ESTIMATES OF ABUNDANCE OF WESTERN/SOUTHERN SPOTTED, WHITEBELLY SPINNER, STRIPED AND COMMON DOLPHINS, AND PILOT, SPERM AND BRYDE'S WHALES IN THE EASTERN TROPICAL PACIFIC OCEAN

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ABSTRACT

Estimates of abundance for the western/southern stock of offshore spotted dolphins (*Stenella attenuata*), the whitebelly stock of spinner dolphins (*S. longirostris*), striped dolphins (*S. coeruleoalba*), three stocks of short-beaked common dolphins (*Delphinus delphis*), short-finned pilot whales (*Globicephala macrorhynchus*), sperm whales (*Physeter macrocephalus*) and Bryde's whales (*Balaenoptera edeni*) in the eastern tropical Pacific Ocean are presented. The estimates are based on large-scale line-transect surveys carried out with oceanographic research vessels in 8 different years between 1986 and 2000. Searching for cetaceans was conducted primarily with pedestal-mounted 25x150 binoculars fitted with azimuth rings and reticles for angle and distance measurements. Aerial photography was used to improve observers' estimates of group sizes. Estimates of abundance for each species or stock in each year were based on modified line-transect methods which included covariates to model the probability of detection. For the 15-year period, the low and high total estimates of abundance (in numbers of animals) were: 598,541 and 1,444,154 for western/southern offshore spotted dolphins, 243,812 and 1,067,540 for whitebelly spinner dolphins, 801,210 and 1,497,428 for striped dolphins; 56,207 and 642,465 for northern common dolphins; 180,460 and 731,652 for central common dolphins; 292,078 and 2,301,478 for southern common dolphins; 136,448 and 589,315 for pilot whales; 4,145 and 49,653 for sperm whales; and 3,364 and 14,413 for Bryde's whales. Most species/stocks did not show significant changes between the 1986-1990 and 1998-2000 periods. Pilot and Bryde's whales were significantly higher in the later period, but interpretation of changes in abundance are confounded by several factors, including movement in and out of the study area and a larger survey area in the later period.

INTRODUCTION

The purse-seine fishery for yellowfin tuna (*Thunnus albacares*) in the eastern tropical Pacific Ocean (ETP) utilizes the association of seabirds, dolphins and fish to locate and catch schools of large tuna (Perrin 1969, Au and Pitman 1986). However, the large bycatch of dolphins in the early years of the fishery led to the decline of several dolphin species, primarily spotted (*Stenella attenuata*) and spinner (*S. longirostris*) dolphins (Smith 1983, Wade 1993). The Southwest Fisheries Science Center (SWFSC) of the National Marine Fisheries Service has carried out numerous research cruises in the ETP since 1974 to study various aspects of the tuna-dolphin problem. In particular, cruises were carried out annually from 1986-1990, and again from 1998-2000, which covered the whole range of the fishery and which were specifically designed to gather data on which to base estimates of cetacean abundance.

Abundance estimates based on the 1986-1990 cruises have previously been published as annual estimates for dolphins (Wade and Gerrodette 1992), and as pooled estimates over the entire 5-year period for all cetacean species (Wade and Gerrodette 1993). These previous estimates have been carried out with conventional line-transect methods (Buckland et al. 1993).

Recent advances in line-transect analysis permit modelling the probability of detecting cetaceans on a survey as a function of factors other than perpendicular distance alone (Buckland et al. 2001, Marques 2001, Forcada 2002). Simulations have shown these new estimators to be more accurate and precise than traditional univariate methods (Forcada 2002). In addition, for the ETP cetacean data, improved estimates of group size (Gerrodette et al. 2002) and distances from ship to sighting (Lerczak and Hobbs 1998, Kinzey and Gerrodette 2001, Kinzey et al. 2002) are now available. Gerrodette and Forcada (2002) used these methods to estimate the abundance of the three dolphin stocks which are declared depleted under the U.S. Marine Mammal Protection Act: the coastal and northeastern offshore stocks of spotted dolphins and the eastern stock of spinner dolphins. Here we use the new methods and the most recent data to estimate the abundance of the western/southern stock of offshore spotted dolphins, the whitebelly stock of spinner dolphins, the northern, central and southern stocks of short-beaked common dolphins (*Delphinus delphis*), and one stock each of striped dolphins (*Stenella coeruleoalba*), short-finned pilot whales (*Globicephala macrorhynchus*), sperm whales (*Physeter macrocephalus*) and Bryde's whales (*Balaenoptera edeni*).

METHODS

Stocks and survey design

The surveys were designed to estimate the abundance of dolphin stocks (management units) most affected by the tuna purse-seine fishery. These stocks were the northeastern offshore spotted dolphin, *Stenella attenuata*, north of 5EN and east of 120EW (Perrin et al. 1994), and the eastern spinner dolphin, *Stenella longirostris orientalis* (Perrin 1990). The range of the fishery and the affected dolphin populations is a large triangular area in the eastern tropical Pacific Ocean (Fig. 1). Although the surveys were designed for these stocks, the data permit estimation of abundance for other cetaceans occurring in the area. Within the study area, striped dolphins, and pilot, sperm and Bryde's whales are considered to be single stocks, while short-beaked common dolphins are divided into northern, central and southern stocks (Dizon et al. 1994). The western/southern stock of offshore spotted dolphins and the whitebelly stock of spinner dolphins occur in the outer portions of the study area.

