The abundance of cetaceans in California waters.
Part II: Aerial surveys in winter and spring of 1991 and 1992

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Abstract.—Two aerial line-transect censuses of cetaceans were conducted along the California coast during March–April 1991 and February–April 1992. The two surveys were designed to provide a combined estimate of cetacean abundance for winter and spring (cold-water) conditions; they complemented a summer and fall ship survey in 1991. The study area (264,270 km^2) extended about 278 km (150 nmi) off the coast of southern California, and 185 km (100 nmi) off the coast of central and northern California. A primary team of two observers searched for cetacean species through bubble windows that allowed an unobstructed view to the sides and directly beneath the aircraft. A third, conditionally independent observer searched through a belly window and reported animals that were missed by the primary team. Approximately 7,069 km and 5,973 km were searched in 1991 and 1992, respectively, resulting in 253 sightings of at least 18 cetacean species (some animals could only be identified to higher taxa). Estimates of abundance and coefficients of variation (in parentheses) for the most common small cetaceans are the following: 306,000 (0.34) common dolphins, *Delphinus* spp.; 122,000 (0.47) Pacific white-sided dolphins, *Lagenorhynchus obliquidens;* 32,400 (0.46) Risso's dolphins, *Grampus griseus*; and 21,300 (0.43) northern right whale dolphins, *Lissodelphis borealis*. Abundance estimates (and CV's) for the most common whales are the following: 892 (0.99) sperm whales, *Physeter macrocephalus*; 392 (0.41) beaked whales, genera *Mesoplodon* and *Ziphius*; 319 (0.41) humpback whales, *Megaptera novaeangliae*; and 73 (0.62) minke whales, *Balaenoptera acutorostrata*.

Manuscript accepted 31 May 1994.
Fishery Bulletin 93:15–26 (1995).

California coastal waters are a productive and highly variable oceanographic region with a diverse marine fauna. Coastal fisheries, primarily gillnet fisheries, cause the incidental death of a variety of marine mammal species (Barlow et al., in press). However, the impact of this mortality can only be evaluated if estimates of population size are available for the affected species. In the late 1970's and early 1980's, abundance estimates were obtained based on aerial surveys,[1,2] but estimates of precision were not obtained for most species. Because of the age and uncertainty of these estimates, the National Marine Fisheries Service conducted aerial and shipboard surveys during 1991 and 1992. Based on evidence of seasonality in the abundance and distribution of some cetaceans (Leatherwood and Walker, 1979; Dohl et al., 1986), separate abundance estimates were obtained for winter and summer conditions. Two aerial surveys (March–April 1991 and February–April 1992) were completed during cold-water conditions, and one ship survey (July–November 1991) was conducted during warm-water conditions (Barlow, this issue). The survey periods were chosen based on climatic atlases of the California coast which show that, on average, March and April have the coldest, and September and October the warmest sea-surface temperatures (U.S. Navy, 1977). Standard line-transect methods (Burnham et al., 1980; Buckland et al., 1993a) were used from both platforms. Preliminary abundance estimates were calculated after completion of the first aerial survey in 1991 (Forney and Barlow, 1993), but confidence limits were large. In this paper, we present combined abundance estimates for the 1991 and 1992 aerial surveys.

Survey methods

The methods used during the 1991–92 aerial surveys are described in detail by Forney and Barlow (1993) and Carretta and Forney (1993), and only a summary is presented below. The study area (264,270 km^2)

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[1] Dohl, T. P., K. S. Norris, R. C. Guess, J. D. Bryant, and M. W. Honig. 1978. Cetacea of the Southern California Bight. Part II of Summary of marine mammal and seabird surveys of the Southern California Bight area, 1975–1978. Final Report to the Bureau of Land Management, 414 p. [NTIS Rep. PB81248189.]

[2] Dohl, T. P., R. C. Guess, M. L. Duman, and R. C. Helm. 1983. Cetaceans of central and northern California, 1980–1983: status, abundance and distribution. OCS Study MMS 84–0045. Minerals Management Service contract No. 14-12-0001-29090, 284 p.

encompasses California waters out to a distance of 185–278 km (100–150 nmi) from the coast and roughly a depth of 3,000–4,000 m (Fig. 1). It was defined on the basis of the distribution of fisheries that are known to take marine mammals and does not reflect a distributional boundary for any marine mammal population. Surveys were conducted along transect lines forming two nearly uniform, overlapping grids (Fig. 1). The resulting overall grid lines were spaced 41–46 km (22–25 nmi) apart. The location of the transect grid was chosen without reference to specific areas or topographical features. To avoid potential differences in regional coverage, an attempt was made in each year to complete all transects of the first grid, providing coarse coverage of the entire study area, before beginning the second grid. However, in both years, poor weather conditions prevented the completion of both survey grids. In 1991, 85% (5,326 km) of transect grid 1 and 27% (1,739 km) of grid 2 were completed, and in 1992, 81% (5,065 km) of transect grid 1 and 14% (890 km) of grid 2 were completed. The relative proportions of survey effort in different sea state and cloud cover conditions were similar for the two years (Table 1).

