Abundance and population density of cetaceans in the California Current ecosystem

Jay Barlow (contact author)[1]

Karin A. Forney[2]

Email address for J. Barlow: Jay.Barlow@noaa.gov

[1] National Ocean and Atmospheric Administration
Southwest Fisheries Science Center
8604 La Jolla Shores Drive
La Jolla, California 92037

[2] NOAA Southwest Fisheries Science Center
110 Shaffer Road
Santa Cruz, California 95060

Abstract—The abundance and population density of cetaceans along the U.S. west coast were estimated from ship surveys conducted in the summer and fall of 1991, 1993, 1996, 2001, and 2005 by using multiple-covariate, line-transect analyses. Overall, approximately 556,000 cetaceans of 21 species were estimated to be in the 1,141,800-km^2 study area. Delphinoids (Delphinidae and Phocoenidae), the most abundant group, numbered ~540,000 individuals. Abundance in other taxonomic groups included ~5800 baleen whales (Mysticeti), ~7000 beaked whales (Ziphiidae), and ~3200 sperm whales (Physeteridae). This study provides the longest time series of abundance estimates that includes all the cetacean species in any marine ecosystem. These estimates will be used to interpret the impacts of human-caused mortality (such as that documented in fishery bycatch and that caused by ship strikes and other means) and to evaluate the ecological role of cetaceans in the California Current ecosystem.

Manuscript submitted 4 October 2006 to the Scientific Editor's Office.

Manuscript approved for publication 27 June 2007 by the Scientific Editor.

Fish. Bull. 105:509–526 (2007).

Estimates of cetacean abundance, biomass, and population density are key to assessing the potential effects of anthropogenic perturbations on cetacean populations (Carretta et al., 2006) and in understanding the ecological role of cetaceans in marine ecosystems (Trites et al., 1997). Along the U.S. west coast, most cetacean species are vulnerable as bycatch in gillnet fisheries (Julian and Beeson, 1998; Carretta et al., 2005), and fisheries catch many of the same species that cetaceans consume (Trites et al., 1997). Large whales also die from ship strikes (Carretta et al., 2006). West coast cetaceans may be affected by anthropogenic sound (e.g., sonar, ship noise, and seismic surveys) and climate change. There is little published information on current abundance to evaluate direct anthropogenic impacts on cetacean species and to estimate their resource needs.

The abundance of cetaceans along the U.S. west coast was previously estimated for some species in some areas, but most available estimates are based on surveys that were conducted 16 to 30 years ago (Dohl et al., 1986; Barlow, 1995). In addition, most estimates are based only on surveys that were conducted within 185 km of the coast. There was only one survey (in 1991) in waters greater than 185 km offshore of California, and there are no published estimates of cetacean abundance for far offshore waters of Oregon or Washington. The lack of recent estimates and the lack of estimates for offshore waters represent clear gaps in our knowledge of west coast cetaceans.

In this study, new estimates of abundance were determined in order to fill our gaps in knowledge about cetaceans in the California Current ecosystem. Line-transect methods were used to analyze data collected from Southwest Fisheries Science Center (SWFSC) ship surveys in 1991, 1993, 1996, 2001, and 2005 off the U.S. west coast. A new multiple-covariate, line-transect approach (Marques and Buckland, 2003) was used to account for multiple factors that affect the distance at which cetaceans can be seen in different conditions. Because cetaceans dive and can be missed by visual observers, the probability of detecting a group of cetaceans directly on the transect line was estimated from observations made by independent observers on those 1991–2005 surveys and from other sources. Observer-specific corrections were applied to remove a bias in estimating group sizes. These results represent one of the most comprehensive analyses of cetacean abundance and density for any large marine ecosystem.

Materials and methods

Survey

Surveys in 1991, 1993, 1996, 2001, and 2005 were conducted in summer and fall with the same line-transect survey methods from two National Oceanographic and Atmospheric Administration (NOAA) research vessels: the 53-m RV *McArthur* and the 52 m RV *David Starr Jordan*. A third ship, the 62-m RV *McArthur II*, was also used for a very short time in 2005. Transect lines followed a grid that was established before each survey to uniformly cover waters between the coast and approximately 556 km (300 nmi) offshore. Surveys were designed with a uniform grid of transect lines anchored by a randomly chosen start point. Ships traveled at 16.7–18.5 km/h (9–10 kt) through the water. The 1991 and 1993 surveys only covered waters off California, but the subsequent surveys also included waters off Oregon and Washington (Fig. 1).

Experienced field biologists (henceforth referred to as "observers") searched for cetaceans from the flying bridge deck of the ships (observation height ~10.5 m for the two primary vessels, 15.2 m for the RV *McArthur II*). Typically, six observers rotated among three observation stations (left station, where 25× binoculars were used; forward station where the data recorder was positioned; and right station, where 25× binoculars were used). Each observer and recorder watched for 2 hours and then rested for 2 hours. The recorder searched with unaided eyes (and occasionally 7× binoculars) and entered effort and sighting data using a data entry program on a laptop computer. The observers were selected on the basis of previous experience searching for and identifying marine mammals at sea; at least four observers on each ship had previous line-transect experience with cetaceans and at least two were experts in marine mammal identification at sea. Before each survey, observers were given a refresher course in marine mammal identification and group size estimation. Group size and the percentage of each species in a group were estimated and recorded independently and confidentially by each on-duty observer. Generally, after a group of cetaceans was seen, observers took as much time as necessary to estimate group size and species composition. Starting in 1996, at least one hour was allocated to group size estimation for sperm whales to provide reasonable confidence that all members of the group surfaced at least once. Species determinations were recorded only if observers were certain of their species identification; otherwise, animals were identified to the lowest taxonomic level or general category (e.g., large whale or baleen whale) that an observer could determine with certainty. Observers were also encouraged to record separately the most probable species if the actual species could not be determined with certainty. In this article, we used probable species identifications if certain identifications were missing, rather than prorating the unidentified sightings into species categories, as done in other studies (Gerrodette and Forcada, 2005). If probable species identifications were not available, species were classified as unidentified delphinoids, small whales, beaked whales, rorqual whales, or large whales. Common and scientific names for all species are given in Table 1.

Most surveys were conducted in closing mode during which the ship diverted from the trackline as necessary to allow closer estimation of group size and species composition. The ship was not diverted if observers felt that group size and species could be determined from the transect line, as was frequently the case of nearby sightings of Dall's porpoise or large baleen whales. To investigate potential biases associated with the use of closing mode surveys, every third day of effort in 1996 was conducted in passing mode during which the ship did not divert from the trackline except for species of particular interest (sperm whales, short-finned pilot whales, and Baird's beaked whales). No consistent biases were found between the two survey modes; however, group size estimation and species determination suffered in passing mode, and therefore the latter (passing mode) was not undertaken during subsequent surveys.

Frequently, a fourth observer searched for cetacean groups that were missed by the primary team of three observers. Sightings made by this fourth observer were recorded after the group had passed abeam and had been clearly missed by the primary team. The data from the fourth observer were considered conditionally independent of the primary team (conditioned on the animals not being seen by the primary team) and were used to estimate the proportion of sightings missed by the primary team.

Calibration of group size

Individual observers may tend to over- or under-estimate group sizes, and their estimates can be improved by calibration based on a subset of groups with known size (Gerrodette and Forcada, 2005) or based on comparison to data from an unbiased observer (Barlow, 1995). Calibration factors were used to correct estimates made by observers who were previously calibrated by using aerial photographic estimates of group size taken from a helicopter on dolphin surveys in the eastern tropical Pacific (Gerrodette and Forcada, 2005). These calibrations were not applied to groups whose size was outside the range of sizes used in the calibration study. A direct helicopter calibration could not be used on these west coast surveys because the weather was too rough and the water is too turbid. Therefore, we used an indirect calibration method (Barlow, 1995) to calibrate these remaining observers in relation to the directly calibrated observers. The indirect calibration coefficient, β_0, for a given observer was estimated by comparison to calibrated estimates of directly calibrated observers by using log-transformed, least-squares regression through the origin:

$$\ln S^* = \beta_0 \cdot \ln \bar{S}, \qquad (1)$$

where S^* = the observer's best estimate of group size; and

$\bar{S}$ = the mean of calibrated, bias-corrected estimates for all other calibrated observers.