Cruises carried out in the 1970s and early 1980s were focussed primarily on spotted and spinner dolphins, and did not consistently record sightings of other species. Beginning in 1986, all cetacean sightings have been recorded. In this report, therefore, we base estimates of abundance on the five cruises conducted annually from 1986-1990 and the three cruises conducted annually from 1998-2000. All of these cruises were designed to estimate abundance and were carried out with consistent field methods described below. The NOAA Ships *David Starr Jordan* and *McArthur* were used in all eight years, and the R/V *Endeavor* from the University of Rhode Island was used in addition in 1998. All ships were oceanographic research vessels similar in length (52-57m) and observer eye height (10.4-10.7m). In each year, the ships were in the study area for over four months, from late July through the first week in December, with port stops every 3-4 weeks. Details of itinerary, tracklines and personnel are given in the cruise data reports (Holt and Jackson 1987, 1988, Holt and Sexton 1987, 1988, 1989, Sexton et al. 1989, Hill et al. 1990a, b, 1991a, b, Kinzey et al. 1999, 2000a, 2001).

Search effort on the 1986-1990 cruises was stratified into inshore, middle, west and south areas (Fig. 2A), while effort on the 1998-2000 cruises was stratified into coastal, core and outer areas (Fig. 2B). Data for western/southern offshore spotted and whitebelly spinner dolphins, as well as for species with a single stock in the study area (striped dolphins, and pilot, sperm and Bryde's whales), were analyzed by these strata. For the analysis of short-beaked common dolphins, which are divided into three stocks, the study area was post-stratified into three areas of approximately uniform effort corresponding to common dolphin stock boundaries (Fig. 2C). In the remainder of this report, the pelagic short-beaked common dolphins will simply be called common dolphins, as distinct from the coastal long-beaked common dolphins (*D. capensis*). Within each stratum, transect lines were randomly but not uniformly spaced, given the logistical constraints of ship range and speed. Ships moved at night, which contributed to some independence among daily transects. The starting point of each day's transect effort was wherever the ship happened to be along the overall trackline. Further details of survey design are available in Holt et al. (1987) for the 1986-1990 cruises and Gerrodette et al. (1998) for the 1998-2000 surveys.

Field methods

Methods of collecting data followed standard protocols for ship-based line-transect surveys conducted by the SWFSC (Kinzey et al. 2000b, Barlow et al. 2001). In workable conditions, a visual search for cetaceans was conducted on the flying bridge of each vessel during daylight hours as the ship moved along the trackline at a speed of 10 knots. On each ship, six marine mammal observers stood watch, three at a time. The team of three observers rotated positions every 40 minutes; thus, each observer stood watch for two hours, then had two hours rest. While on duty, two observers, one on each side of the ship, searched with pedestal-mounted 25x150 binoculars. Each 25X observer scanned from abeam (90E from the trackline) on the side of the vessel where the binocular was mounted to 10E past the trackline on the opposite side. Together, the two 25X observers thus searched the 180E forward of the ship with a 20E area of overlap near the trackline. The third observer searched by eye and with a hand-held 7X binocular, covering areas closer to the ship over the whole 180E.

When marine mammals were sighted, observers measured the distance to the animals. The 25X binoculars were fitted with azimuth rings on the pedestal for measurement of horizontal angles from the trackline to the animals, and reticles in the ocular lenses for measurement of vertical angles from the horizon to the animals in the water. Reticle values were converted to angular values (Kinzey and Gerrodette 2001), and angular values converted to radial distance from the observer, based on height above the water (Gordon 1990, Lerczak and Hobbs 1998). Radial distance r was converted to perpendicular distance y from the trackline by $y = r \sin \theta$, where θ was the horizontal angle of the sighting from the trackline. Radial distance measurements made with reticles were checked against radar measurements under a variety of field conditions and found to be accurate except for a slight tendency to underestimate distance beyond 4 km (Kinzey et al. 2002). Atmospheric refraction of light rays causes the horizon to be perceived slightly higher than it actually is, and hence distance to objects near the horizon to be underestimated (Leaper and Gordon 2001). Inclusion of a factor for refraction decreased this slight tendency to underestimate the distance to sightings near the horizon (Kinzey et al. 2002).

Data on sightings and transect effort were entered into a laptop computer (or on paper forms in 1986-90) by the observer who was currently not searching with a 25X binocular. In addition to angle and reticle, Beaufort sea state, visibility, sun angle, swell height, presence of birds, sighting cue and other factors that might affect detection probability were recorded with each sighting. The data entry program automatically recorded the position of the ship with a GPS signal from the ship. If the sighting was less than 5.6 km (3 nm) from the trackline, the observer team went "off-effort" and directed the ship to leave the trackline and to approach the animal(s) sighted. The observers identified the sighting to species or subspecies (if possible) and made group size estimates. Observers discussed distinguishing field characteristics for purposes of species and stock identification, but they estimated group sizes and, in the case of mixed-species schools, group composition, independently. When the cruise was completed, all data underwent a thorough checking and editing process (Jackson 2001).

Species identification

Each observer team had at least one observer highly experienced in the field identification of marine mammals in the ETP. If a sighting could not be identified to species or subspecies with certainty, it was placed into a less specific category which reflected the degree of identification (unidentified rorqual, for example, or, even less specifically, unidentified large whale). Abundance of these unidentified sightings was prorated by species (see below).

Within the ETP study area, certain sightings, while not identified to species in the field, could be assigned to species with confidence for the purposes of analysis. For example, it was frequently difficult to obtain a sufficiently good view of the three ridges on the rostrum of a Bryde's whale to distinguish it from a sei whale (*B. borealis*), which has a single ridge. Such sightings were recorded as unidentified Bryde's/sei whale. However, sei whales generally occur in higher latitudes than Bryde's whales, and in the eight years of data considered here, we had only two confirmed sightings of sei whales, compared to over 200 confirmed sightings of Bryde's whales. We therefore assumed in this analysis that all unidentified Bryde's/sei sightings were in fact Bryde's whales. Similarly, we assumed that all unidentified pilot whale sightings were short-finned pilot whales, since long-finned pilot whales (*G. melas*) have not been recorded in the ETP area (Rice 1998).