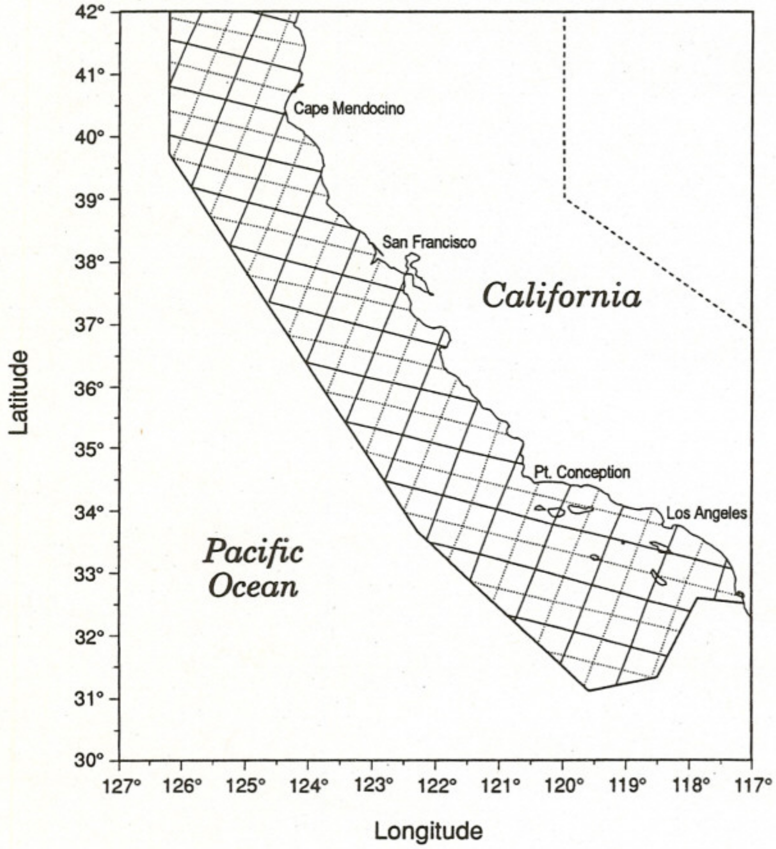

Figure 1

Study area with two overlapping transects grids. The solid line represents grid 1, the dotted line grid 2.

The survey platform was a twin-engine turbo-prop DeHavilland Twin Otter, flown approximately at an altitude of 213 m (700 ft) and an airspeed of 165–185 km/h (90–100 knots). All cetacean and sea turtle sightings were recorded, but because of the high densities of pinnipeds near rookeries, these species were recorded only when seen farther than 10 km from land. Two "primary" observers searched through bubble windows on the left and right sides of the aircraft. These windows allowed observers to view to the side and directly beneath the aircraft with at least 10° of overlap between sides. To achieve higher sighting efficiency near the transect line, observers searched for cetaceans only out to a declination angle of 12° (1,004 m perpendicular distance). An additional "secondary" observer monitored the trackline area out to 55° declination angles (on both sides) through a round 45-cm (18-in) viewing hole in the belly of the aircraft and reported sightings missed by the primary team. A fourth person recorded all sighting, effort, and environmental data. To minimize observer fatigue, all observers rotated between these four active positions and one resting position roughly every 30 minutes. All observers had previous experience in identifying cetacean species from aerial or shipboard platforms, or both.

All survey data were recorded on a laptop computer connected to a LORAN or GPS (Global Positioning System) navigational receiver, providing a continuous record of position (updated every few seconds), altitude, air speed, and survey conditions. Environmental conditions, such as Beaufort sea state, percent cloud cover, and glare, were updated whenever changes occurred. Conversation in the aircraft was recorded on a central cassette recorder as a backup to the computer record. Observers also recorded individual sighting information into personal notebooks. Surveys were conducted only in Beaufort sea states 0–4.

Following the methods described in Forney and Barlow (1993) and Carretta and Forney (1993), the aircraft circled for each sighting to obtain species identifications and school size estimates

Table 1

Survey effort (in km) stratified by sea state and percent cloud cover.

% Cloud cover	Beaufort sea state 0 and 1	2	3	4	Total
1991					
0–24	212	913	1,932	1,346	4,403
25–49	26	66	96	85	273
50–74	45	58	331	241	676
75–100	76	129	980	532	1716
Total	359	1,166	3,338	2,205	7,069
1992					
0–24	406	933	1,349	1,220	3,908
25–49	0	8	141	113	262
50–74	2	43	192	47	284
75–100	78	251	758	433	1,519
Total	486	1,235	2,440	1,813	5,973
Both years combined					
0–24	618	1,846	3,280	2,566	8,311
25–49	26	74	238	199	536
50–74	47	101	523	288	960
75–100	154	380	1,737	965	3,235
Total	845	2,401	5,778	4,018	13,042

(each observer made a confidential record of best, high, and low estimate into a personal field notebook). Any additional schools sighted while the aircraft was diverted from the transect were recorded as 'off-effort' sightings. Only sightings made during active searches on predetermined transect lines ('on-effort') were included for abundance estimation. The secondary observer only reported sightings missed by the primary observer team; these secondary sightings were used to estimate the fraction of animals missed on the transect line.

Analytical methods

Stratification

Because we were not able to complete both grids in all regions of the coast, the study area was divided into four a posteriori geographic areas to approximate uniform coverage within each stratum (Fig. 2). Environmental conditions such as sea state and percent cloud cover were recorded throughout the survey, as they have been shown to influence cetacean sighting rates (Holt and Cologne, 1987; Forney et al., 1991). However, because of the small number of sightings made during each combination of environmental conditions, it was not possible to evaluate their effect quantitatively.

Because of the difficulty in identifying beaked whales to species level during aerial surveys, only a combined abundance estimate was obtained for this group. In the preliminary analyses of the 1991 aerial survey data, Forney and Barlow (1993) assigned other unidentified species based on a 'nearest identified neighbor' approach. In the analyses presented here, unidentified cetacean sightings were treated separately as either 'unidentified dolphin or porpoise,' 'unidentified small whale,' or 'unidentified large whale,' because they represented only a small fraction of the total animals seen.

The small number of sightings for each species made it necessary to pool distributions of perpendicular sighting distances for line-transect calculations. Forney and Barlow (1993) created preliminary species groups based on considerations of school size, body size and behavior, and pooled distributions for groups that were not statistically different from one another. The same procedure was used for this analysis, resulting in the same three species/group-size categories: 1) small cetacean groups with 1–10 animals; 2) small cetacean groups with more than 10 animals; and 3) medium and large cetaceans (Table 2).

Table 2

Estimates of $f(0)$ and $g(0)$, and number of sightings (n) for the three species/group-size categories used in the analysis.