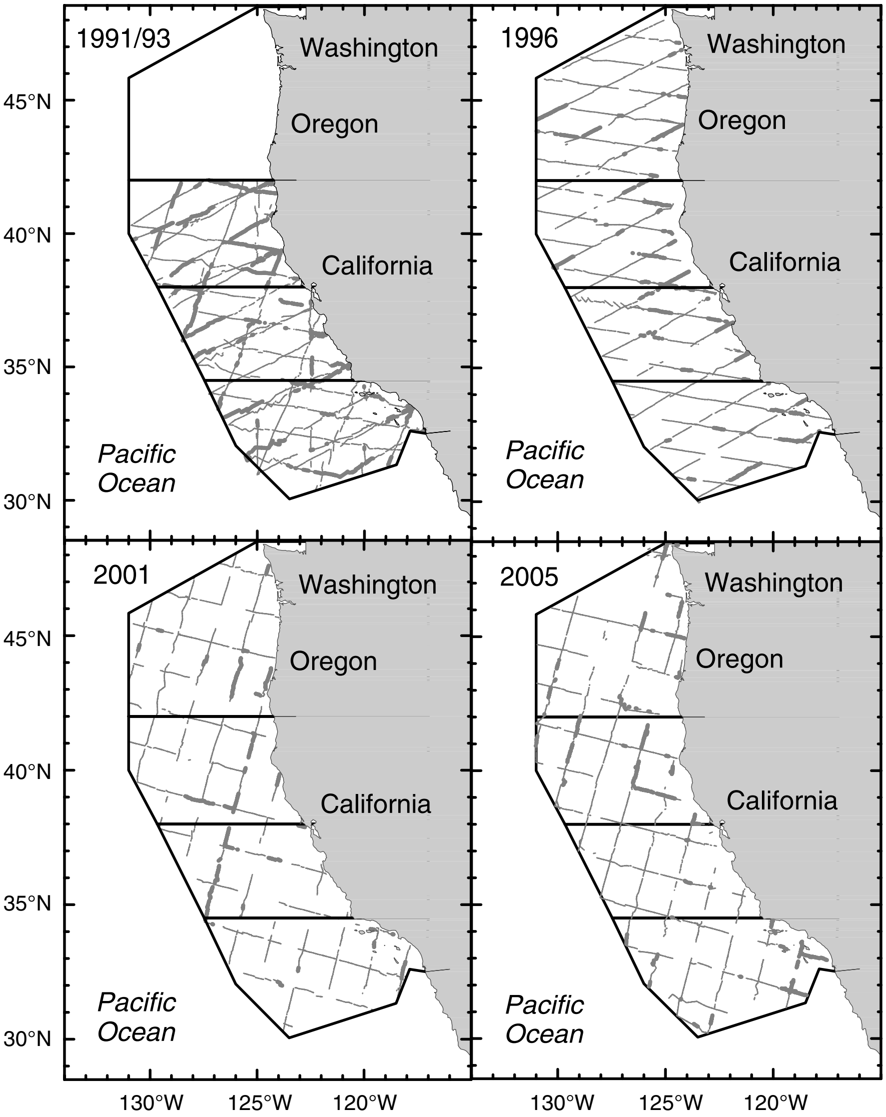

Figure 1

Transect lines (gray) surveyed during 1991 and 1993, 1996, 2001, and 2005 surveys. Thick transect lines were surveyed in Beaufort sea states of 0–2 and thin lines in Beaufort sea states 3–5. Black lines on all maps indicate the boundaries of the four geographic regions.

Logarithms were used in Equation 1 because standard errors were found to be proportional to the mean. Sightings were included in calculating indirect calibration coefficients if group size estimates were made by at least two other directly calibrated observers. We use a weighted geometric mean of the individual, calibrated group-size estimates (weighted by the inverse of the mean squared estimation error) as the best estimate of overall group size in all of the analyses presented here.

Estimation of abundance from line-transect data

Cetacean abundance was estimated by using line-transect methods (Buckland et al., 2001) with multiple covariates (Marques and Buckland, 2003). The entire study area (1,141,800 km^2) was divided into four geographic strata (Fig. 1): 1) waters off Oregon and Washington (322,200 km^2 north of 42°N); 2) northern California (258,100 km^2 south of 42°N and north of Point Reyes at 38°N); 3) central California (243,000 km^2 between Point Conception at 34.5°N and Point Reyes); and 4) southern California (318,500 km^2 south of Point Conception). The OR-WA region was not surveyed in 1991 or 1993 and thus received less survey effort. The density, D_i, for a given species within geographic region i was estimated as

$$D_i = \frac{1}{2L_i} \sum_{j=1}^{n_i} \frac{f(0\,|\,z_j)\cdot s_j}{g_j(0)}, \tag{2}$$

Table 1

Species groups that were pooled and the range of Beaufort sea states used in estimating line-transect detection probabilities as functions of perpendicular sighting distance and other covariates. Within a group, the indicated subgroups were identified and tested as covariates in the line-transect parameter estimation. When sample size and patterns of species co-occurrence permitted, groups and subgroups comprised only one species. Mean effective strip widths (ESWs) are the product of the truncation distance (W) and the mean probability of detection within that distance for each group.

Species group Subgroup Common name	Scientific name(s)	Beaufort sea state	Mean ESW (km)	Truncation distance, W (km)
Delphinids				
Small delphinids				
Short-beaked common dolphin	*Delphinus delphis*	0–5	2.22	4.0
Long-beaked common dolphin	*Delphinus capensis*	0–5	2.85	4.0
Unclassified common dolphin	*Delphinus* spp.	0–5	2.28	4.0
Striped dolphin	*Stenella coeruleoalba*	0–5	2.41	4.0
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	0–5	2.24	4.0
Northern right whale dolphin	*Lissodelphis borealis*	0–5	2.05	4.0
Unidentified delphinoid		0–5	1.71	4.0
Large delphinids				
Bottlenose dolphin	*Tursiops truncatus*	0–5	2.54	4.0
Risso's dolphin	*Grampus griseus*	0–5	2.37	4.0
Short-finned pilot whale	*Globicephalus macrorhynchus*	0–5	2.70	4.0
Dall's porpoise	*Phocoenoides dalli*	0–2	1.09	2.0
Small whales				
Small beaked whales				
Mesoplodon spp.	*Mesoplodon* spp.	0–2	2.85	4.0
Cuvier's beaked whale	*Ziphius cavirostris*	0–2	2.68	4.0
Unidentified ziphiid whale	*Mesoplodon* spp. or *Z. cavirostris*	0–2	2.95	4.0
Kogia spp.	*Kogia breviceps* or *Kogia sima*	0–2	1.01	4.0
Minke whale	*Balaenoptera acutorostrata*	0–2	2.16	4.0
Unidentified small whale		0–2	2.71	4.0
Medium-size whales				
Baird's beaked whale	*Berardius bairdii*	0–5	1.94	4.0
Bryde's whale	*Balaenoptera edeni*	0–5	3.54	4.0
Sei whale	*Balaenoptera borealis*	0–5	1.59	4.0
Sei or Bryde's whale	*B. edeni* or *B. borealis*	0–5	2.89	4.0
Fin, blue, and killer whales				
Fin whale	*Balaenoptera physalus*	0–5	2.61	4.0
Blue whale	*Balaenoptera musculus*	0–5	2.58	4.0
Killer whale	*Orcinus orca*	0–5	2.65	4.0
Humpback whale	*Megaptera novaeangliae*	0–5	3.20	4.0
Sperm whale	*Physeter macrocephalus*	0–5	2.97	4.0
Unidentified rorqual		0–5	2.70	4.0
Unidentified large whale		0–5	2.78	4.0

where L_i = the length of on-effort transect lines in region i;
$f(0|z_j)$ = the probability density function evaluated at zero perpendicular distance for group j with associated covariates z;
s_j = the number of individuals of that species in group j;
$g_j(0)$ = the trackline detection probability of group j; and
n_i = the number of groups of that species sighted in region i.

Annual abundances for each species in California (1991–2005) and in Oregon–Washington (1996–2005) were estimated from Equation 2 based on the sightings and search effort for the given year. The California total was the sum of the three California region. Because transects covered only 35 km in calm conditions in the central California region in 2005, that region was pooled in 2005 with the northern California region to estimate abundance for Dall's porpoises and small whales (whose abundance was based only on surveys in calm sea states—see below). Only half-normal detection models were considered for estimating $f(0|z_j)$ because hazard-rate models have been shown to give highly variable estimates (Gerrodette and Forcada, 2005) and because hazard-rate models often did not converge on best-fit solutions. In estimating $f(0|z_j)$, data from all years and geographic strata were pooled, and species were pooled into groups with similar sighting characteristics (Barlow et al., 2001): delphinids (excluding killer whales); Dall's porpoise; small whales; medium whales; blue, fin, and killer whales; humpback whales; and sperm whales (Table 1). To improve the ability to fit the probability density function, $f(0|z_j)$, sightings were excluded if they were farther from the trackline than an established truncation distance (Buckland et al., 2001): 2 km for Dall's porpoises and 4 km for all other species. This procedure eliminated approximately 15% of sightings. The covariates for the $f(0)$ function were chosen by forward step-wise model building by using the corrected Akaike information criterion (AIC_c). Potential covariates included the total group size or its natural logarithm (*TotGS* or *LnTotGS*), Beaufort sea state (*Beauf*), survey year (*Year*: 1991, 1993, 1996, 2001, or 2006), survey vessel (*Ship*: *McArthur* or *Jordan*), geographic region (*Region*), the presence of rain or fog within 5 km of the ship (*RainFog*), the presence of glare on the trackline (*Glare*), the estimated visibility in nautical miles (*Vis*), the method used to first detect the group (*Bino*: 25× binoculars or other tool), and the cue that first drew an observer's attention to the presence of a group (*Cue*: splash, blow, or other). As covariates, *TotGS*, *LnTotGS*, *Beauf*, and *Vis* were treated as continuous variables and the others as categorical. Categorical covariates were used only if all factor levels had at least ten observations. See Barlow et al. (2001) for a more complete description of these covariates and their influence on the distance at which various species can be seen. When sample size permitted, another covariate (*SppGroup*, a coded value for the most abundant species within a group) was added to sub-stratify a species group, allowing for differences in detection distances between members of the *a priori* species groupings (Table 1). Because very few cryptic species, such as small whales and Dall's porpoise, are seen in rough conditions and sample sizes were too small to estimate $g(0)$ for those conditions, the abundance of these species was estimated by using search effort conducted only in calm seas (Beaufort sea state 0 to 2); abundance of other species was based on search effort in Beaufort sea states 0 to 5.

Some animals sighted could not be identified to species or probable species, and, for completeness, we also estimated the abundance of the cetaceans represented by these sightings. Sample sizes were small; therefore these unidentified categories were pooled with other similar species for estimating $f(0|\ z_j)$. Unidentified delphinoids were pooled with all delphinids; unidentified small whales were pooled with *Ziphius, Mesoplodon* and *Kogia* spp.; unidentified rorquals were pooled with all rorqual species; and unidentified large whales were pooled with rorquals and sperm whales.