Group size

For animals that occur in groups, accurate determination of the size of the group is fundamental for accurate estimation of abundance. Determining the size of a large groups of active cetaceans is a difficult task. Aerial photography was used to improve dolphin school size estimates. From 1987-2000, the *David Starr Jordan* carried a helicopter equipped with a medium-format, motion-compensated, military reconnaissance camera. In suitable conditions of sea state, sun angle and school configuration, it was possible to photograph entire schools of dolphins and to count the number of dolphins directly from the negatives (Gilpatrick 1993). However, aerial photographs were available for only a subset of schools seen on the *Jordan*, mostly spotted and spinner dolphin schools, and none of the schools seen on the other ships. For most schools, school size was estimated from the best, high and low estimates made by each observer.

By comparing each observer's estimates of school size to the photographic counts, the observer's group size estimation tendencies could be assessed. Based on a regression of estimates on counts, individual correction or "calibration" factors for 52 observers were estimated (Gerrodette and Perrin 1991, Barlow et al. 1998, Gerrodette et al. 2002). These factors were used to produce a calibrated estimate of school size when the observer's original ("best") estimate of school size fell in the range of photographed schools for which he/she had been calibrated. Calibration factors were not available for every observer, either because (1) the observer worked prior to the start of the aerial calibration program in 1987, or (2) the observer had an insufficient number of photographed schools to estimate the regression coefficients. For school size estimates made by uncalibrated observers, or for schools which fell outside the range of school sizes for which an observer had been calibrated, we adjusted the observer's best estimate by dividing the estimate by 0.860, the mean of ratios of best estimate to photo count for the 52 calibrated observers (Gerrodette et al. 2002).

For most schools, it was possible to obtain improved "calibrated estimates" of school size using these coefficients, assuming the same correction factors for each observer applied to all species. Previous analyses have not indicated differences among species in an observer's estimation tendencies (Gerrodette and Perrin 1991). Thus the calibration procedure applied mainly to sightings of spotted, spinner, striped and common dolphins and pilot whales, because group sizes of sperm and Bryde's whales were frequently too small for calibration to apply.

We combined the individual estimates made by each observer, adjusted as described above, to obtain a single estimate of school size for each school. Because the calibration procedure was based on the logarithm of the estimates, the weighting and averaging was also carried out on the logarithms, using the inverse of the variance of each observer as weights. The logarithm of the final calibrated estimate of school size for each sighting was

$$\ln \hat{s} = n^{-1} \sum_{i=1}^{n} w_i \ln C_i ,$$

with variance

$$\text{var}\,(\ln \hat{s}) = n^{-1} \sum_{i=1}^{n} \frac{v_i w_i^2}{k_i} ,$$

where n = number of calibrated estimates C for the school, k_i = number of points (photographed schools) used to estimate the regression coefficients for the observer making the i-th estimate, $w_i = v_i^{-1} / \Sigma v_i^{-1}$, and v_i = residual variance from the regression of the log of school size estimates on log of photo counts for the observer making the i-th estimate (Gerrodette et al. 2002).

Abundance estimation

Estimation of abundance was based on distance sampling (Buckland et al. 2001). A multivariate extension of conventional line-transect analysis (Forcada 2002) estimated abundance N as

$$\hat{N} = \sum_j \frac{A_j}{2L_j} \sum_i \hat{f}_{ij}(0, c_{ij})\, \hat{s}_{ij} \ ,$$

where A_j was the area and L_j the length of search effort in stratum j, $\hat{f}_{ij}(0, c_{ij})$ the estimated probability density evaluated at zero perpendicular distance of the ith sighting in stratum j under conditions c_{ij}, and $\hat{s}_{ij}$ the estimated group size of the ith sighting in stratum j (subgroup size of the species of interest in the case of mixed-species schools). Estimation was based on search effort and sightings that occurred during on-effort periods, in conditions of Beaufort < 6 and visibility > 4km. It was conventionally assumed that all cetacean groups on or near the trackline were detected [*i.e.*, $g(0)=1.0$]. This was likely to be true, at least to a close approximation, for all species except sperm whales (see Discussion). The vector of covariates c_{ij} included continuous variables group size, Beaufort sea state and time of day, and categorical variables species, ship, stratum, sighting cue, glare, whether the school was a single- or mixed-species group, and whether seabirds were present or not. Sea state measured on the Beaufort scale was actually a discrete variable, but the ordinal scale could be modeled satisfactorily as a continuous variable (Barlow et al. 2001). The continuous variable swell height was also recorded on the 1998-2000 cruises.

We explored half-normal and hazard-rate models, each with variable numbers and types of covariates (Forcada 2002). Hazard-rate models gave highly variable estimates of effective strip width among years, and unpublished analyses suggested grounds for biased $f_{ij}\,(0,c_{ij})$ estimates using this model in the study data. For consistency we used the half-normal model in each year, with sightings truncated at 5.5km. For each species or stock in each year, covariates were tested singly and in additive combination, and a set of best models was chosen on the basis of Akaike's Information Criterion corrected for sample size (AIC_c) (Hurvich and Tsai 1989). For computational efficiency, we retained as reasonable models all models with an AIC_c difference (ΔAIC) of less than 2 from the best model (Burnham and Anderson 1998). Final estimates of $f_{ij}\,(0,c_{ij})$ were produced with model averaging, using the AIC_c scores as weighting factors. The weight of the estimate from the jth model was (Burnham and Anderson 1998)

$$w_j = \frac{\exp(-\frac{1}{2}\Delta AIC_j)}{\sum_j \exp(-\frac{1}{2}\Delta AIC_j)}.$$

Strictly speaking, model-averaged estimates were no longer maximum likelihood estimates, but for all of the analyses presented here, they were checked and found to be extremely close.