Small cetaceans	Group size	n	$f(0)$	$g(0)$
	1–10	99	4.70	0.67
	> 10	53	2.85	0.85
Species				
Harbor porpoise, *Phocoena phocoena*				
Dall's porpoise, *Phocoenoides dalli*				
Pacific white-sided dolphin, *Lagenorhynchus obliquidens*				
Risso's dolphin, *Grampus griseus*				
Bottlenose dolphin, *Tursiops truncatus*				
Common dolphins *Delphinus delphis* and *D. capensis*				
Northern right whale dolphin, *Lissodelphis borealis*				

Medium and large cetaceans	Group size	n	$f(0)$	$g(0)$
	1–22	57	2.49	0.95
Species				
Killer whale, *Orcinus orca*				
Small beaked whales, *Ziphius cavirostris* and *Mesoplodon* spp.				
Sperm whale, *Physeter macrocephalus*				
Right whale, *Eubalaena glacialis*				
Gray whale, *Eschrichtius robustus*				
Minke whale, *Balaenoptera acutorostrata*				
Blue whale, *B. musculus*				
Fin whale, *B. physalus*				
Humpback whale, *Megaptera novaeangliae*				

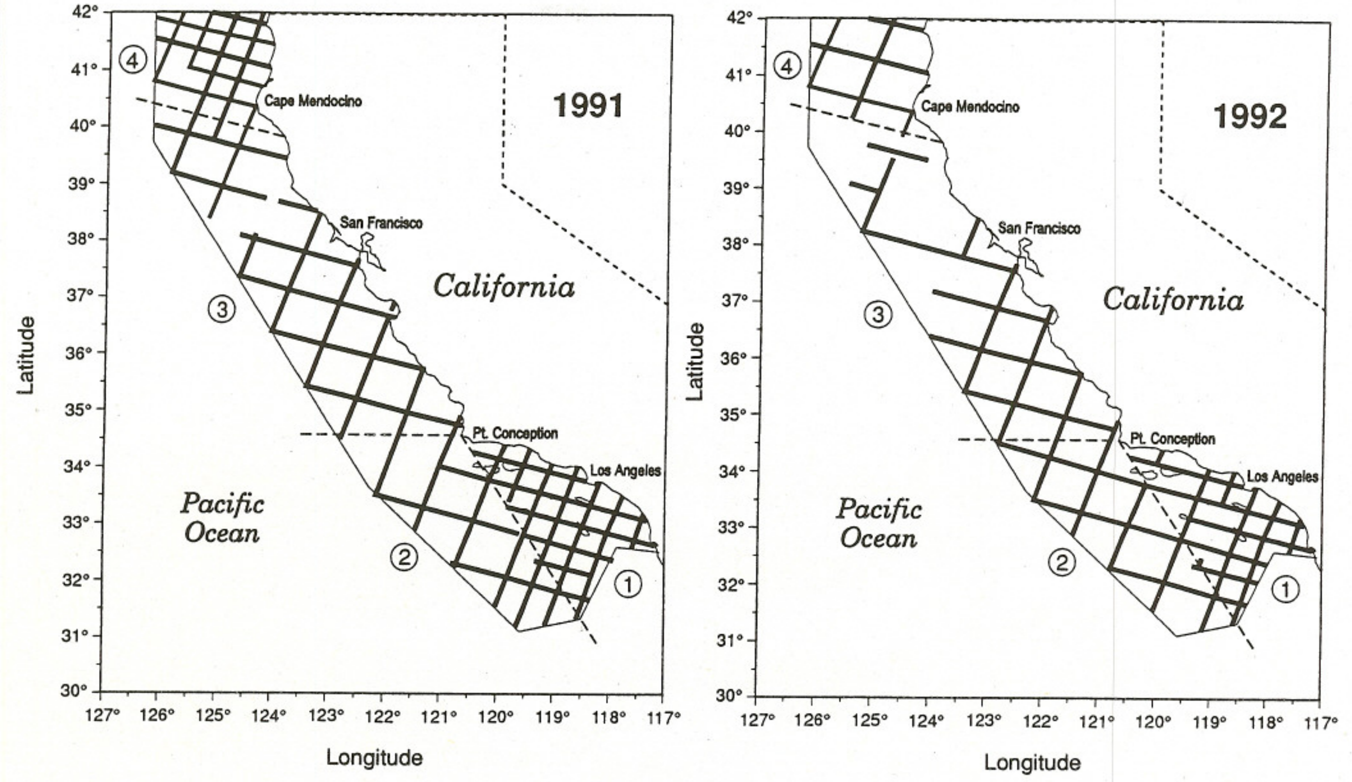

Figure 2

Completed transects (solid lines) for 1991 and 1992, and a posteriori geographic strata (separated by broken lines) used in the analysis. Area numbers are shown in circles.

Abundance estimation

Line transect methods (Burnham et al., 1980; Buckland et al., 1993a) were applied to estimate abundances separately for each species in each stratum:

$$N_k = \sum_{j=1}^{3}\sum_{i=1}^{4} \frac{A_i\, n_{i,j,k}\, S_{i,j,k}\, f_j(0)}{2 L_i\, g_j(0)}, \qquad (1)$$

where

N_k = estimated total number of animals of species k in the study area;
$n_{i,j,k}$ = number of sightings of species k in area i and species/group-size category j;
$s_{i,j,k}$ = average group size of species k in area i and species/group-size category j, calculated as the total number of animals in all groups divided by the number of groups sighted;
$f_j(0)$ = the probability density function evaluated at zero perpendicular distance for species/group-size category j;
$g_j(0)$ = the probability of detecting a group of animals on the transect line for species/group-size category j;
L_i = the length of transect surveyed in area i (in km); and
A_i = the size of area i (in km^2).