In traditional (noncovariate) line-transect analyses, effective strip width (ESW) gives a measure of the distance from the trackline at which species were seen (with an upper limit defined by a chosen truncation distance). For the covariate line-transect method, ESW varies with the covariates for each sighting. The mean ESW was calculated as the truncation distance multiplied by the mean probability of detecting a group within that distance for all sightings of a species.

The total abundance, N, for a species was estimated as the sum over the four geographic regions of the densities, D_i, in each stratum multiplied by the size of the stratum, A_i :

$$N = \sum_{i=1}^{4} D_i \bullet A_i. \tag{3}$$

Abundance and density were not estimated for harbor porpoises (*Phocoena phocoena*), gray whales (*Eschrichtius robustus*), or the coastal stock of bottlenose dolphins (*Tursiops truncatus*) because their inshore habitats were inadequately covered in our study and because good abundance estimates are available for these species from specialized studies (Carretta et al., 1998; Rugh et al., 2005; Carretta et al., 2006).

The areas, A_i , within each stratum were limited to waters deeper than 20 m (the safe operating limit of the vessels). The total areas between the coast and the offshore boundaries were estimated with the program GeoArea (available from Gerrodette[1]). The stratum areas were estimated by subtracting the area between 0 and 20 m depth (and the areas of the Channel Islands in the southern California stratum) from these total areas. The area between the 0- and 20-m depth contours in the southern California stratum (including the Channel Islands) was estimated with the ArcGIS 9.1 software package. The 20-m contour was derived from a bathymetry data set with grids providing 200 m horizontal resolution, 0.1 m vertical resolution) from the California Department of Fish and Game, Marine Region. Coastline data from the NOAA National Ocean Service Medium Resolution Digital Vector Shoreline (1:70,000 scale) was used for the 0-m contour.

The coefficients of variation (CV) for abundance were estimated by using mixed parametric and nonparametric bootstrap methods (Efron and Gong, 1983). Variance attributed to sampling and model fitting were estimated with the nonparametric bootstrap method by using 150-km segments of survey effort as the sampling unit (roughly the distance surveyed in one day). Adjacent survey segments, sometimes from different days, were appended together to make bootstrap segments. A new bootstrap segment was begun for each survey and whenever a ship crossed into a new region. Within each geographic region, effort segments were

---

[1] Gerrodette, T. 2007. National Oceanic and Atmospheric Administration, Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla CA 92037. Website: http://swfsc.noaa.gov/prd.aspx (accessed 26 June 2007).

sampled randomly with replacement from all survey years, and the sightings associated with those segments were used with step-wise model building to fit the multiple-covariate model of $f(0|z_j)$. For each of 1000 bootstrap iterations, a parametric bootstrap was used to choose the values of $g(0)$ by drawing randomly from a logit-transformed normal distribution with a mean and variance selected to give the values of $g(0)$ and CV($g(0)$) used for abundance estimation.

Probability of detection of a cetacean group along the trackline

The line-transect parameter $g(0)$ represents the probability of detecting a group that is located directly on the transect line. This value is often assumed to be 1.0 in estimating abundance for dolphins that are found in large groups (Gerrodette and Forcada, 2005); therefore, in these analyses it was implicit that 100% of the groups located on the trackline were detected. In our study, for dolphins, porpoises, and large baleen whales, data from the conditionally independent observer were used to estimate the trackline detection probability for the primary observer team, $g_1(0)$, with the method developed by Barlow (1995):

$$g_1(0) = 1.0 - \frac{n_{w2} \bullet f_2(0)}{n_{w1} \bullet f_1(0)}, \qquad (4)$$

where the subscript 1 refers to parameters for the primary observers, subscript 2 refers to parameters for the conditionally independent observer, and n_w = the number of sightings within the truncation distance w used for estimating the line-transect parameter $f(0)$.

Sightings by the primary team were included in estimating n_1 and $f_1(0)$ only if a conditionally independent observer was also on duty. This estimator (Eq. 4) is positively biased (Barlow, 1995), which results in an overestimation of $g(0)$ for the primary observers. Fully independent observer methods (Buckland et al., 2004) are generally superior to this conditionally independent method (referred to as the "removal method" by Buckland et al. [2004]); however, such methods could not be used because of the need to approach groups to determine species and estimate group sizes. The line-transect parameter $f(0)$ was estimated independently for the primary and independent observers with the software program Distance 5.0 (available from Thomas[2]); half-normal models were fitted with cosine adjustments (Buckland et al., 2001), and the best-fit model was selected by AIC_c. Because of sample size limitations, species were pooled into three categories for estimating $g(0)$: 1) delphinids (excluding killer whales), 2) large whales (most baleen whales and killer whales), and 3) Dall's porpoises. Killer whales were included with large baleen whales because they are very conspicuous and are seen at greater distances than are other delphinids (Barlow et al., 2001). Because trackline detection probabilities may vary with the size of the group (Barlow, 1995) or observation conditions, the numbers of sightings made by primary and independent observers were tested with Fisher's exact test to determine if the proportion varied with group size or Beaufort sea state. Delphinids and large whales were stratified into large and small groups with cutpoints at 20 and 3 individuals, respectively. Because of sample size limitations, a single detection function was fitted to large and small groups of delphinids seen by the independent observer. Estimates of $g(0)$ were stratified if this test was significant for either factor. Data for estimating $g(0)$ included transects covered on the preplanned survey grid and during more opportunistic survey periods, such as transits from a port to the starting point on the survey grid. Coefficients of variation for $g(0)$ estimates from the conditionally independent method were based on Equation 9 in Barlow (1995).

The above conditionally independent observer method for estimating $g(0)$ requires that all animals be available to be seen by the primary observer team. This approach does not work with long-diving species that may be submerged for the entire time that the ship is within visual range. Values of $g(0)$ for sperm whales, dwarf sperm whales, pygmy sperm whales, and all beaked whales were taken from a model of their diving behavior, detection distances, and the searching behavior of observers (Barlow, 1999).

Trackline detection probabilities for minke whales posed a special problem. Insufficient sightings were made to estimate $g(0)$ from the conditionally independent observer method (only one conditionally independent sighting was made) and insufficient information exists on their diving behavior to use the modeling approach. Here we assumed that $g(0)$ for minke whales was similar to that for small groups of delphinids (but see "Discussion" section).

Results

Surveys

Survey effort in Beaufort sea states from 0 to 5 covered the study areas fairly uniformly (Fig. 1). Although not all the planned transects were surveyed (because of inclement weather and mechanical breakdowns), the holes in the survey grid were small in relation to the entire study area, and all areas appeared to be well represented. Survey effort in calm sea conditions (Beaufort states 0–2) was not as uniformly distributed (Fig. 1) and was particularly poor in the Oregon-Washington region. Survey effort varied among years because of the availability of ship time.

---

[2] Thomas, L. 2005. Research Unit for Wildlife Population Assessment, University of St. Andrews, Scotland, UK. Website: http://www.ruwpa.st-and.ac.uk/distance/ (accessed 26 June 2007).

Table 2

Numbers of sightings (n) and mean group sizes for all species in the four geographic regions. For each group, size was estimated as the geometric mean of the observers' individual estimates and therefore is not necessarily an integer. The mean for each region is an arithmetic mean over all groups used in the abundance estimation. The overall mean group size is an average of all regions weighted by the number of sightings in each region.

	Southern California		Central California		Northern California		Oregon–Washington		All regions
Species	n	Mean group size	n	Mean group size	n	Mean group size	n	Mean group size	Mean group size
Short-beaked common dolphin	239	168.0	165	142.7	52	210.2	3	238.3	164.1
Long-beaked common dolphin	16	286.6	3	465.8	0	—	0	—	314.9
Unclassified common dolphin	17	67.6	11	19.8	1	8.0	0	—	47.4
Striped dolphin	37	67.2	22	28.6	13	33.8	1	2.2	48.7
Pacific white-sided dolphin	15	33.7	19	153.8	18	59.0	19	57.0	78.5
Northern right whale dolphin	12	13.9	13	45.0	17	20.9	18	35.4	29.1
Bottlenose dolphin	31	13.4	4	4.0	3	10.0	0	—	12.2
Risso's dolphin	50	15.1	25	32.1	13	16.4	22	29.7	22.0
Short-finned pilot whale	1	31.6	1	9.6	3	16.3	0	—	18.0
Killer whale	2	4.1	6	4.9	5	8.1	10	7.5	6.6
Dall's porpoise	5	2.5	27	3.8	115	3.6	67	3.7	3.6
Mesoplodon spp.	1	2.3	4	1.3	4	2.4	2	2.2	2.0
Cuvier's beaked whale	3	2.7	10	2.5	4	2.8	0	—	2.6
Baird's beaked whale	1	7.0	3	14.5	3	13.8	8	5.9	9.3
Kogia spp.	0	—	3	1.5	1	1.0	1	1.0	1.3
Sperm whale	19	8.1	5	7.2	22	8.5	9	7.6	8.1
Minke whale	4	1.6	7	1.1	4	1.1	3	1.0	1.2
Bryde's whale	0	—	1	2.1	0	—	0	—	2.1
Sei whale	0	—	2	1.0	3	1.8	2	1.3	1.4
Sei or Bryde's whale	2	1.0	2	1.0	0	—	0	—	1.0
Fin whale	35	2.4	100	2.4	51	2.1	28	1.3	2.2
Blue whale	106	1.8	67	1.8	18	1.5	7	1.0	1.8
Humpback whale	5	2.1	83	2.0	16	1.7	25	1.7	1.9
Unidentified delphinoid	14	44.9	18	13.6	10	5.4	4	4.8	20.6
Unidentified ziphiid whale	2	1.7	1	1.0	3	1.3	0	—	1.4
Unidentified small whale	7	1.5	1	1.1	3	1.4	1	1.0	1.4
Unidentified roqual whale	4	2.4	26	1.4	7	1.0	7	1.0	1.4
Unidentified large whale	12	1.5	8	1.7	7	1.4	3	1.4	1.5