Unidentified sightings

The number of unidentified sightings was first reduced by assigning unidentified sightings that were recorded as "probable" sightings of an identified category to that identified category. For the remaining unidentified sightings, we estimated abundance for the unidentified category and prorated the abundance among appropriate stocks in proportion, by stratum, to the estimated abundance from identified sightings of those stocks that were included in the broader unidentified category. The general form of the proration was

$$\hat{N}_{ij}^{*} = \hat{N}_{ij} + \hat{N}_{uj}\left(\frac{\hat{N}_{ij}}{\hat{N}_{ij} + \sum_{k}\hat{N}_{kj}}\right),$$

where $\hat{N}_{ij}^{*}$ was the revised abundance estimate of stock i in stratum j, $\hat{N}_{ij}$ the abundance of stock i in stratum j estimated from identified sightings of stock i, $\hat{N}_{uj}$ the abundance of the unidentified category estimated from unidentified sightings in stratum j, and $\hat{N}_{kj}$ the abundance of stock k in stratum j for stocks other than i included in the unidentified sighting category.

RESULTS

Area, effort and sightings

The areas of each stratum (A_j) and length of search effort in each stratum (L_j) are given in Table 1. The total size of the ETP study area was 19.6 million km^2 in 1986-1990 and 21.3 million km^2 in 1998-2000, about 9% larger. The three strata for short-beaked common dolphins (Fig. 2C) were a 15.4 million km^2 subset of the whole ETP study. During the four months of surveying each year, the total length of transect effort varied between 24,000 and 31,000 km, except for 42,000 km in 1998 with the additional ship (Table 1). Restricting effort to conditions of Beaufort < 6 and visibility > 4 km resulted in a loss of about 1% of the effort and <1% of the sightings. The number of identified sightings, before truncation, for the species considered in this paper is shown in Table 2, together with the species groups used for proration. Striped dolphins were the most frequently identified species every year, with between 141 and 204 sightings. Of the species considered here, sperm and Bryde's whales tended to be the least frequently seen.

Model selection and parameter estimation

A variety of models were selected for $f_{ij}(0,c_{ij})$ estimation (Table 3). The conventional line-transect model using perpendicular distance alone was rarely indicated as the best model; rather, the AIC$_c$ scores indicated that a variety of covariates, most frequently Beaufort sea state and group size, but also including birds, time, ship, cue, species and stratum, were important factors in the detection of cetaceans. Common and striped dolphins usually had a single model that was clearly better than others (ΔAIC$_c$ > 10), while pilot, sperm and Bryde's whales frequently had several models that had AIC$_c$ scores within 1 or 2 units of the top model (Table 3). However, different models usually gave very similar estimates for the mean $f(0)$. Stratum and species, the stratifications most frequently used in conventional line-transect analysis, were selected in only a few cases. Means of group size and $f(0)$ for each species or stock in each year are presented in Table 4.

Abundance

Estimates of abundance are presented in Table 5, together with standard errors, coefficients of variation and confidence limits. The estimates are presented as a graph in Fig. 3. Striped dolphins were among the most abundant of the species considered here, with estimates ranging from about 0.8 to 1.5 million dolphins in the ETP (Table 5), with no clear trend in estimated abundance with year (Fig. 3). The southern stock of common dolphins was also abundant, but estimates were highly variable. The recent (1998-2000) estimates of both the northern and central stocks of common dolphins were between 500,000 and 600,000 animals. Short-finned pilot whales tended to have higher estimates in recent years, while sperm whales tended to have lower. Bryde's whales also tended to have higher estimates in recent years. An analysis of variance showed significantly higher estimates of abundance for pilot and Bryde's whales in the later (1998-2000) period than in the earlier (1986-1990) period; all other species or stocks did not show a significant difference at the $\alpha = 0.05$ level.

For the 15-year period, the low and high total estimates of abundance (in numbers of animals) were: 598,541 and 1,444,154 for western/southern offshore spotted dolphins, 243,812 and 1,067,540 for whitebelly spinner dolphins, 801,210 and 1,497,428 for striped dolphins; 56,207 and 642,465 for northern common dolphins; 180,460 and 731,652 for central common dolphins; 292,078 and 2,301,478 for southern common dolphins; 136,448 and 589,315 for pilot whales; 4,145 and 49,653 for sperm whales; and 3,364 and 14,413 for Bryde's whales.

DISCUSSION

Previous pooled estimates for 1986-1990 (Wade and Gerrodette 1993) for these species were based on conventional line-transect methods (Buckland et al. 1993). Conventional methods modelled perpendicular distance only, and relied on "pooling robustness" (Burnham et al. 1980) to deal with the multiple sources of heterogeneity in the detection process. The use of multivariate techniques (Forcada 2002) to model the effects of covariates such as school size, sea state and sighting cue, on the detection process, evidently had a strong effect. Models incorporating covariates such as Beaufort sea state and group size were nearly always selected by AIC_c as the best model, indicating that these covariates had important influences on the probability of school detection. In addition, the improved methods have allowed reliable estimates in each year rather than having to pool estimates over 5 years to obtain a sufficient sample size for proper estimation. The means of the estimates presented here are generally similar to previous (Wade and Gerrodette 1993) estimates for 1986-1990, except that striped dolphins are lower and pilot whales are higher.