Values for $f(0)$ were obtained for each species/group-size category by fitting the distribution of all perpendicular sighting distances (primary and secondary; measured in km) to the Hazard rate model with the statistical software program HAZARD (Buckland, 1985). A value for $g(0)$ was estimated following the methods described in Forney and Barlow (1993), but because of small sample sizes, it was not possible to estimate the variance in $g(0)$. This should result in a downward bias in the variance of the abundance estimates, but bias in the abundance estimates themselves will be reduced. The lengths of transect lines flown, L_i (and total sizes, A_i), for the four areas are 3,715 km (46,300 km^2) for area 1; 2,831 km (63,772 km^2) for area 2; 4,461 km (120,108 km^2) for area 3; and 2,035 km (34,090 km^2) for area 4.

Variance estimation

Variance in estimated abundance was calculated with bootstrap techniques applied to the complete data set. The data were subdivided by area into effort segments of equal length, and the segments were then drawn randomly with replacement until the total number of kilometers actually surveyed in each area was reached. This process was replicated 1,000 times. Forney and Barlow (1993) demonstrated that the choice of segment lengths between 5 km and 20 km did not influence the resulting estimates of precision. In this analysis we also performed bootstrap simulations for 50 km and 100 km segments and again found that segment length did not affect estimates of variance. For the bootstrap analysis, we chose a segment length of 50 km, which roughly reflects the degree of sampling variability for these surveys (i.e. the dimension of actual gaps in the sampling grid in Figure 2).

Each of the 1,000 bootstrap replicates was treated and analyzed as a separate survey: sightings were first stratified into the three species/group-size categories given above. Individual values for n and s were calculated, and $f(0)$ was estimated with the program HAZARD. The estimated value of $g(0)$ was treated as a correction factor known without error. The variance, coefficient of variation, and 95% confidence intervals were obtained from the distribution of the 1,000 bootstrap abundance estimates with standard formulae. Because the bootstrap method (Buckland, 1984) of obtaining confidence intervals can result in the lower 95% confidence intervals being smaller than the actual number of animals seen (or even zero) we also calculated log-normal confidence intervals based on the bootstrap coefficient of variation.

Results

Detailed results of the survey, including sighting information and plots of sighting locations for all species sighted are presented elsewhere (Carretta and Forney, 1993). Results relevant to the analyses presented in this paper are given below. A total of 253 cetacean sightings were made (Fig. 3): 213 on effort (while actively searching), and an additional 40 off effort (24 while in transit, 8 beyond 12° declination angle, 7 while circling over another group of animals, and 1 by an off-effort observer). Twenty eight on-effort sightings could not be positively identified to the

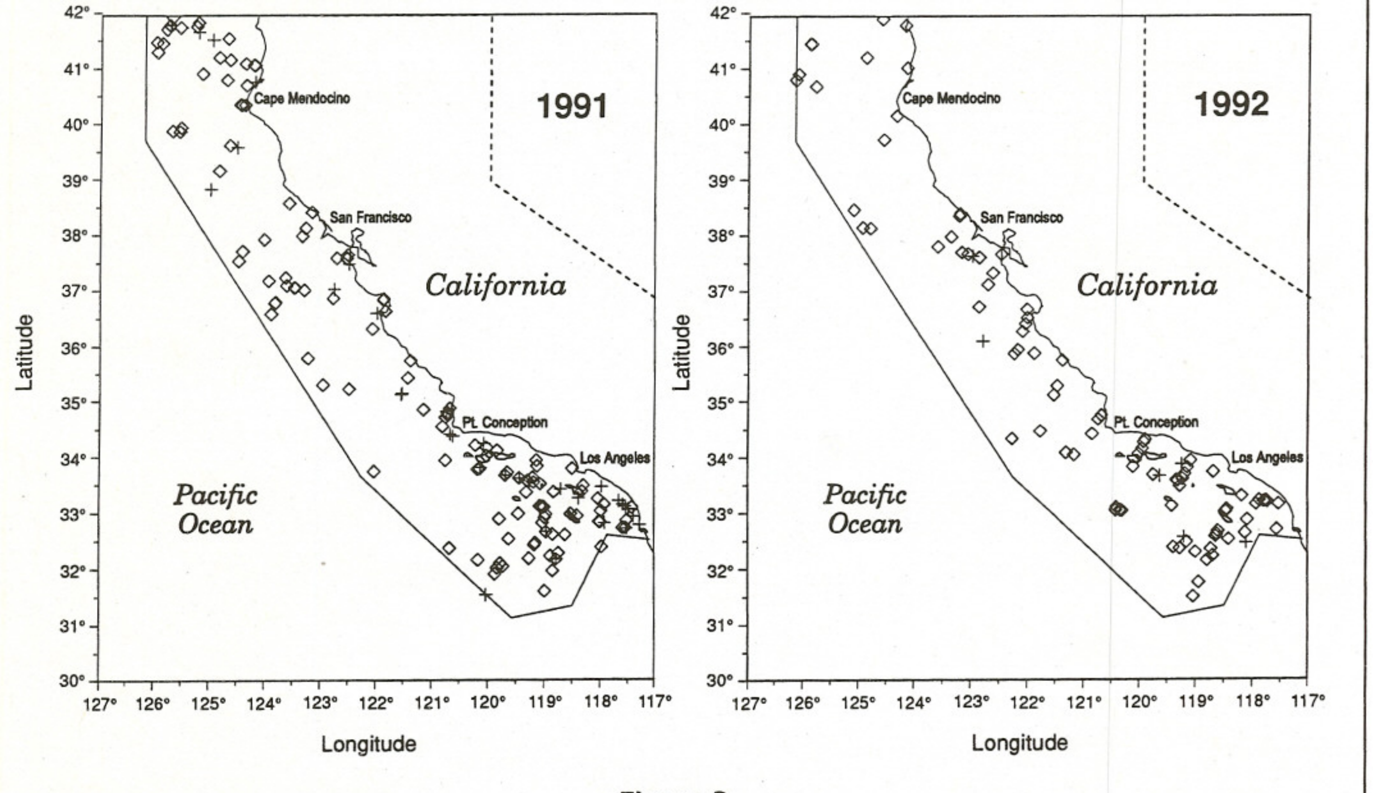

Figure 3

Locations of all 253 cetacean sightings made during the 1991 and 1992 surveys. The 213 on-effort sightings (used in the abundance estimation) are shown by diamonds, and the 40 off-effort sightings (e.g. made while circling or in transit) are shown with plus signs.

species level. Four of these sightings were identified as ziphiid whales, for which a combined abundance estimate was calculated. The remaining 24 sightings were treated separately in the analyses.