The number of sightings of most species varied among geographic regions (Table 2). Short- and long-beaked common dolphins and striped dolphins were seen much more frequently in central and southern California. Dall's porpoises were seen much more commonly in the northern California and Oregon-Washington regions. The number of sightings of other dolphin species (including Risso's dolphins, Pacific white-sided dolphins, northern right whale dolphins, and killer whales) showed no clear pattern with geographic region. Dolphin group sizes were generally largest for the two species of common dolphin, but Pacific white-sided dolphins were consistently found in large groups in the central California region (Table 2). Blue whales were the most commonly seen baleen whale in the southern region, but were replaced by fin whales and humpback whales as the most common baleen whale in the northern regions (Table 2). The sighting locations are illustrated in Figure 2 for some common species. Locations of sightings of all species have been provided in the reports for each survey (Hill and Barlow, 1992; Mangels and Gerrodette, 1994; Von Saunder and Barlow, 1999; Appler et al., 2004; Forney, 2007).

Cetaceans were often found in mixed species assemblages. In some cases, species were obviously traveling together in close association; in other cases, the individual species may have been in the same area because they were feeding on the same resource or were there by coincidence. Some species (striped dolphins, bottle-

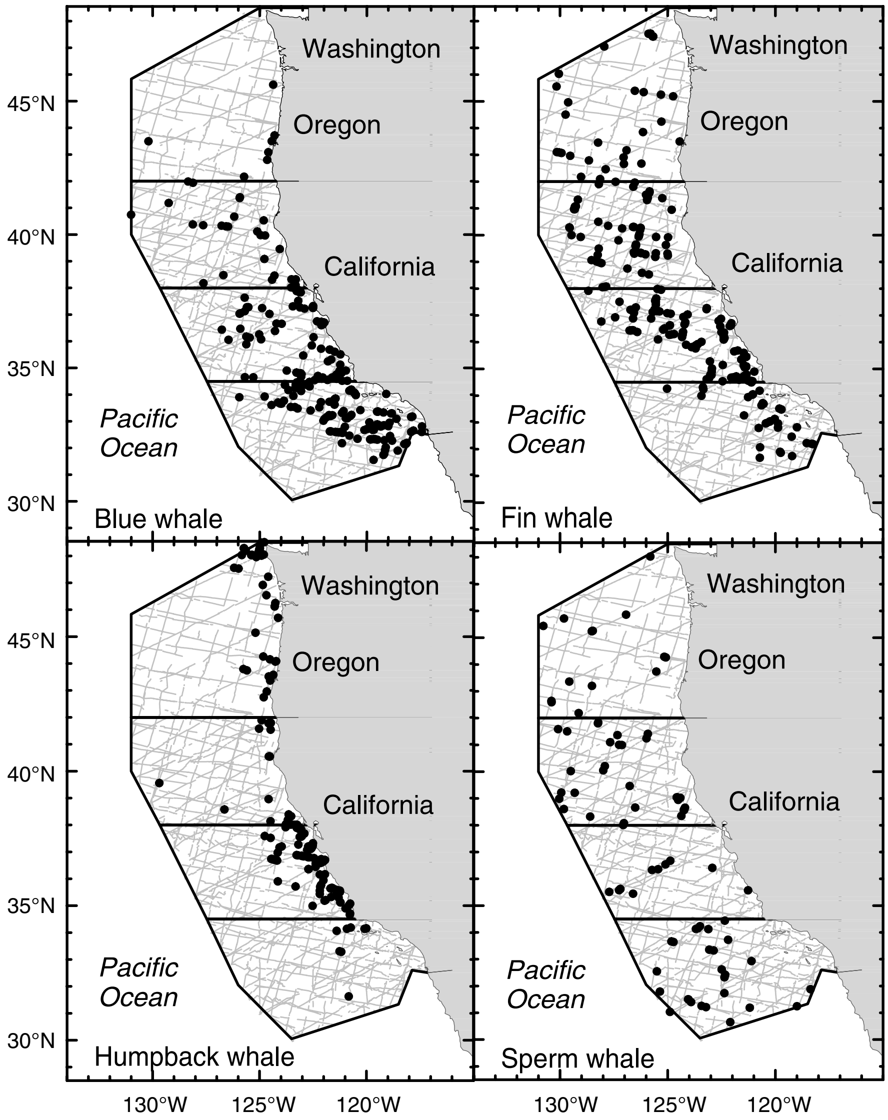

Figure 2

Sighting locations (•) for the species most commonly seen on the 1991–2005 surveys. Light gray lines indicate transects surveyed, and black lines indicate the four geographic regions.

nose dolphins, and Pacific white-sided dolphins) were found with other species more often than they were found alone, indicating that these associations were not coincidental.

Calibration of group size

Most regression coefficients for the indirect method of group-size calibration were less than one, indicating that observers were more likely to underestimate group size. For all groups and all species in this study, the ratio of the sum of all uncalibrated group sizes divided by the sum of all calibrated group sizes was 0.79. The mean ratio of calibrated to uncalibrated group size estimates was 0.92. This difference implies that proportionately larger corrections were applied to larger groups.

Probability of detection along the trackline

New trackline detection probabilities, $g(0)$, were estimated from sightings that were made by the independent observers but missed by the primary observers (Table 3). Beaufort sea state was not a significant factor in the numbers of delphinids or large whales seen by the independent observers (Fisher's exact test, $P=0.60$ and 0.87, respectively). Group size was a significant factor for delphinids ($P<0.0001$), but not for large whales ($P=0.79$). Consequently, estimates of $g(0)$ for delphinids were stratified by group size. The number of Dall's porpoise sightings by independent observers ($n=12$) was insufficient to stratify estimates of $g(0)$ for this species. Values of $g(0)$ from the literature that were used for other long-diving species are given in Table 4.

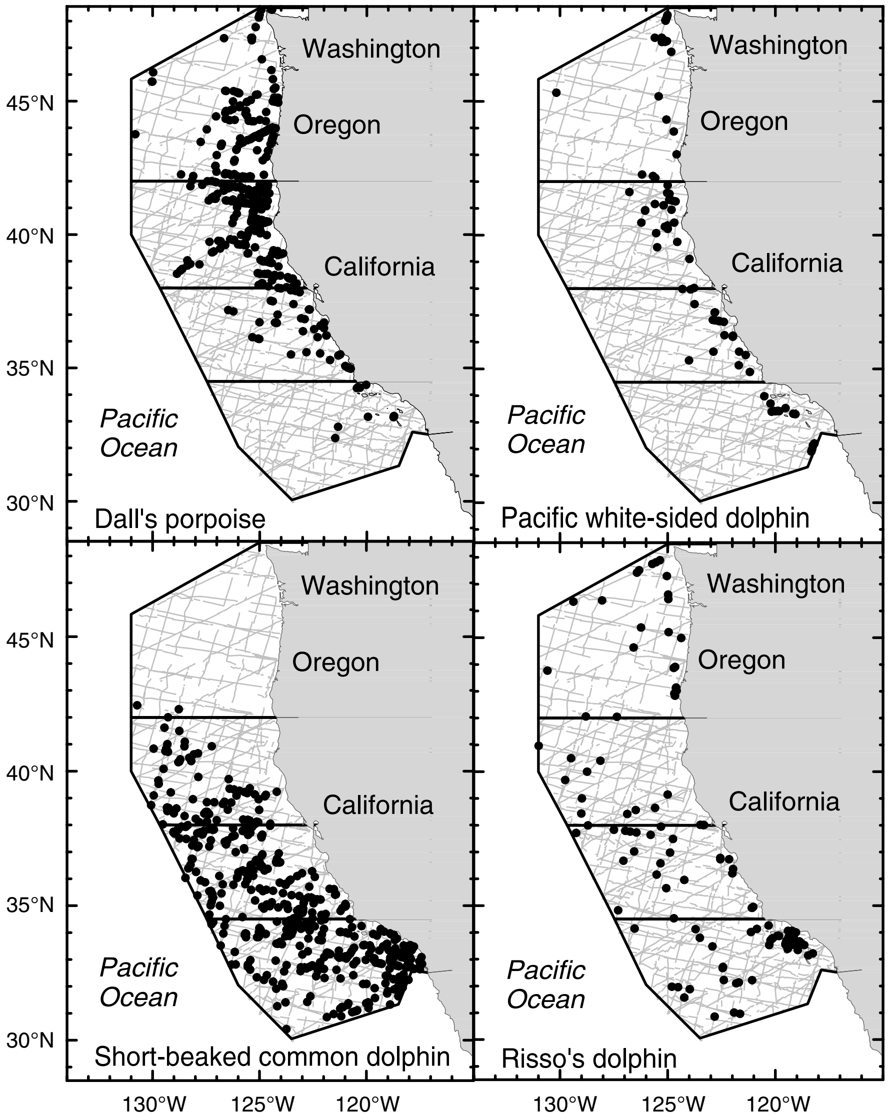

Figure 2 (continued)

Estimation of abundance from line-transect data

Short-beaked common dolphins dominated the abundance estimates for all regions except Oregon-Washington (Table 5), both because of the large number of sightings and the large group sizes for this species. Dall's porpoise was, by far, the most abundant small cetacean in the Oregon-Washington region (Table 5). Short-beaked common dolphins and Dall's porpoises together represented approximately 81% of all delphinoids and 79% of all cetaceans, and baleen whales (mysticetes) represented only about 1% of the total estimated cetacean individuals along the U.S. west coast (Table 6).