Distance sampling conventionally assumes that all objects on or near the trackline are detected [*i.e.*, $g(0)=1.0$]. For the dolphins, this appeared to be satisfied to a close approximation. A tally of dolphin sightings missed by marine mammal observers but seen by bird observers indicated that the marine mammal observers detected 96.5% of all dolphin sightings within 300m of the trackline (Brandon et al. 2002). This was reasonable considering that the dolphins tended to occur in medium to large schools, individual dolphins did not have long dive times, and diving was not synchronous among individuals in a school. Therefore, it is likely that some members of the school were at the surface at all times. Pilot and Bryde's whales were also unlikely to be missed if present on the trackline due to their short dive times relative to the speed of the ship. Sperm whales, on the other hand, could be missed due to their long dive times. An estimate of $g(0)$ for sperm whales on these surveys is available, but this applies only to single animals, not groups (Barlow and Sexton 1996). In addition, due to their long dive times and sometimes asynchronous diving behavior, the sizes of sperm whale groups are difficult to estimate accurately. Extended observation of sperm whale groups has indicated that a count of whales during a 10 min period (as was done in 1986-1990) underestimates group size by a factor of 2 on average, but with large variance (B. Taylor, pers. comm). Because $g(0)$ was < 1 and group size was underestimated as well, the estimates for sperm whales are biased low. However, the bias should be consistent across years, so the estimate of sperm whale abundance should be considered an index of relative abundance rather than an estimate of absolute abundance.

An analysis of variance for difference in abundance indicated significant increases in abundance for pilot whales and Bryde's whales between the early period (1986-1990) and later (1998-2000) periods. Other species or stocks did not show a temporal trend. However, the large variability in year-to-year estimates for most species meant there was low power for the anova to detect any changes. The large variability and high CVs (Table 5) are due in part to the fact that the surveys were designed for other stocks, and hence the survey effort was not optimized for these stocks.

The interpretation of temporal changes in abundance for the species and stocks considered in this paper is complicated by several factors in addition to internal population dynamics. Most of the stocks have distributions that extend beyond the surveyed area. Only the central stock of common dolphins has a distribution entirely within the study area. The distributions of northern and southern stocks of common dolphins extend northward and southward outside the study area. Striped dolphins, and pilot, sperm and Bryde's whales occur throughout the study area, but have broader distributions throughout the tropical Pacific. For species or stocks whose distributions extend beyond the surveyed area, movement into or out of the study area in response to changes in oceanographic conditions may contribute to variability in annual estimates of abundance or to differences between the two periods considered here. Further, pilot whales and sperm whale populations were reduced due to whaling in the past, and their populations may still be recovering. Finally, the study area in the later period was about 9% larger than the early period. This will tend to make the later estimates higher for species that occur throughout the study area. If a species occurs uniformly the study area, estimates would be expected to be 9% higher; if the distribution is not uniform, such a simple adjustment is not possible. No correction for the difference in survey area has been attempted for the estimates presented here.

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Table 1. Area (in km^2) and length of survey effort (in km) in conditions of Beaufort < 6 and visibility > 4 km, 1986-2000, by stratum. Strata are shown in Fig. 2.

	Year	Stratum				Total
		Inshore	Middle	West	South	
Area		6,003,327	3,809,787	5,217,851	4,539,451	19,570,416
Effort	1986	11,707	7,553	3,848	3,882	26,990
	1987	11,295	7,805	3,823	4,491	27,414
	1988	9,401	6,178	3,209	5,019	23,807
	1989	11,725	7,900	3,659	4,788	28,072
	1990	10,048	8,863	5,484	6,556	30,951
		Core	Outer	Coastal		
Area		5,869,484	14,777,853	706,287		21,353,624
Effort	1998	19,955	17,185	5,247		42,387
	1999	15,797	11,821	2,112		29,730
	2000	15,044	11,523	3,429		29,996
Common dolphins						
		Northern	Central	Southern		
Area		3,286,419	7,049,050	5,078,072		15,413,541
Effort	1986	5,708	12,308	6,763		24,779
	1987	5,044	14,538	5,201		24,783
	1988	4,568	11,158	5,468		21,194
	1989	6,169	12,077	6,930		25,176
	1990	4,536	13,522	8,759		26,817
	1998	11,576	18,256	6,431		36,263
	1999	9,265	13,399	3,727		26,391
	2000	8,864	12,856	3,794		25,514

Table 2. Number of sightings (schools) and species groups used in $f(0)$ estimation and proration of unidentified sightings.

	Common and striped dolphins					Pilot whales					Sperm and Bryde's whales				
	common dolphin	striped dolphin	other small dolphin	medium dolphin	unID dolphin	pilot whale	other blackfish	all ziphiids	all Kogia	unID small whale	sperm whale	Bryde's whale	other rorqual	unID rorqual	unID large whale
1986	44	141	255	130	155	34	25	55	36	28	43	15	6	19	8
1987	30	165	263	138	208	39	34	37	13	57	43	17	4	21	7
1988	53	189	195	133	173	51	21	48	16	28	30	26	10	18	19
1989	44	193	276	125	203	52	28	55	25	59	40	20	11	13	31
1990	36	146	207	129	208	57	29	40	8	18	26	31	11	41	33
1998	132	204	540	408	292	51	41	71	33	17	40	83	21	34	14
1999	117	197	315	204	182	44	22	65	14	8	14	44	23	15	11
2000	88	170	345	230	141	42	27	65	28	15	7	58	28	11	6

Table 3. Models for $f(0)$ estimation. Each cell of the table shows the variables (perpendicular distance plus possible covariates) of the model(s), in the order selected by AIC_c, used with the half-normal model for estimation of $f(0)$ for that species and year. If more than one model is shown, model-averaging was used. Abbreviations are: pd = perpendicular distance, st = stratum, sp = species (as grouped in Table 2), gs = group (total school) size, t = time of day, s = ship, bf = Beaufort, b = birds present, c=sighting cue. Variables within a model are connected with "+".