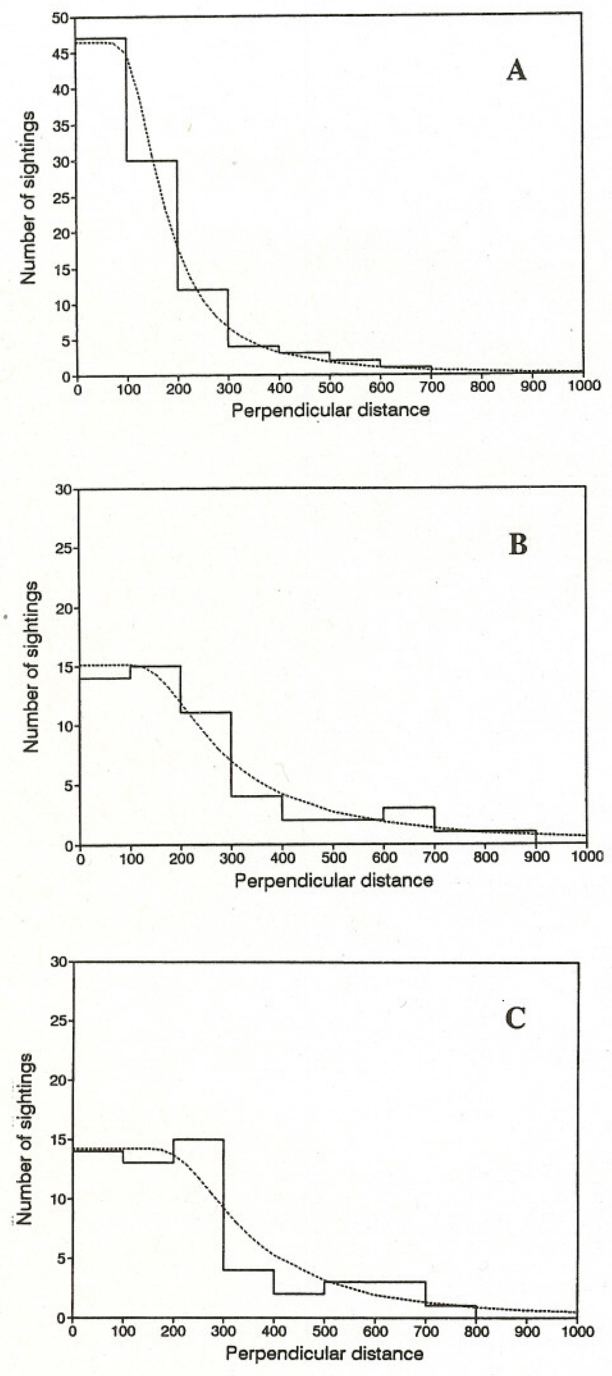

Figure 4

Distribution of perpendicular sighting distances (100-m intervals; solid line) and Hazard model fit (dotted line) for (**A**) small cetaceans in groups ≤10, (**B**) small cetaceans in groups >10, and (**C**) medium and large cetaceans.

The Hazard model provided adequate fits to the perpendicular distance distributions for the three species/group-size categories (Fig. 4). Estimates of $f(0)$ and $g(0)$ are given for each group in Table 1. Although the full transect grid was not completed in either year because of poor weather, the resulting estimates of abundance (Table 3) are the most precise that have been produced to date for this area and season. CV's range from 0.24 to 0.49 for small cetaceans and from 0.35 to 1.11 for large cetaceans.

Discussion

Comparisons with previous abundance estimates

Our abundance estimates (Table 3) can be compared directly with estimates based on 1975–83 aerial surveys,[1,2] which are likely to have similar biases. The estimate of 8,460 Dall's porpoise, *Phocoenoides dalli*, is similar to previous aerial survey estimates of 3,000–4,000 in winter and spring.[1,2] The current estimate of 122,000 Pacific white-sided dolphins,[3] *Lagenorhynchus obliquidens*, is greater than the combined estimates of 26,000 (spring) to 33,500 (winter) for central and northern California[2] and 5,300 (Jan–Jun) for southern California.[1] Our estimate of 21,300 northern right whale dolphins is less than the combined estimates of 29,000 (spring) to 61,500 (winter) for central and northern California[2] and 5,900 (Jan–Jun) for southern California.[1] The prior studies do not give estimates of statistical precision for any of the above species, but given the CV's of our estimates, the above differences are not likely to be statistically significant.

In contrast to the species above, common dolphins, *Delphinus* spp., appear to be much more abundant at present than during the period 1975–83. The current winter estimate (306,000; CV=0.34) is more than an order of magnitude larger than the previous value of 15,488 (CV=0.36; Dohl et al., 1986), and the 99% log-normal confidence limits for these two estimates do not overlap. Preliminary comparisons (Barlow, unpubl. data) of 1979 and 1980 ship surveys with the 1991 ship survey (Barlow, this issue) also show a significant increase in common dolphin abundance. Based on these two separate lines of evidence for winter and summer conditions, the abundance of common dolphins in California appears to have in-

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[3] Although estimates for Pacific white-sided dolphins based on the combined 1991 and 1992 survey data are over twice the preliminary estimate of 46,000 from only the 1991 data (Forney and Barlow, 1993), the new estimate lies well within the 95% confidence limit of the previous value.

Table 3

Number of groups seen, mean group size, density of individuals, and abundance estimates for cetaceans in the entire California study area, and subdivided by geographic stratum (See Fig. 2). Coefficients of variation (CV) and 95% confidence intervals (CI) for the overall abundance estimates are also given. Unid.=unidentified.