The estimated abundance of most species varied considerably among years (Tables 7 and 8). In large part, the year-to-year variation in abundance for most species could be attributed to low sample size and sampling variation; however, the distributions of all species extended beyond the boundaries of the study area and some of the annual variation was likely due to a different portion of a larger population being in the study area within a given year (Forney and Barlow, 1998). Because all years and all regions were pooled for estimating the line-transect parameters, the abundance estimates for different regions (Table 5) and for different years (Tables 7 and 8) were correlated and these estimates cannot be used in standard statistical tests of difference among regions or among years.

The most important covariates, z, for estimating line-transect function $f(0|z)$ varied among species and species groups (Table 4). Covariates appearing in more than one model were *Bino*, *Beauf*, *LnTotGS*, *Ship*, and *RainFog*. In addition to these, a covariate that coded for difference among species within a group (*SppGrp*) was chosen in the model for delphinids (large vs. small delphinids) and for small whales (beaked whales vs. *Kogia* spp. vs. minke whales). The mean ESWs for most

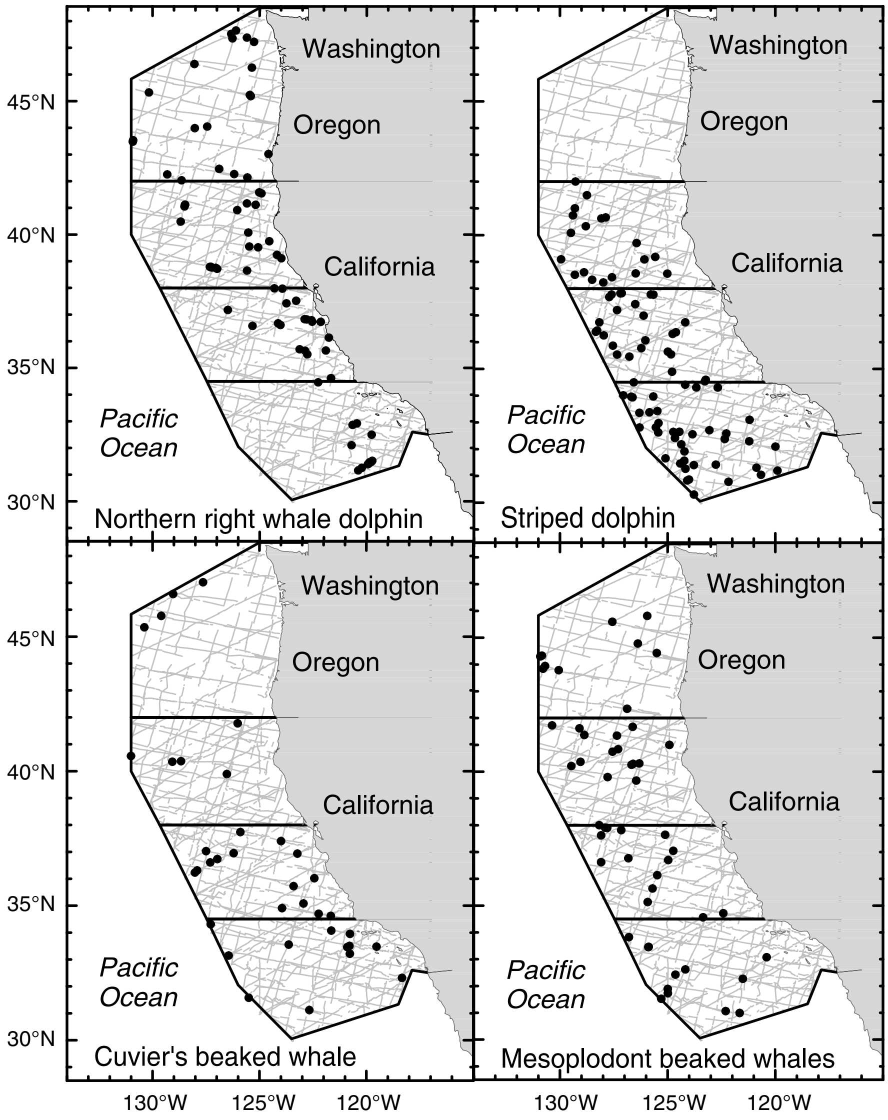

Figure 2 (continued)

species were between 2 and 3 km (Table 1). Dall's porpoise and *Kogia* species had the narrowest effective strip widths (~1 km), and humpback whales had the greatest values (~3.2 km).

Discussion

Abundance and density of cetaceans

Delphinidae Delphinids off the U.S. west coast can be classified as warm-temperate (short- and long-beaked common dolphins, striped dolphins, and short-finned pilot whales), cold-temperate (Pacific white-sided dolphins and northern right whale dolphins), or cosmopolitan (Risso's dolphin, bottlenose dolphins, and killer whales). The warm temperate species are generally more common in southern and central California, and the cold-temperate species are more common in the northern California and Oregon-Washington regions. In 1996, when waters were relatively cool off California, the abundance of striped dolphins (the most tropical species) was lower than average and the abundance of the two cold-temperate species was higher. Four of the five sightings of short-finned pilot whales were in 1993, a warm year. All four species have distributions that extend outside our study area. These changes in abundance are consistent with shifts in the distribution of these species into and out of our study area with changes in water temperature. The tendency for these species to change distribution with water temperature is also seen in seasonal distribution changes (Forney and Barlow, 1998). The abundance of common dolphins and the cosmopolitan species did not vary consistently with warm and cold years (Table 7).

Table 3

Trackline detection probabilities, $g(0)$, estimated with the conditionally independent observer method for delphinids, large whales, and Dall's porpoises. Values of $g(0)$ were derived from the estimated probability density functions evaluated at zero distance, $f(0)$, for sightings made by primary observers (n_1) and independent observers (n_2) (Eq. 4). Coefficients of variation (CV) are given for $f(0)$ and $g(0)$ values. Delphinids include all species except killer whales and are stratified into small (≤20) and large (>20) groups. Large whales include killer whales and all baleen whales, except minke whales.

	Primary observers			Independent observers				
Species groups and group size strata	n_1	$f(0)$	CV $f(0)$	n_2	$f(0)$	CV $f(0)$	$g(0)$	CV $g(0)$
Delphinids (truncation distance=1 km)								
Group size ≤20	141	2.74	0.13	25	2.23	0.21	0.856	0.056
Group size >20	188	1.60	0.11	4	2.23	0.21	0.970	0.017
Large whales (truncation distance=2.5 km)								
All group sizes	296	0.58	0.05	32	0.42	0.19	0.921	0.023
Dall's porpoises (truncation distance=1 km)								
All group sizes	115	1.34	0.09	12	2.30	0.34	0.822	0.101

Table 4

The covariates selected for the best-fit line-transect models and the trackline detection probabilities ($g(0)$ and its coefficient of variation, CV, in parentheses) for each of the species and species groups used for abundance estimates. Covariates in parentheses were not included in all of the models that were averaged. The species group (*SppGrp*) covariate allowed variation in the scale factor of the detection function for different subgroups within a species group for delphinids (small delphinids vs. large delphinids—see Table 1) and small whales (small ziphiids vs. *Kogia* spp. vs. minke whales). Other selected covariates included binocular type (*Bino*), total group size (*TotGS*), the logarithm of total group size (*LnTotGS*), Beaufort sea state (*Beauf*), survey vessel (*Ship*), initial sighting event (*Cue*), the presence of rain or fog (*RainFog*), visibility (*Vis*), and geographic region (*Region*). Values of $g(0)$ are from Table 3, Barlow (1999), and Barlow and Taylor (2005).

Species		Small groups		Large groups	
Species group	Best-fit line-transect model	$g(0)$	CV $g(0)$	$g(0)$	CV $g(0)$
Delphinids	*Bino+Beauf+LnTotGS+Cue+SppGrp+Ship*	0.856	(0.056)	0.970	(0.017)
Dall's porpoise	*Bino+Ship (+LnTotGS+RainFog)*	0.822	(0.101)	0.822	(0.101)
Small whales	*SppGrp (+LnTotGS+TotGS+Ship+Beauf)*				
Mesoplodon spp.		0.450	(0.230)	0.450	(0.230)
Cuvier's beaked whale		0.230	(0.350)	0.230	(0.350)
Unidentified ziphiid whale		0.340	(0.290)	0.340	(0.290)
Kogia spp.		0.350	(0.290)	0.350	(0.290)
Minke whale		0.856	(0.056)	0.856	(0.056)
Unidentified small whale		0.856	(0.056)	0.856	(0.056)
Medium-size whales	*Vis+Beauf (+LnTotGS+TotGS+Ship)*				
Baird's beaked whales		0.960	(0.230)	0.960	(0.230)
Bryde's and sei whales		0.921	(0.023)	0.921	(0.023)
Fin, blue, and killer whales	*Bino+RainFog+Region (+Ship)*	0.921	(0.023)	0.921	(0.023)
Humpback whale	*Null model*	0.921	(0.023)	0.921	(0.023)
Sperm whale	*Null model (+LnTotGS+Ship+Vis)*	0.870	(0.090)	0.870	(0.090)
Unidentified rorqual	*Bino+RainFog+LnTotGS*	0.921	(0.023)	0.921	(0.023)
Unidentified large whale	*Bino+RainFog+LnTotGS (+Ship)*	0.921	(0.023)	0.921	(0.023)

Table 5

Estimated abundances (N) and coefficients of variation (CV) for each species in each of the four geographic regions. Data from 1991 to 2005 were pooled. CVs were not available (NA) if no sightings were made. Variances were assumed to be additive in estimating the CVs of the column totals. Unidentified large whales and small whales were not sufficiently specified to be included in the subtotals.