	Common and striped dolphins	Pilot whales	Sperm and Bryde's whales
1986	pd+bf+s	pd, pd+t	pd+bf
1987	pd+bf+b	pd+bf, pd, pd+bf+t	pd, pd+bf, pd+t
1988	pd, pd+bf	pd+gs, pd+gs+t	pd+c, pd, pd+gs, pd+gs+c
1989	pd+gs+s, pd+s+b	pd+t	pd+sp
1990	pd+bf+b	pd+bf, pd	pd+gs+sp
1998	pd+c+b	pd+bf, pd+s, pd+bf+s, pd+bf+t	pd, pd+bf
1999	pd+gs	pd	pd+st, pd+st+bf
2000	pd+gs+s	pd, pd+gs, pd+t, pd+s	pd, pd+s, pd+gs

Table 4. Mean $f(0)$ in km^{-1} and mean group size (gs) by stock and year.

	Northern common dolphins		Central common dolphins		Southern common dolphins		Striped dolphins		Short-finned pilot whales		Sperm whales		Bryde's whales	
	$f(0)$	gs	$f(0)$	gs	$f(0)$	gs	$f(0)$	gs	$f(0)$	gs	$f(0)$	gs	$f(0)$	gs
1986	0.382	187.5	0.349	158.3	0.458	399.7	0.388	42.9	0.421	14.8	0.371	7.0	0.406	1.5
1987	0.326	81.2	0.344	215.5	0.334	165.6	0.405	52.7	0.458	20.2	0.303	8.2	0.304	1.4
1988	0.331	190.0	0.332	435.7	0.331	425.6	0.341	63.5	0.297	16.1	0.324	11.5	0.299	1.6
1989	0.313	163.5	0.297	265.2	0.359	466.9	0.335	57.2	0.441	17.4	0.305	10.0	0.325	2.3
1990	0.329	221.8	0.318	206.1	0.309	565.9	0.419	66.9	0.457	22.5	0.269	7.3	0.533	1.8
1998	0.291	538.0	0.293	122.2	0.294	209.8	0.336	45.6	0.430	24.0	0.351	5.6	0.351	1.4
1999	0.328	292.8	0.328	139.0	0.327	261.4	0.345	39.4	0.418	17.0	0.297	16.8	0.350	1.6
2000	0.311	267.1	0.304	317.6	0.316	392.8	0.339	52.8	0.415	30.2	0.307	9.8	0.309	1.6

Table 5. Estimates of abundance with measures of precision. W/S = Western/southern, SE = standard error, %CV = coefficient of variation expressed as a percentage, LCL = lower 95% confidence limit, and UCL = upper 95% confidence limit.

1986	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	1,077,662	410,992	35.3	547,857	2,186,263
Whitebelly spinner dolphin	642,446	181,732	28.2	348,741	1,065,797
Short-finned pilot whale	136,448	57,289	39.1	61,767	279,995
Sperm whale	19,584	6,501	32.5	9,790	36,237
Bryde's whale	4,489	2,002	43.9	1,681	9,512
Striped dolphin	801,210	162,908	19.1	519,792	1,096,743
Northern common dolphin	306,177	158,442	54.0	55,680	657,017
Central common dolphin	180,668	86,054	47.5	37,548	359,181
Southern common dolphin	1,365,255	658,460	52.5	213,436	2,709,167
Total common dolphin	1,825,841	679,828	39.9	638,200	3,153,322

1987	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	1,335,011	322,067	25.1	872,560	2,225,199
Whitebelly spinner dolphin	617,333	278,698	42.7	317,368	1,530,271
Short-finned pilot whale	252,459	82,051	31.3	109,978	440,302
Sperm whale	23,763	5,166	21.5	14,774	35,072
Bryde's whale	3,364	929	26.7	1,965	5,504
Striped dolphin	1,336,057	248,089	19.2	981,297	2,187,901
Northern common dolphin	56,207	44,975	79.1	590	161,316
Central common dolphin	250,107	116,471	46.2	76,604	524,573
Southern common dolphin	292,078	157,522	53.5	64,403	652,606
Total common dolphin	599,066	201,832	33.5	261,925	1,028,880

1988	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	969,367	408,368	41.6	338,297	1,865,658
Whitebelly spinner dolphin	724,339	245,628	31.9	335,795	1,267,470
Short-finned pilot whale	249,605	62,276	23.1	163,351	400,416
Sperm whale	25,001	14,367	50.1	8,748	62,855
Bryde's whale	7,420	1,919	24.6	4,177	11,893
Striped dolphin	1,497,428	209,455	13.9	1,131,334	1,956,828
Northern common dolphin	66,747	56,188	79.8	2,285	209,226
Central common dolphin	731,652	270,958	37.0	279,484	1,316,738
Southern common dolphin	1,825,654	738,510	40.0	536,429	3,402,486
Total common dolphin	2,602,524	786,508	29.9	1,226,161	4,315,923

1989	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	1,444,154	456,151	30.2	763,375	2,544,658
Whitebelly spinner dolphin	1,067,540	436,790	39.6	385,279	2,082,648
Short-finned pilot whale	232,629	52,683	22.0	143,026	354,584
Sperm whale	49,653	19,301	37.7	23,354	93,461
Bryde's whale	9,917	3,569	34.6	4,452	18,720
Striped dolphin	1,163,697	267,824	20.6	811,078	1,653,793
Northern common dolphin	81,229	43,632	53.3	14,998	178,872
Central common dolphin	180,460	80,871	45.6	37,983	357,599
Southern common dolphin	1,620,062	751,088	43.1	523,452	3,471,423
Total common dolphin	1,887,599	763,682	38.0	824,725	3,806,559