Species and area	Number of groups	Mean group size	Animal density km^{-2}	Population size N	CV	Bootstrap CI		Log-normal CI	
						Lower 95%	Upper 95%	Lower 95%	Upper 95%
Harbor porpoise[1]	18	1.2	0.0060	1,599	0.345	664	2,915	829	3,085
Area 1	0	0.0	0.0000	0					
Area 2	0	0.0	0.0000	0					
Area 3	10	1.0	0.0079	949					
Area 4	8	1.4	0.0191	650					
Dall's porpoise	38	3.1	0.0320	8,460	0.240	5,203	13,361	5,320	13,453
Area 1	9	4.0	0.0342	1,582					
Area 2	2	4.5	0.0112	716					
Area 3	19	2.6	0.0395	4,744					
Area 4	8	3.0	0.0416	1,418					
Pacific white-sided dolphin	21	151.6	0.4605	121,693	0.466	35,404	261,524	51,041	290,144
Area 1	5	24.6	0.0573	2,654					
Area 2	7	69.4	0.2945	18,779					
Area 3	7	237.1	0.6218	74,678					
Area 4	2	457.0	0.7505	25,583					
Risso's dolphin	19	47.6	0.1225	32,376	0.456	10,255	65,984	13,812	75,891
Area 1	14	28.5	0.2029	9,396					
Area 2	1	8.0	0.0100	636					
Area 3	4	124.3	0.1860	22,343					
Area 4	0	0.0	0.0000	0					
Bottlenose dolphin	8	17.9	0.0123	3,260	0.487	618	6,783	1,320	8,052
Area 1	7	20.3	0.0684	3,165					
Area 2	0	0.0	0.0000	0					
Area 3	1	1.0	0.0008	95					
Area 4	0	0.0	0.0000	0					
Common dolphins	27	514.9	1.1568	305,694	0.340	124,730	539,319	159,864	584,552
Area 1	22	592.7	5.8769	272,101					
Area 2	4	176.0	0.4161	26,535					
Area 3	1	157.0	0.0588	7,058					
Area 4	0	0.0	0.0000	0					
Northern right whale dolphin	31	18.9	0.0807	21,332	0.428	9,151	42,629	9,548	47,658
Area 1	18	12.3	0.1378	6,381					
Area 2	4	56.5	0.1395	8,895					
Area 3	6	11.8	0.0341	4,091					
Area 4	3	22.7	0.0577	1,966					
Killer whale	2	1.0	0.0002	65	0.689	0	133	19	220
Area 1	0	0.0	0.0000	0					
Area 2	1	1.0	0.0005	30					
Area 3	1	1.0	0.0003	35					
Area 4	0	0.0	0.0000	0					
Beaked whales[2]	8	1.9	0.0015	392	0.408	151	774	182	845
Area 1	0	0.0	0.0000	0					
Area 2	3	1.0	0.0014	89					
Area 3	2	1.5	0.0009	106					
Area 4	3	3.0	0.0058	197					
Sperm whale	3	10.0	0.0034	892	0.990	0	2,798	176	4,506
Area 1	0	0.0	0.0000	0					
Area 2	2	14.5	0.0134	857					

Table 3 (Continued)

Species and area	Number of groups	Mean group size	Animal density km^{-2}	Population size N	CV	Bootstrap CI		Log-normal CI	
						Lower 95%	Upper 95%	Lower 95%	Upper 95%
Area 3	1	1.0	0.0003	35					
Area 4	0	0.0	0.0000	0					
Northern right whale	1	1.0	0.0001	16	1.110	0	59	3	95
Area 1	1	1.0	0.0004	16					
Area 2	0	0.0	0.0000	0					
Area 3	0	0.0	0.0000	0					
Area 4	0	0.0	0.0000	0					
Gray whale[3]	25	4.2	0.0108	2,844	0.347	1,187	5,270	1,469	5,507
Area 1	12	3.4	0.0145	669					
Area 2	0	0.0	0.0000	0					
Area 3	11	5.3	0.0170	2,043					
Area 4	2	3.0	0.0039	132					
Minke whale	3	1.0	0.0003	73	0.616	0	181	24	223
Area 1	1	1.0	0.0004	16					
Area 2	0	0.0	0.0000	0					
Area 3	1	1.0	0.0003	35					
Area 4	1	1.0	0.0006	22					
Blue whale	1	1.0	0.0001	30	0.990	0	100	6	149
Area 1	0	0.0	0.0000	0					
Area 2	1	1.0	0.0005	30					
Area 3	0	0.0	0.0000	0					
Area 4	0	0.0	0.0000	0					
Fin whale	2	1.5	0.0002	49	1.012	0	57	9	254
Area 1	2	1.5	0.0011	49					
Area 2	0	0.0	0.0000	0					
Area 3	0	0.0	0.0000	0					
Area 4	0	0.0	0.0000	0					
Humpback whale	8	1.6	0.0012	319	0.407	114	622	148	688
Area 1	1	1.0	0.0004	16					
Area 2	0	0.0	0.0000	0					
Area 3	2	1.5	0.0009	106					
Area 4	5	1.8	0.0058	197					
Unid. large whale	5	1.2	0.0006	160	0.457	40	348	68	376
Area 1	1	2.0	0.0007	33					
Area 2	0	0.0	0.0000	0					
Area 3	3	1.0	0.0009	106					
Area 4	1	1.0	0.0006	22					
Unid. small whale	3	1.0	0.0003	68	0.676	0	188	20	226
Area 1	2	1.0	0.0007	33					
Area 2	0	0.0	0.0000	0					
Area 3	1	1.0	0.0003	35					
Area 4	0	0.0	0.0000	0					
Unid. dolphin or porpoise	15	4.4	0.0180	4,766	0.331	2,050	8,368	2,533	8,966
Area 1	2	1.5	0.0028	132					
Area 2	5	4.2	0.0223	1,419					
Area 3	7	5.7	0.0258	3,096					
Area 4	1	2.0	0.0035	118					

[1] More appropriate estimates for harbor porpoise are recently available in Barlow and Forney (1994). (See Discussion section.)

