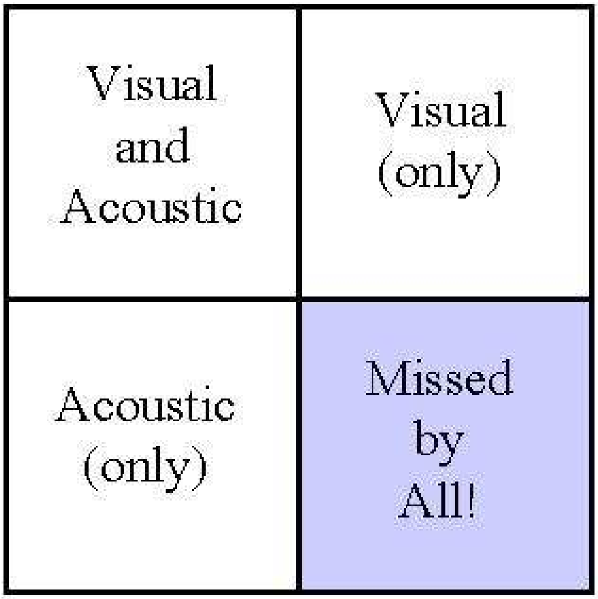


Figure 39. Map of study area for combined cruises with locations of sonobuoy deployments. Symbols represent sonobuoy deployments for different species. Cetacean vocalizations were not recorded at all locations.



Visual and Acoustic	Visual (only)
Acoustic (only)	Missed by All!

Figure 40. Two by two matrix of the detection scenarios for cetacean schools on the trackline.

VIII. APPENDICES

A. Publications

Appler, J., J. Barlow, and S. Rankin. 2004. Marine mammal data collected during the Oregon, California, & Washington Line-Transect Expedition (ORCAWALE) conducted aboard the NOAA Ships *McArthur* and *David Starr Jordan*, July-December 2001. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-359. 32pp.

Barlow, J. and R. Gentry. 2004. Report of the NOAA Workshop on Anthropogenic Sound and Marine Mammals, 19-20 February 2004. NOAA Technical Memorandum TM-NOAA-MNFS-SWFSC-361. 28 pp.

Barlow, J., S. Rankin, A. Jackson, and A. Henry. 2008. Marine mammal data collected during the Pacific Islands Cetacean and Ecosystem Assessment Survey (PICEAS) conducted aboard the NOAA ship *McArthur II*, July – December 2005. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-420. 27 pp.

Barlow, J. and S. Rankin. 2007. False killer whale abundance and density: preliminary estimates for the PICEAS study area south of Hawaii and new estimates for the US EEZ around Hawaii. Southwest Fisheries Science Center (SWFSC) Administrative Report LJ-07-02. 15pp.

Barlow, J., S. Rankin, E. Zele, and J. Appler. 2004. Marine mammal data collected during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) conducted aboard the NOAA ships *McArthur* and *David Starr Jordan*, July-December 2002. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-362. 39pp.

Barlow, J. 2006. Cetacean abundance in Hawaiian waters estimated from a summer/fall survey in 2002. Mar. Mamm. Sci. 22(2):446-464.

Barlow, J., and B. L. Taylor. 2005. Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. Mar. Mamm. Sci. 21(3):429-445.

Barlow, J., S. Rankin, and S. Dawson. 2008. A guide to constructing hydrophones and hydrophone arrays for monitoring marine mammal vocalizations. NOAA Technical Memorandum NOAA-NMFS-TM-417. 19pp.

Branch, T. A., K. M. Stafford, D. M. Palacios, C. Allison, J. L. Bannister, C. L. K. Burton, E. Cabrera, C. A. Carlson, B. Galletti Vernazzani, P. C. Gill, R. Hucke-Gaete, K. C. S. Jenner, M. –N. M. Jenner, K. Matsuoka, Y. A. Mikhalev, T. Miyashita, M. G. Morrice, S. Nishiwaki, V. J. Sturrock, D. Tormosov, R. C. Anderson, A. N. Baker, P. B. Best, P. Borsa, R. L. Brownell Jr., S. Childerhouse, K. P. Findlay, T. Gerrodette, A. D. Ilangakoon, M. Joergensen, B. Kahn, D. K. Ljungblad, B. Maughan, R. D. McCauley, S. McKay, T. F. Norris, Oman Whale and Dolphin Research Group, S. Rankin, F. Samaran, D. Thiele, K. Van Waerebeek, and R. M. Warneke. 2007. Past and present distribution, densities, and movements of blue whales *Balaenoptera musculus* in the Southern Hemisphere and northern Indian Ocean. Mamm. Rev. 37(2):116-175.