1990	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	598,541	131,299	22.0	368,965	884,030
Whitebelly spinner dolphin	499,356	290,001	54.4	130,125	1,191,210
Short-finned pilot whale	305,948	71,907	22.5	195,878	474,206
Sperm whale	12,407	4,946	35.7	5,793	25,063
Bryde's whale	8,224	1,873	22.8	4,899	12,202
Striped dolphin	1,216,919	195,164	15.8	887,402	1,630,693
Northern common dolphin	642,465	176,926	101.1	13,834	729,808
Central common dolphin	628,971	178,387	62.3	39,970	717,107
Southern common dolphin	1,808,003	501,318	64.1	204,428	2,355,970
Total common dolphin	3,078,781	744,096	59.5	491,693	3,742,092

1998	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	809,163	239,752	28.9	425,958	1,338,535
Whitebelly spinner dolphin	243,812	86,852	34.9	96,627	442,966
Short-finned pilot whale	344,131	78,369	22.0	221,008	513,987
Sperm whale	19,717	7,284	37.7	7,473	35,712
Bryde's whale	14,413	2,972	21.2	8,921	20,250
Striped dolphin	1,056,605	149,273	14.1	793,134	1,394,937
Northern common dolphin	541,787	288,384	55.1	109,293	1,201,173
Central common dolphin	584,742	128,800	22.6	341,161	855,446
Southern common dolphin	1,159,140	363,946	32.2	473,683	1,915,461
Total common dolphin	2,290,271	486,278	21.8	1,327,918	3,259,481

1999	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	823,084	234,159	31.6	335,686	1,253,782
Whitebelly spinner dolphin	780,362	307,377	40.4	231,536	1,405,867
Short-finned pilot whale	356,242	72,741	19.2	248,294	533,721
Sperm whale	26,652	16,101	60.0	6,108	66,146
Bryde's whale	10,823	2,658	24.0	6,664	16,722
Striped dolphin	1,006,090	170,352	16.7	689,830	1,358,088
Northern common dolphin	496,427	194,834	40.0	188,408	937,361
Central common dolphin	539,326	135,282	25.5	296,462	833,670
Southern common dolphin	2,301,478	839,331	37.2	930,922	4,075,142
Total common dolphin	3,316,813	909,928	28.0	1,730,021	5,175,167

2000	Estimate	SE	%CV	LCL	UCL
W/S offshore spotted dolphin	876,075	320,581	30.8	516,619	1,728,073
Whitebelly spinner dolphin	801,048	305,304	37.4	346,023	1,477,634
Short-finned pilot whale	589,315	147,904	25.5	336,036	908,425
Sperm whale	4,145	3,033	72.6	354	12,114
Bryde's whale	10,411	2,106	20.3	6,531	14,747
Striped dolphin	1,047,236	178,150	16.8	741,513	1,439,329
Northern common dolphin	577,947	204,956	35.0	256,750	1,047,011
Central common dolphin	621,135	216,033	34.6	249,775	1,091,938
Southern common dolphin	1,766,551	638,887	35.4	706,532	3,149,036
Total common dolphin	2,963,403	730,230	24.2	1,691,337	4,457,229

Fig. 1. Study area in the eastern tropical Pacific Ocean, with ranges of the main dolphin stocks for which the surveys were designed.