[2] This category includes beaked whales of the genus *Mesoplodon* and Cuvier's beaked whale, *Ziphius cavirostris*. No Baird's beaked whales, *Berardius bairdii*, were seen during the surveys.

[3] A more accurate estimate of the entire population of California gray whales is presented in Buckland et al., 1993. (See Discussion section.)

creased dramatically since the early 1980's. The causes of this increase are not known, but it is possible that long-term oceanographic changes (Roemmich, 1992; Roemmich and McGowan, 1994) have resulted in a shift in the distribution of common dolphins into this area. This hypothesis is consistent with the observed decline in population size of the northern common dolphin south of our study area (Anganuzzi and Buckland, 1994).

Similarly, an apparent decrease in abundance was seen in short-finned pilot whales, *Globicephala macrorhynchus*. This species was commonly seen in the Southern California Bight on surveys during the late 1970's and early 1980's,[1,2] but only one off-effort sighting of four animals was made during our surveys.

Our estimate of 304 humpback whales is roughly half the recent estimate obtained from photo-identification studies.[4] This is quite surprising because humpback whales, *Megaptera novaeangliae*, in the California feeding population are expected to be in waters off Mexico during the winter and spring season. However, it is possible that some animals had already moved north into California at the time of the sightings. Alternatively, the sighted animals may have been part of the southeastern Alaska feeding population that migrates southward to breed in Mexican waters in spring (Baker et al., 1986).

Previously published estimates for harbor porpoise, *Phocoena phocoena* (Barlow, 1988; Barlow et al., 1988; Barlow and Forney, 1994) and gray whales, *Eschrichtius robustus* (Reilly, 1984; Buckland et al., 1993b), are substantially higher than the estimates presented here. This is probably because the defined study area is not appropriate for the range of these animals. Gray whales have a much larger range and migrate through California waters (southward and then northward) from roughly November to May. Our estimate represents that portion of the population which was migrating through California in March and early April. Harbor porpoise are limited to a narrow coastal band, and our transect lines only overlapped with this region at specific points. More appropriate abundance estimates for harbor porpoise are published in Barlow (1988) and in Barlow and Forney (1994).

Comparisons with 1991 ship surveys

Although a statistical comparison between these winter and spring aerial survey estimates and the 1991 summer and fall ship survey estimates (Barlow, this issue) is precluded at this time because of differences in the sizes of the two study areas, a few patterns are noteworthy. Despite the differences in seasonal timing and areal coverage, estimates of abundance are very similar for several species. Similar estimates of abundance were obtained for total common dolphins (306,000 vs. 246,000), northern right whale dolphins, *Lissodelphis borealis* (21,300 vs. 9,340), bottlenose dolphins, *Tursiops truncatus* (3,260 vs. 1,500), and sperm whales, *Physeter macrocephalus* (892 vs. 756) (aerial vs. ship estimates, respectively). More disparate estimates were obtained for Pacific white-sided dolphins (122,000 vs. 12,300), Risso's dolphins, *Grampus griseus* (32,400 vs. 8,500), harbor porpoise (1,600 vs. 52,700), Dall's porpoise (8,460 vs. 78,400), and total beaked whales, *Ziphius cavirostris* and *Mesoplodon* spp. (392 vs. 3,230).

It may be important to note that all cases in which the ship estimates are substantially larger than the aerial estimates are for species which spend a large fraction of their time diving (harbor porpoise, Dall's porpoise, and beaked whales). Such species could be more easily missed by aerial observers owing to availability bias. In the case of Pacific white-sided dolphins and Risso's dolphins, the winter and spring aerial estimates may be larger because of a seasonal movement of animals out of Oregon and Washington in winter.[5] Additional analyses, which account for differences in geographic extent of the aerial vs. ship surveys, are planned in the future.

Bias

There are several sources of potential bias in this study. First, abundance estimates may be biased low because animals are missed by aerial observers (perception bias; Marsh and Sinclair, 1989). This is most likely to be a problem with poor observation conditions (high sea state or overcast conditions, or both). We have attempted to estimate the magnitude of perception bias in this study through the use of a conditionally independent observer and have corrected abundance estimates to reduce this effect. A second source of downward bias, availability bias (Marsh and Sinclair, 1989), is introduced because animals that are submerged when the aircraft passes overhead are not available to be seen. This effect is

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[4] Calambokidis, J., G. H. Steiger, and J. R. Evenson. 1993. Photographic identification and abundance estimates of humpback and blue whales off California in 1991–92. Final Contract Report 50ABNF100137 to Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038, 67 p.

[5] Green, G. A., J. J. Brueggeman, R. A. Grotefendt, C. E. Bowlby, M. L. Bonnell, and K. C. Balcomb III. 1992. Cetacean distribution and abundance off Oregon and Washington, 1989–1990. Ch. 1 *in* J. J. Brueggeman (ed.), Oregon and Washington marine mammal and seabird surveys. Minerals Management Service Contract Report 14-12-0001-30426 prepared for the Pacific OCS (Outer Continental Shelf) Region.

expected to be smallest for species which tend to occur in large groups, such as common dolphins, and largest for species which spend relatively little time at the surface, such as porpoise, beaked whales, and sperm whales.

Dive studies (Barlow et al., 1988) may provide information on the magnitude of availability bias, but each species requires a separate assessment of the average proportion of time it spends at the surface (and hence is 'available'), and adequate estimates are not currently available for most species in California waters. Rough estimates can be made for Dall's porpoise and humpback whales based on prior studies. Dall's porpoise have similar sighting characteristics to those of harbor porpoise (both have a small body size and generally are found in small groups); thus, assuming that dive patterns are similar and applying the correction factor of 3.1 (CV=0.17) for harbor porpoise,[6] one would obtain a corrected estimate of approximately 26,200 Dall's porpoise. Based on a very small sample, a correction factor of 2.7 has been estimated for humpback whales.[7] This would yield a corrected abundance estimate of 861 humpback whales. Clearly, given the magnitude of these correction factors, availability bias can be substantial.