	Southern California		Central California		Northern California		Oregon–Washington	
Species	Abundance N	CV(N)	Abundance N	CV(N)	Abundance N	CV(N)	Abundance N	CV(N)
Short-beaked common dolphin	165,400	0.19	115,200	0.21	66,940	0.42	4555	0.77
Long-beaked common dolphin	17,530	0.57	4375	1.03	0	NA	0	NA
Unclassified common dolphin	4281	0.85	1313	0.49	35	1.00	0	NA
Striped dolphin	12,529	0.28	2389	0.42	4040	0.76	16	1.07
Pacific white-sided dolphin	2196	0.71	9486	0.74	4137	0.54	7998	0.37
Northern right whale dolphin	1172	0.52	2032	0.55	1652	0.46	6242	0.42
Bottlenose dolphin (offshore)	1831	0.47	61	0.77	133	0.68	0	NA
Risso's dolphin	3418	0.31	3197	0.30	1036	0.41	4260	0.52
Short-finned pilot whale	118	1.04	48	1.02	184	0.60	0	NA
Killer whale	30	0.73	116	0.47	142	0.47	521	0.37
Dall's porpoise	727	0.99	8870	0.64	27,410	0.26	48,950	0.71
Mesoplodon spp.	132	0.96	269	0.53	341	0.78	435	0.70
Cuvier's beaked whale	911	0.68	2647	0.74	784	1.18	0	NA
Baird's beaked whale	127	1.14	159	1.02	200	0.74	520	0.54
Kogia spp.	0	NA	710	0.58	130	1.25	397	1.25
Sperm whale	607	0.57	143	0.66	736	0.40	448	0.63
Minke whale	226	1.02	284	0.74	102	1.56	211	0.84
Bryde's whale	0	NA	7	1.01	0	NA	0	NA
Sei whale	0	NA	14	0.78	47	0.68	37	1.14
Sei or Bryde's whale	7	1.07	11	0.79	0	NA	0	NA
Fin whale	359	0.40	992	0.27	448	0.43	299	0.33
Blue whale	842	0.20	528	0.27	115	0.37	63	0.51
Humpback whale	36	0.51	586	0.38	90	0.47	231	0.36
Unidentified delphinoid	2845	0.53	1609	0.54	299	0.47	214	0.58
Unidentified ziphiid whale	226	0.86	65	1.11	172	0.65	0	NA
Unidentified small whale	357	0.66	27	1.44	73	0.60	72	1.14
Unidentified roqual whale	34	0.53	147	0.31	30	0.42	59	0.37
Unidentified large whale	72	0.33	54	0.61	35	0.44	28	0.82
Subtotal: Delphinoids	212,077	0.16	148,695	0.18	106,007	0.27	72,756	0.49
Subtotal: Ziphiidae	1396	0.49	3140	0.63	1497	0.66	955	0.43
Subtotal: Physeteridae	607	0.57	853	0.49	866	0.39	845	0.68
Subtotal: Balaenopteridae	1504	0.21	2568	0.17	831	0.31	900	0.25
Total	216,014	0.15	155,336	0.17	109,309	0.27	75,556	0.47

Dall's porpoise Abundance estimation for Dall's porpoise is difficult because of their attraction to vessels (Turnock and Quinn, 1991). To obtain unbiased estimates, these animals must be detected before they react to the survey vessel. Our data indicate that the behavior of the vast majority of Dall's porpoise seen at low sea states is "slow rolling." This contrasts with the "roostertailing" or fast swimming behavior seen by animals that are approaching the ship. However, when effort is limited to calm conditions (Beaufort states 0–2), the amount of search effort is greatly reduced (Fig. 1). As a result, the coefficients of variation for Dall's porpoise abundance are greater than would be expected for such a common species. Off California, the temporal pattern shows higher Dall's porpoise abundance in 1996 (Table 7), mirroring the higher abundance that year of cold-temperate delphinids. Forney (2000) found that sea surface temperature was a very good predictor of Dall's porpoise distribution. In their 12 year time series of surveys off central California, Keiper et al. (2005) also found that

Table 6

Total numbers of sightings (n), estimated cetacean abundance (N), and density per 1000 km^2 within the entire study area. Data from 1991 to 2005 were pooled within geographic regions, and estimates of abundance for each region were summed to give total abundance. Coefficients of variation (CV) apply to both abundance and density estimates. CVs and 95% confidence intervals (CI) were based on a bootstrap calculation. Variances were assumed to be additive in estimating the CVs of the subtotals and totals. Unidentified large whales and small whales were not sufficiently specified to be included in the subtotals.

Species	n	Abundance N	CV(N)	Lower 95% CI	Upper 95% CI	Density per 1000 km^2
Short-beaked common dolphin	459	352,069	0.18	234,430	489,826	309.35
Long-beaked common dolphin	19	21,902	0.50	4833	43,765	19.24
Unclassified common dolphin	29	5629	0.64	1127	14,231	4.95
Striped dolphin	73	18,976	0.28	9286	29,038	16.67
Pacific white-sided dolphin	71	23,817	0.36	9991	40,760	20.93
Northern right whale dolphin	60	11,097	0.26	5654	16,712	9.75
Bottlenose dolphin (offshore)	38	2026	0.44	743	4443	1.78
Risso's dolphin	110	11,910	0.24	7501	19,255	10.46
Short-finned pilot whale	5	350	0.48	68	708	0.31
Killer whale	23	810	0.27	408	1157	0.71
Dall's porpoise	214	85,955	0.45	42,318	211,118	75.53
Mesoplodon spp.	11	1177	0.40	311	1648	1.03
Cuvier's beaked whale	17	4342	0.58	1636	11,555	3.82
Baird's beaked whale	15	1005	0.37	382	1821	0.88
Kogia spp.	5	1237	0.45	0	4981	1.09
Sperm whale	55	1934	0.31	991	3163	1.70
Minke whale	18	823	0.56	403	2874	0.72
Bryde's whale	1	7	1.01	0	21	0.01
Sei whale	7	98	0.57	15	227	0.09
Sei or Bryde's whale	4	18	0.65	0	46	0.02
Fin whale	214	2099	0.18	1448	2934	1.84
Blue whale	198	1548	0.16	1138	2087	1.36
Humpback whale	129	942	0.26	584	1411	0.83
Unidentified delphinoid	46	4968	0.36	2044	8585	4.37
Unidentified ziphiid whale	6	463	0.50	115	986	0.41
Unidentified small whale	12	528	0.50	209	1370	0.46
Unidentified roqual whale	44	270	0.20	170	373	0.24
Unidentified large whale	30	189	0.25	107	292	0.17
Subtotal: Delphinoids	1147	539,509	0.14			474.05
Subtotal: Ziphiidae	49	6987	0.37			6.14
Subtotal: Physeteridae	60	3171	0.26			2.79
Subtotal: Balaenopteridae	615	5805	0.12			5.10
Total	1913	556,189	0.14			488.71

Dall's porpoise abundance was inversely related to sea surface temperature.

Balaenopteridae The common baleen whales in California waters were blue, fin, and humpback whales. The abundance of these species was consistently high during the summer and fall study period. Our estimates of humpback whale abundance increased from 1991 to 1996 and decreased slightly in 2001 and 2005; however, humpback whales were observed to be highly concentrated in productive nearshore waters off California and northern Washington during 2005 that were not well sampled during our surveys. A more comprehensive and precise abundance estimate of 1769 humpback whales (CV=0.16) was obtained when additional survey effort was included within these areas (Forney, 2007). More precise estimates from mark-recapture studies also indicate an increase in abundance from 1991 to 1997 (Calambokidis and Barlow, 2004), a decrease in 1999–2000 and in 2000–2001, and a subsequent increase to about 1400

Table 7

Number of sightings (n) and estimated abundance (N) for each species in the three California regions for the years 1991, 1993, 1996, 2001, and 2005. The total lengths of transects surveyed were 9893, 6287, 10,251, 6438, and 7779 km for these years, respectively, in Beaufort sea states of 5 or less and were 2160, 1521, 1556, 852, and 1055 km, respectively, in Beaufort sea states of 2 or less. Unidentified large whales and small whales were not sufficiently specified to be included in the subtotals.