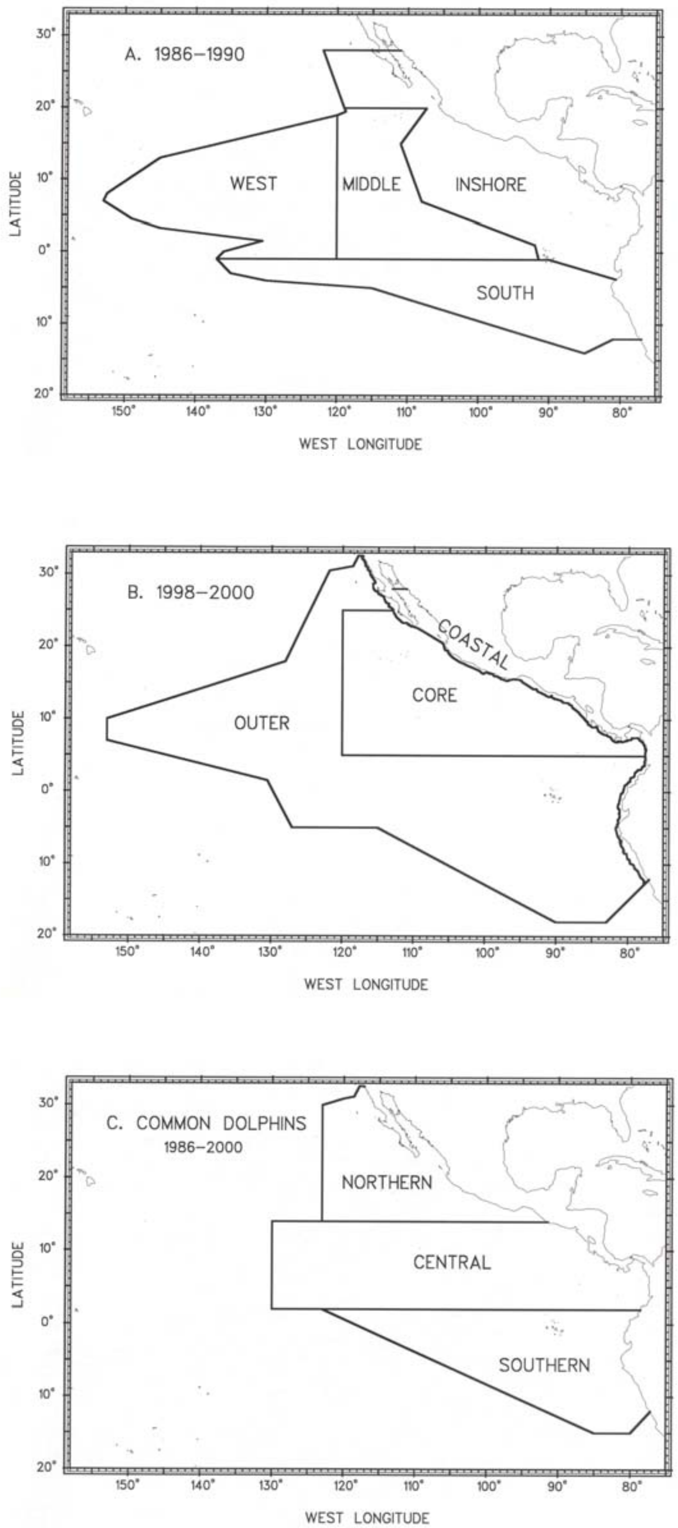

Fig. 2. Strata for the (A) 1986-1990 surveys, (B) 1998-2000 surveys, and (C) short-beaked common dolphin stocks, all years.

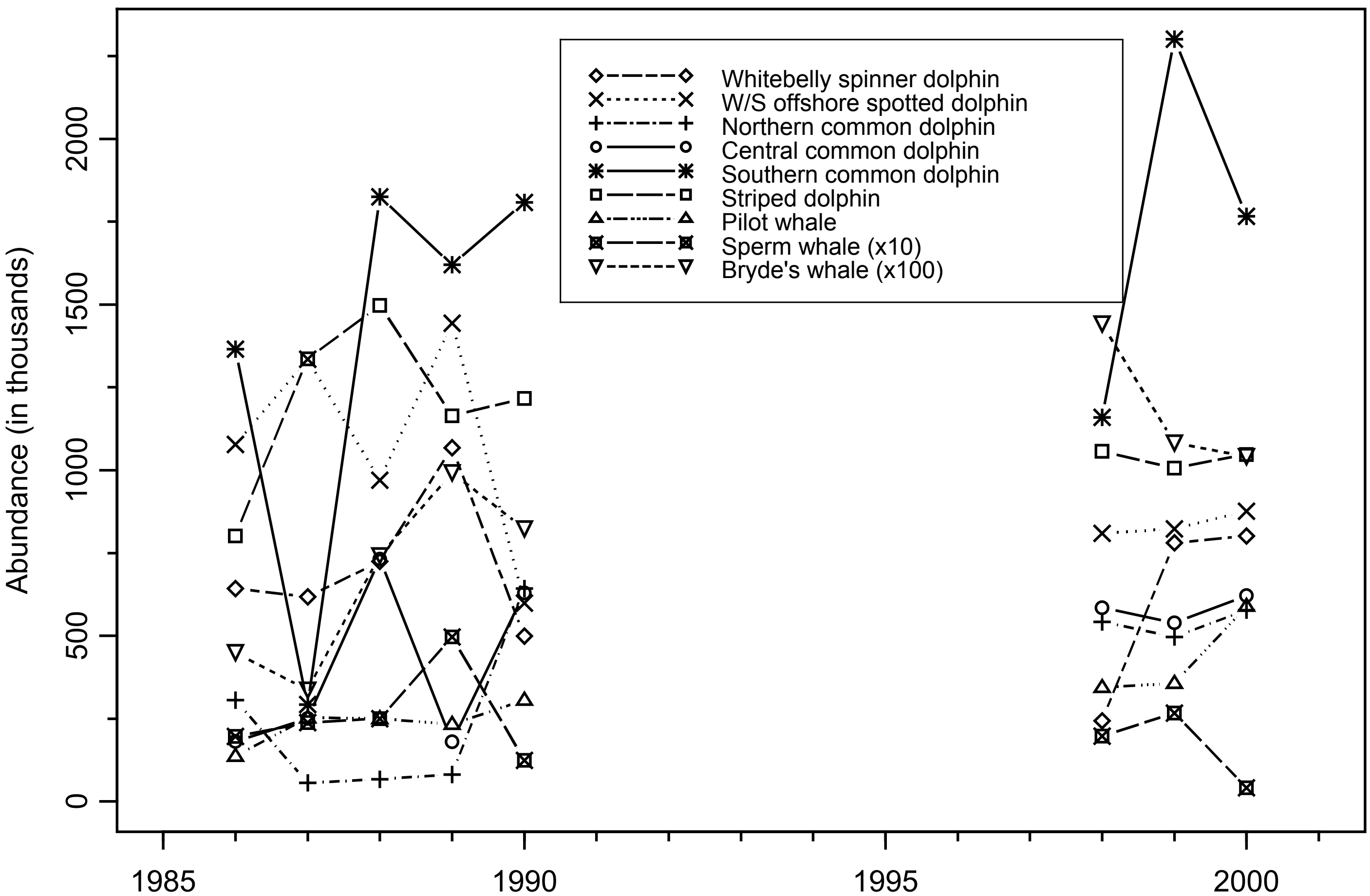

Fig. 3. Estimates of abundance for the whitebelly stock of spinner dolphins, the western/southern stock of offshore spotted dolphins, three stocks of short-beaked common dolphins, striped dolphins, short-finned pilot whales, sperm whales and Bryde's whales in the eastern tropical Pacific, 1986-2000. Note that the estimates of sperm and Bryde's whales have been multiplied by 10 and 100, respectively, to present all the estimates on one scale.