Potential upward bias in line-transect analysis can result if factors other than distance to the trackline affect the probability of seeing a school. School size has been shown to affect the probability of detection (Drummer, 1985; Holt and Sexton, 1989), and this can lead to an upward bias in the abundance estimate (Quinn, 1985; Drummer and McDonald, 1987; Buckland et al., 1993a). To counteract this effect, we have stratified small cetacean sightings by group size and estimated abundances separately for small and large groups of the same species. This is an artificial separation, but it reduces potential biases that are due to large variation in group size within a single species, such as common dolphins or Pacific white-sided dolphins. Within each stratum, correlations of perpendicular sighting distance with group size are weak and not significant at $\alpha=0.05$ ($r=0.195$ for small cetaceans in groups of 1–10 animals; $r=0.169$ for small cetaceans in groups of greater than 10 animals; and $r=0.183$ for whales in groups of all sizes).

In summary, we have attempted to correct for perception bias by estimating the fraction of animals missed during these surveys and have minimized potential upward bias with a poststratification by school-size range. However, species-specific availability bias cannot currently be estimated, and overall our abundance estimates are likely to be biased downward.

Precision

Estimation of variance for line-transect abundance calculations can be difficult. We have attempted to include most of the sources of sampling error in the bootstrap procedure, which reestimates n, s, and $f(0)$ (in Eq. 1) for each replicate. Our analysis revealed that the choice of segment length used for the bootstrap did not affect the resulting estimates of precision within the range of appropriate segment lengths for this study (5–100 km; longer segments would not be appropriate because surveys extended only 100–150 km offshore). However, potential heterogeneity due to the pooling of different species and group sizes for estimation of $f(0)$ and $g(0)$ was not accounted for in precision estimates. Furthermore, we did not include the variance in $g(0)$ or in the estimation of group size for each school encountered (however, the variance in the estimated mean group size for the survey was included in the bootstrap procedure). Thus, the coefficients of variation for the abundance estimates (Table 3) are likely to be underestimated and the confidence intervals are likely to be too narrow.

Considerations for future aerial surveys

Two species of common dolphins, short-beaked and long-beaked, are recognized in California waters (Rosel, 1992; Dizon et al., 1994; Heyning and Perrin, 1994). Although clear differences in color pattern, size, and beak length exist between these two forms, it is not currently possible to differentiate them during aerial surveys; therefore the abundance estimate here is a combined estimate. Unless reliable means of identifying the two species from the air are developed, aerial surveys will not be adequate for future assessments requiring separate estimates of short-beaked and long-beaked common dolphins.

Similarly, it was difficult to distinguish between the smaller species of beaked whales during our aerial surveys. The estimates presented for the beaked whales as a group are therefore a combined estimate for *Ziphius cavirostris* and *Mesoplodon* spp. All unidentified beaked whale sightings could be narrowed down to these two genera. The only other beaked whale species known to occur in this region, *Berardius bairdii*, can be readily distinguished based

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[6] Calambokidis, J., J. R. Evenson, J. C. Cubbage, P. J. Gearin, and S. D. Osmek. 1993. Development of a correction factor for aerial surveys of harbor porpoise. Draft Final Contract Report to the National Marine Mammal Laboratory, NMFS, NOAA, 7600 Sand Point Way NE, BIN C-15700, Seattle, WA 98115. 36 p.

[7] Calambokidis, J., G. H. Steiger, J. C. Cubbage, K. C. Balcomb, and P. Bloedel. 1989. Biology of humpback whales in the Gulf of the Farallones. Final report for Contract CX-8000-6-0003 to Gulf of the Farallones National Marine Sanctuary, NOAA, Fort Mason Center, Bldg. 201, San Francisco, CA 94123, 93 p.

on its size and was not sighted during this survey. It is likely that the categorization of "small beaked whales" will be necessary on future aerial surveys.

The survey grid used here was not designed for species which are restricted to a narrow coastal region. Harbor porpoise are found primarily in waters inshore of the 50-fathom (92-m) isobath (Barlow, 1988). Two distinct populations of bottlenose dolphins are found in California; the inshore form is found only within about 1 km of shore (Hansen, 1990; NMFS[8]). All of the bottlenose dolphins seen during this aerial survey were at least several miles from the mainland; therefore our estimate is assumed to represent the population of offshore animals. Precise estimates of abundance for harbor porpoise and inshore bottlenose dolphins will require dedicated aerial surveys designed for those species. Work is currently in progress on both of these projects.[8]

Acknowledgments

Funding for this project was provided by the Office of Protected Species, U.S. Department of Commerce. The aircraft was provided by the NOAA Aircraft Operations Center. We express special thanks to the pilots: T. O'Mara, J. Vance, P. Wehling, and M. White. We are grateful to the meteorological staff of the National Weather Service for their valuable assistance in planning flights. Observers were D. Everhart, S. Kruse, C. LeDuc, R. LeDuc, and M. Lycan (also J. B., J. V. C., and K. A. F). Survey design was improved by comments from D. Ainley, H. Braham, S. Buckland, K. P. Burnham, D. DeMaster, D. Goodman, T. Gerrodette, L. Hansen, W. Hoggard, D. Palka, and T. Polacheck. Data recording software was developed by J. Cubbage (and J. B.). An earlier draft of this manuscript was reviewed by the participants of the Status of California Cetacean Stocks Workshop in March–April 1993; we thank all for their efforts and reviews. The submitted manuscript was reviewed by J. Calambokidis, R. Hobbs, and an anonymous reviewer. Surveys were conducted under Marine Mammal Protection Act permit 748 and permits GFNMS-01-92 and CINMS-01-92 from the National Marine Sanctuary Program.

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