Cox, T. M., T. J. Ragen, A. J. Read, E. Vos, R. W. Baird, K. Balcomb, J. Barlow, J. Caldwell, T. Cranford, L. Crum, A. D'Amico, G. D'Spain, A. Fernández, J. Finneran, R. Gentry, W. Gerth, F. Gulland, J. Hildebrand, D. Houser, T. Hullar, P. D. Jepson, D. Ketten, C. D. MacLeod, P. Miller, S. Moore, D. C. Mountain, D. Palka, P. Ponganis, S. Rommel, T. Rowles, B. Taylor, P. Tyack, D. Wartzok, R. Gisiner, J. Mead, and L. Benner. 2006. Understanding the impacts of anthropogenic sound on beaked whales. J. Cetacean Res. Manage. 7(3):177-187.

Jackson, A., T. Gerrodette, S. Chivers, M. Lynn, P. Olson, and S. Rankin. 2004. Marine mammal data collected during a survey in the eastern tropical Pacific Ocean aboard the NOAA ships *McArthur II* and *David Starr Jordan*, July 29 – December 10, 2003. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-366. 98 pp.

Kinzey, D., T. Gerrodette, A. Dizon, W. Perryman, P. Olson, and S. Rankin. 2001. Marine mammal data collected during a survey in the eastern tropical Pacific Ocean aboard the NOAA ships *McArthur* and *David Starr Jordan*, July 28-December 9, 2000. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-303. 100 pp.

Mellinger, D. K., and J. Barlow. 2003. Future directions for acoustic marine mammal surveys: Stock assessment and habitat use. NOAA OAR Special Report, NOAA/PMEL Contribution 2557, available from NOAA Pacific Environmental Laboratory. 38pp.

Munger, Lisa M. 2007. North Pacific right whale calling behavior and habitat characterization in the southeastern Bering Sea. Ph.D. dissertation, University of California, San Diego.

Norris, T. F., M. A. Smultea, A. M. Zoidis, S. Rankin, C. Loftus, C. Oedekoven, J. L. Hayes, and E. Silva. 2005. A preliminary acoustic-visual survey of cetaceans in deep waters around Ni'ihua, Kauai'I, and portions of O'ahu, Hawai'I from aboard the R/V *Dariabar*, February 2005. Report prepared by: Cetos Research Organization, Bar Harbor, ME., under contract #2057sa05-F to Geo-Marine, Inc. for NAVFAC Pacific.

Oleson, E. M., J. Barlow, J. Gordon, S. Rankin and J. A. Hildebrand. 2003. Low frequency calls of Bryde's whales. Mar. Mamm. Sci. 19(2):160-172.

Oswald, J. N., S. Rankin, and J. Barlow. 2008. To whistle or not to whistle? Geographic variation in the whistling behavior of small odontocetes. Aquat. Mamm., *In press.*

Oswald, J.N., S. Rankin, and J. Barlow. 2007. First description of whistles of Pacific Fraser's dolphins, *Lagenodelphis hosei*. Bioacoustics 16:99-111.

Oswald, J.N., S. Rankin, J. Barlow, and M.O. Lammers. 2007. A tool for real-time acoustic species identification of delphinid whistles. J. Acoust. Soc. Am 122(1):587-595.

Oswald, J. N. 2006. An examination of the Whistling Behavior of Small Odontocetes and the Development of Methods for Species Identification of Delphinid Whistles. Ph.D. Dissertation, University of California, San Diego.

Oswald, J.N., S. Rankin, and J. Barlow. 2004. The effect of recording and analysis bandwidth on acoustic identification of delphinid species. J. Acoust. Soc. Am. 116(5):3178-3185.

Oswald, J.N., J. Barlow, and T.F. Norris. 2003. Acoustic identification of nine delphinid species in the eastern tropical Pacific Ocean. Mar. Mamm. Sci. 19(1):20-37.

Oswald, J.N. 1999. Delphinid whistles recorded in the eastern tropical Pacific Ocean. NOAA Administrative Report LJ-99-07C. 50 pp.

Rankin, S., D. Ljungblad, C. Clark, and H. Kato. 2005. Vocalisations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001/2002 and 2002/2003 IWC/SOWER circumpolar cruises, Area V, Antarctica. J. Cetacean res. Manage. 7(1):13-20.

Rankin, S., T. F. Norris, M. A. Smultea, C. Oedekoven, A. M. Zoidis, E. Silva, and J. Rivers. 2007. A visual sighting and acoustic detections of minke whales, *Balaenoptera acutorostrata* (Cetacean: Balaenopteridae), in nearshore Hawaiian Waters. Pac. Sci. 61(3):395-398.

Rankin, S., J.N. Oswald, and J. Barlow. 2008. Acoustic behavior of dolphins in the Pacific Ocean: Implications for using passive acoustic methods for population studies. Can. J. Acoustics, 36(1):88-92.

Rankin, S. and J. Barlow. 2005. Source of the North Pacific “boing” sound attributed to minke whales. J. Acoust. Soc. Am. 118(5):3346-3351.

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