	1991		1993		1996		2001		2005	
Species	*n*	Abundance *N*	*n*	Abundance *N*	*n*	Abundance *N*	*n*	Abundance *N*	*n*	Abundance *N*
Short-beaked common dolphin	119	249,044	94	397,813	103	313,994	64	335,365	76	483,353
Long-beaked common dolphin	5	16,714	0	0	6	49,431	2	20,076	6	11,191
Unclassified common dolphin	8	4568	3	1454	10	2768	1	383	7	18,968
Striped dolphin	21	32,370	14	14,622	13	4796	6	12,570	18	29,037
Pacific white-sided dolphin	11	4843	10	4222	19	37,762	9	9209	3	13,677
Northern right whale dolphin	14	4554	6	2554	9	7950	12	6337	1	897
Bottlenose dolphin (offshore)	14	2165	2	1058	7	382	9	5375	6	2066
Risso's dolphin	28	10,746	15	7510	15	5083	17	8521	13	7036
Short-finned pilot whale	0	0	4	1506	0	0	0	0	1	639
Killer whale	3	193	2	385	4	380	2	270	2	203
Dall's porpoise	57	59,112	1	206	50	54,501	23	18,125	16	45,373
Mesoplodon spp.	3	697	5	2116	1	202	0	0	0	0
Cuvier's beaked whale	9	9546	4	5137	2	1152	1	3217	1	2615
Baird's beaked whale	2	99	3	1591	2	913	0	0	0	0
Kogia spp.	2	1970	2	1345	0	0	0	0	0	0
Sperm whale	11	837	7	1335	6	593	9	2495	13	2795
Minke whale	4	502	0	0	4	522	2	486	5	236
Bryde's whale	1	28	0	0	0	0	0	0	0	0
Sei whale	0	0	2	117	1	114	1	29	1	47
Sei or Bryde's whale	2	27	2	75	0	0	0	0	0	0
Fin whale	23	892	29	1514	55	1832	19	1784	60	3082
Blue whale	53	1908	39	1965	74	1927	9	516	16	665
Humpback whale	6	196	15	570	49	1282	14	765	20	662
Unidentified delphinoid	11	1237	5	7697	14	4890	3	587	9	9768
Unidentified ziphiid whale	0	0	2	652	2	615	0	0	2	1104
Unidentified small whale	6	582	0	0	2	482	2	825	1	483
Unidentified roqual whale	3	63	2	93	18	423	2	70	12	296
Unidentified large whale	9	221	1	23	9	246	3	75	5	143
Subtotal: Delphinoids	291	385,546	156	439,027	250	481,937	148	416,818	158	622,208
Subtotal: Ziphiidae	14	10,342	14	9496	7	2881	1	3217	3	3719
Subtotal: Physeteridae	13	2807	9	2680	6	593	9	2495	13	2795
Subtotal: Balaenopteridae	92	3616	89	4334	201	6100	47	3650	114	4988
Total	425	403,114	269	455,561	475	492,238	210	427,080	294	634,335

in 2002–2003 (Calambokidis[3]). Our estimates of blue whale abundance decreased markedly in 2001 and 2005 compared to previous estimates, and they were more widespread in offshore and northern waters than during the 1990s. The lower abundance estimates, rather than reflecting a true population decline, appear to be caused by a redistribution of animals outside of the study area. Mark-recapture estimates of blue whale abundance remained high (1781) in the period of 2000–2003, but blue whales have recently been seen off British Columbia (Calambokidis[3]) and in the Gulf of Alaska (J. Barlow, unpubl. data). The recruitment of krill off central and northern California was poor during 2005 (Peterson et al., 2006), and given that this is the sole food for blue whales, the redistribution may be a result of decreased food supplies. Fin whales appeared to be monotonically increasing in abundance during the three

---

[3] Calambokidis, J. 2005. Personal commun. Cascadia Research, 218½ W. 4th Avenue, Olympia, WA 98501.

Table 8

Number of sightings (n) and estimated abundance (N) for each species in the Oregon-Washington region for the years 1996, 2001, and 2005. The total lengths of transects surveyed were 4336, 3100, and 2525 km for these years, respectively, in Beaufort sea state of 5 or less and were 532, 380, and 292 km, respectively, for Beaufort sea state of 2 or less. Unidentified large whales and small whales were not sufficiently specified to be included in the subtotals.

	1996		2001		2005	
Species	*n*	Abundance N	*n*	Abundance N	*n*	Abundance N
Short-beaked common dolphin	1	3749	1	219	1	11,286
Long-beaked common dolphin	0	0	0	0	0	0
Unclassified common dolphin	0	0	0	0	0	0
Striped dolphin	1	37	0	0	0	0
Pacific white-sided dolphin	7	5812	7	8884	5	10,708
Northern right whale dolphin	5	3397	10	8600	3	8265
Bottlenose dolphin (offshore)	0	0	0	0	0	0
Risso's dolphin	11	5248	9	5584	1	549
Short-finned pilot whale	0	0	0	0	0	0
Killer whale	3	250	4	881	3	548
Dall's porpoise	46	79,479	12	17,315	8	28,806
Mesoplodon spp.	1	479	0	0	1	926
Cuvier's beaked whale	0	0	0	0	0	0
Baird's beaked whale	3	179	2	348	3	1319
Kogia spp.	1	899	0	0	0	0
Sperm whale	3	318	2	98	4	1103
Minke whale	2	340	1	194	0	0
Bryde's whale	0	0	0	0	0	0
Sei whale	0	0	0	0	2	147
Sei or Bryde's whale	0	0	0	0	0	0
Fin whale	8	210	10	334	10	409
Blue whale	0	0	3	87	4	141
Humpback whale	1	13	7	331	17	483
Unidentified delphinoid	2	292	1	126	1	189
Unidentified ziphiid whale	0	0	0	0	0	0
Unidentified small whale	1	162	0	0	0	0
Unidentified roqual whale	1	20	2	60	4	127
Unidentified large whale	1	14	0	0	2	85
Subtotal: Delphinoids	76	98,264	44	41,609	22	60,351
Subtotal: Ziphiidae	4	658	2	348	4	2245
Subtotal: Physeteridae	4	1217	2	98	4	1103
Subtotal: Balaenopteridae	12	583	23	1006	37	1307
Total	98	100,897	71	43,061	69	65,091

survey periods, and a more detailed study of trends in fin whale abundance is warranted.

Bryde's and sei whales are very rare off the U.S. west coast, and minke whales are not common, particularly in offshore waters. Bryde's whales are commonly viewed as tropical baleen whales and therefore their low abundance is expected. However, sei whales were previously harvested commercially along the west coast by coastal whaling stations, and their near absence is more of a mystery. Minke whales are known to be common in some nearshore areas (Stern, 1992), which were not well sampled during our broad-scale cruises, but overall densities were low. Minke whale densities may have been underestimated in the study area because trackline detection probabilities were not directly estimated. There are no previous estimates of $g(0)$ for minke whales based on observers searching with 25× binoculars. Skaug et al. (2004) used observers searching with naked eyes and estimated $g(0)$ values between approximately 0.7 in Beaufort 1 and

0.5 in Beaufort 2. We assumed that $g(0)$ for minke whales in Beaufort 0 to 2 would be the same as for small groups of delphinids (0.846), but minke whales are very difficult to detect and an overestimate of this parameter would lead to an underestimate of minke whale abundance.

Physeteridae The estimated abundance of sperm whales is temporally variable off California (Table 7), but the two most recent estimates (2001 and 2005) were markedly higher than the estimates for 1991–96. Following the 1997–98 Niño, giant squid (*Dosidicus gigas*) have been more frequently observed off northern California and Oregon, in particular beginning in 2002 (Pearcy, 2002; Field et al., in press). Sperm whales are known to forage on giant squid, and their increased abundance within our study area may have been related to the increased availability of this prey species in recent years. Compared to baleen whales, sperm whales are found in larger groups, and fewer groups were seen on each survey, both of which contribute to more variable estimates. Also, the sperm whale population is likely to extend outside the study area, at least during certain times of the year. Of 176 tags that were implanted in sperm whales off southern California in winter, only three were later recovered by whalers (Rice, 1974); of these three, one was recovered outside the study area (far west of British Columbia). It is likely that at least some fraction of the population is absent during part of the year, and that fraction may vary with oceanographic conditions. This pattern of distribution differs from the situation with humpback whales; the majority of the humpback population appeared to be feeding in U.S. west coast waters during the time of the surveys. The density of sperm whales estimated in our study for the California Current (1.7 per 1000 km^2) is similar to the worldwide global average for this species (1.4 per 1000 km^2; Whitehead, 2002) but is less than recent estimates for waters in the eastern temperate Pacific (3–5 per 1000 km^2; Barlow and Taylor, 2005) and around Hawaii (2.8 per 1000 km^2; Barlow, 2006).

Dwarf and pygmy sperm whales are seldom seen by people because of their offshore distribution and cryptic behavior. Nonetheless, the estimated number of individuals found off the U.S. west coast exceeds the number of some much more commonly seen species, such as killer whales.

Ziphiidae Although they are rarely seen, approximately 7000 beaked whales were found in west coast waters—a number that exceeds that documented for baleen whales. The absence of California sightings for two beaked whale genera (*Mesoplodon* and *Berardius,* Table 7) since 1996 is disconcerting, especially in light of recent discoveries about the susceptibility of this group to loud anthropogenic sounds (Simmonds and Lopez-Jurado, 1991; Cox et al., 2006); however, weather conditions were less favorable for the detection of beaked whales during the more recent surveys (Fig. 1) and it is unclear whether this may have played a role in their apparent decrease. The distributions of all beaked whale species extend outside the study area, and it is likely that some individuals move in to and out of the study area as habitat changes. An analysis of trends in beaked whale abundance should include consideration of these effects.

Previous abundance estimates

Estimates presented in this study differ, typically by a small amount, from previous estimates from the 1991 survey (Barlow, 1995) and preliminary estimates from the 1993 (Barlow and Gerrodette, 1996), 1996 and 2001 (Carretta et al., 2006), and 2005 (Forney, 2007) surveys. The differences are primarily due to differences in the stratification and in the use of multiple covariates in the line-transect modeling. Both modifications should result in more precise estimates of cetacean abundance. In addition, some of these previous estimates did not include group-size calibration for individual observers, and therefore our estimates corrected a small negative bias present in those earlier estimates. The principle weakness of the current analysis is the small sample size for several rare species. However, we believe it is better to include all species for completeness and to properly quantify uncertainty in the estimates for rare species.

Acknowledgments

We thank the marine mammal observers (W. Armstrong, L. Baraff, S. Benson, J. Cotton, A. Douglas, D. Everhardt, H. Fearnbach, G. Friedrichsen, J. Gilpatrick, J. Hall, N. Hedrick, K. Hough, D. Kinzey, E. LaBrecque, J. Larese, H. Lira, M. Lycan, S. Lyday, R. Mellon, S. Miller, L. Mitchell, L. Morse, S. Noren, S. Norman, C. Oedekoven, P. Olson, T. O'Toole, S. Perry, J. Peterson, B. Phillips, R. Pitman, T. Pusser, M. Richlen, J. Quan, C. Speck, K. Raum-Suryan, S. Rankin, J. Rivers, R. Rowlett, M. Rosales, J. C. Salinas, G. Serra-Valente, B. Smith, C. Stinchcomb, N. Spear, S. Tezak, L. Torres, B. Troutman, and E. Vasquez,), cruise leaders (E. Archer, L. Ballance, E. Bowlby, J. Carretta, S. Chivers, T. Gerrodette, P. S. Hill, M. Lowry, K. Mangels, S. Mesnick, R. Pitman, J. Redfern, B. Taylor, and P. Wade), survey coordinators (J. Appler, A. Henry, P. S. Hill, A. Lynch, K. Mangels, and A. VonSaunder), and officers and crew who dedicated many months of hard work collecting these data. T. Gerrodette was the chief scientist for the 1993 survey. J. Cubbage and R. Holland wrote the data entry software. Data were edited and archived by A. Jackson. Areas within the 20-m depth contour were calculated by R. Cosgrove. J. Laake provided his R-language code for fitting the multiple-covariate line-transect models. This article benefited from the reviews and comments by M. Ferguson, L. Thomas, and the Pacific Scientific Review Group. Funding was provided by National Oceanic and Atmospheric Administration and the Strategic Environmental Research and Development Program (SERDP). This work was supported in part by the Monterey Bay Sanctuary Foundation.

Literature cited

Appler, J., J. Barlow, and S. Rankin.
2004. Marine mammal data collected during the Oregon, California and Washington line-transect expeditions (ORCAWALE) conducted aboard the NOAA ships McArthur and David Starr Jordan, July–Dec 2001. NOAA Tech. Memo. NMFS-SWFSC-359, 28 p.

Barlow, J.
1995. The abundance of cetaceans in California waters. Part I: Ship surveys in summer and fall of 1991. Fish. Bull. 93:1–14.
1999. Trackline detection probability for long-diving whales. *In* Marine mammal survey and assessment methods (G. W. Garner, S. C. Amstrup, J. L. Laake, B. F. J. Manly, L. L. McDonald, and D. G. Robertson, eds.), p. 209–221. Balkema Press, Rotterdam, The Netherlands.
2006. Cetacean abundance in Hawaiian waters estimated from a summer/fall survey in 2002. Mar. Mamm. Sci. 22(2):446–464.

Barlow, J., and T. Gerrodette.
1996. Abundance of cetaceans in California waters based on 1991 and 1993 ship surveys. NOAA Tech. Memo. NMFS-SWFSC-233, 15 p.

Barlow, J., T. Gerrodette, and J. Forcada.
2001. Factors affecting perpendicular sighting distances on shipboard line-transect surveys for cetaceans. J. Cetacean Res. Manage. 3(2):201–212.

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.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, and L. Thomas.
2001. Introduction to Distance Sampling: Estimating abundance of biological populations, 432 p. Oxford Univ. Press, Oxford, England.
2004. Advanced Distance Sampling: Estimating abundance of biological populations, 416 p. Oxford Univ. Press, Oxford, England.

Calambokidis, J., and J. Barlow.
2004. Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods. Mar. Mamm. Sci. 21(1):63–85.

Carretta, J. V., K. A. Forney, and J. L. Laake.
1998. Abundance of southern California coastal bottlenose dolphins estimated from tandem aerial surveys. Mar. Mamm. Sci. 14(4):655–675.

Carretta, J. V., K. A. Forney, M. M. Muto, J. Barlow, J. Baker, B. Hanson, and M. S. Lowry.
2006. U.S. Pacific Marine Mammal Stock Assessments: 2005. NOAA Tech. Memo. NMFS-SWFSC-388, 317 p.

Carretta, J. V., T. Price, D. Petersen, and R. Read.
2005. Estimates of marine mammal, sea turtle, and seabird mortality in the California drift gillnet fishery for swordfish and thresher shark, 1996–2002. Mar. Fish. Rev. 66(2):21–30.

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. Fernandez, 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.

Dohl, T. P., M. L. Bonnell, and R. G. Ford.
1986. Distribution and abundance of common dolphin, *Delphinus delphis*, in the Southern California Bight: A quantitative assessment based on aerial transect data. Fish. Bull. 84:333–343.

Efron, B., and G. Gong.
1983. A leisurely look at the bootstrap, the jackknife, and cross-validation. Am. Stat. 37(1):36–48.

Field, J. C., K. Baltz, A. J. Phillips, and W. A. Walker.
In press. Range expansion and trophic interactions of the jumbo squid, *Dosidicus gigas* in the California Current. Calif. Coop. Fish. Invest. Rep.

Forney, K. A.
2000. Environmental models of cetacean abundance: reducing uncertainty in population trends. Conserv. Biol. 14(5):1271–1286.
2007. Preliminary estimates of cetacean abundance along the U.S. West Coast and within four National Marine Sanctuaries during 2005. NOAA Tech. Memo. NMFS-SWFSC-TM-406, 27 p.

Forney, K. A., and J. Barlow.
1998. Seasonal patterns in the abundance and distribution of California cetaceans, 1991–92. Mar. Mamm. Sci. 14(3):460–489.

Gerrodette, T., and J. Forcada.
2005. Non-recovery of two spotted and spinner dolphin populations in the eastern tropical Pacific Ocean. Mar. Ecol. Prog. Ser. 291:1–21.

Hill, P. S., and J. Barlow.
1992. Report of a marine mammal survey of the California coast aboard the research vessel McARTHUR July 28–November 5, 1991. NOAA Tech. Memo. NMFS-SWFSC-169, 103 p.

Julian, F., and M. Beeson.
1998. Estimates of marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990–95. Fish. Bull. 96:271–284.

Keiper, C. A., D. G. Ainley, S. G. Allen, and J. T. Harvey.
2005. Marine mammal occurance and ocean climate off central California, 1986 to 1994 and 1997 to 1999. Mar. Ecol. Prog. Ser. 289:285–306.

Mangels, K. F., and T. Gerrodette.
1994. Report of cetacean sightings during a marine mammal survey in the eastern Pacific Ocean and the Gulf of California aboard the NOAA ships *McArthur* and *David Starr Jordan* July 28–November 6, 1993. NOAA Tech. Memo. NMFS-SWFSC-211, 86 p.

Marques, F. C., and S. T. Buckland.
2003. Incorporating covariates into standard line transect analysis. Biometrics 59:924–935.

Pearcy, W. G.
2002. Marine nekton off Oregon and the 1997–98 El Niño. Prog. Oceanogr. 54: 399–403.

Peterson, W. T., R. Emmett, R. Goericke, E. Venrick, A. Mantyla, S. J. Bograd, F. B. Schwing, R. Hewitt, N. Lo, W. Watson, J. Barlow, M. Lowry, S. Ralston, K. A. Forney, B. E. Lavaniegos, W. J. Sydeman, D. Hyrenbach, R. W. Bradley, P. Warzybok, F. Chavez, K. Hunter, S. Benson, M. Weise, J. Harvey, G. Gaxiola-Castro, and R. Durazo.
2006. The state of the California Current, 2005–2006:

warm in the north, cool in the south. Calif. Coop. Fish. Invest. Rep. 47:30–74.

Rice, D. W.
1974. Whales and whale research in the eastern North Pacific. *In* The whale problem: a status report (W. E. Schevill, ed.), p. 170–195. Harvard Press, Cambridge, MA.

Rugh, D. J., R. C. Hobbs, J. A. Lerczak, and J. M. Breiwick.
2005. Estimates of abundance of the eastern North Pacific stock of gray whales 1997 to 2002. J. Cetacean Res. Manage. 7(1):1–12.

Simmonds, M. P., and L. F. Lopez-Jurado.
1991. Whales and the military. Nature 51:448.

Skaug, H. J., N. Øien, T. Schweder, and G. Bøthun.
2004. Abundance of minke whales (*Balaenoptera acutorostrata*) in the Northeast Atlantic: variability in time and space. Can. J. Fish. Aquat. Sci. 61:870–886.

Stern, J. S.
1992. Surfacing rates and surfacing patterns of minke whales (*Balaenoptera acutorostrata*) off central California, and the probability of a whale surfacing within visual range. Reports of the International Whaling Commission 42:379–385.

Trites, A. W., V. Christensen, and D. Pauly.
1997. Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. J. Northwest Atl. Fish. Sci. 22:173–187.

Turnock, B. J., and T. J. Quinn, II.
1991. The effect of responsive movement on abundance estimation using line transect sampling. Biometrics 47: 701–715.

Von Saunder, A., and J. Barlow.
1999. A report of the Oregon, California and Washington Line-transect Experiment (ORCAWALE) conducted in west coast waters during summer/fall 1996. NOAA Tech. Memo. NMFS-SWFSC-264, 40 p.

Whitehead, H.
2002. Estimates of the current global population size and historical trajectory for sperm whales. Mar. Ecol. Prog. Ser. 242:295–304.