

Abstract—We estimate abundance and describe the depth distribution of harbor porpoise (*Phocoena phocoena*) in northern California from a November 1995 ship survey. This was the first ship survey designed to systematically survey different depth strata out to 91 m (50 fathoms) in this region. Harbor porpoise abundance in northern California is estimated at 5686 (CV=0.29, log-normal 95% CI=3498–9242), based on 377 km of transect effort and 153 porpoise sightings. Using a confidence interval of differences approach, we determined that our abundance estimate was significantly different ($P=0.08$; $\alpha=0.10$) from an aerial survey estimate obtained 1 to 2 months earlier in the same region, where abundance was estimated at 13,145 (CV=0.39, log-normal 95% CI=6316–27,357). Possible explanations for differences in estimates include seasonal movement of porpoise to other areas or depths, insufficient transect effort during the ship survey, or underestimates of the fraction of porpoise groups missed on the trackline due to large swells. Porpoise distribution in northern California was not random with respect to water depth; significantly more porpoise than expected occurred at depths of 20 to 60 m and fewer porpoise than expected occurred at depths >60 m.

Abundance and depth distribution of harbor porpoise (*Phocoena phocoena*) in northern California determined from a 1995 ship survey

James V. Carretta

Barbara L. Taylor

Susan J. Chivers

Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA

P.O. Box 271

La Jolla, California 92038

E-mail address (for J. V. Carretta): Jim.Carretta@noaa.gov

The abundance and distribution of harbor porpoise (*Phocoena phocoena*) in California waters has recently been described from a series of aerial surveys conducted by the U.S. National Marine Fisheries Service (NMFS) (Forney et al., 1991; Barlow and Forney, 1994; Forney 1995; Forney, 1999). The most recent abundance estimate was 5732 (CV=0.28) for central California and 11,066 (CV=0.39) for northern California, based on aerial surveys conducted from 1993 to 1997.¹ Declining trends in porpoise abundance have recently been described in central California based on aerial surveys conducted from 1986 to 1995 (Forney, 1995, 1999). This perceived decline is unexpected because the central California population was expected to recover following a substantial reduction in fishery-related mortality beginning in the late 1980s (Barlow and Forney, 1994; Barlow and Hanan, 1995; Julian and Beeson, 1998). Forney (1999) noted that harbor porpoise abundance was negatively correlated with positive sea surface temperature anomalies off central California and suggested that perceived declines in porpoise abundance may be due to interannual movement of animals in and out of the study area in response to changing oceanographic conditions, rather than an actual population decline. Because the aerial survey study area was limited to nearshore waters ≤ 91 m (50 fathoms) in depth, one possible explanation was that porpoise might move into deeper waters in response to anomalous periods of

warm water (Forney, 1999). Another explanation is that harbor porpoise moved north into northern California in response to warm-water episodes (Forney's trend data showed an increase in porpoise abundance in northern California during the same period of decline in central California, although sample sizes from northern California were too small to make unequivocal statements about trends in population size). Forney (1995, 1999) recommended that directed vessel surveys examine the influence of oceanographic and environmental variables on the distribution and abundance of harbor porpoise and focus on possible changes in the depth distribution of porpoise and the distribution of prey species (Forney 1995, 1999). Current knowledge of harbor porpoise stock structure off California suggests that porpoise do not make long-distance movements; thus it is possible that a perceived population decline in central California is the result of small-scale changes in porpoise distribution, given that aerial survey transects have remained unchanged since 1986 (Forney 1995, 1999).

Today, NMFS recognizes (and manages separately) four stocks of harbor porpoise along the U.S. west coast; 1)

¹ Forney, K. A. 1999. The abundance of California harbor porpoise estimated from 1993–97 aerial line-transect surveys. Administrative report LJ-99-02, National Marine Fisheries Service, Southwest Fisheries Science Center, 16 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]

central California; 2) northern California; 3) Oregon-Washington outer coast; and 4) inland Washington waters (Barlow et al., 1997, 1998, Forney et al., 1999). Evidence for geographic subdivision of harbor porpoise populations along the U.S. west coast is apparent from pollutant studies (Calambokidis and Barlow, 1991), which reveal latitudinal gradients in chlorinated hydrocarbon levels in waters off Washington, Oregon, and California. Molecular genetic studies have also demonstrated larger-scale geographic population subdivisions within the northeast Pacific, where four putative populations (Alaska, British Columbia, Washington, and California) are recognized (Rosel et al., 1995). More recent genetic analyses, based on more sampling locations and different genetic markers, have provided evidence to support recognition of these four populations. Smaller-scale geographic subdivision within California remains unresolved.²

We present the results of a 13–30 November 1995 line-transect ship survey in waters off California, which was designed to estimate abundance and describe the depth distribution of harbor porpoise. This was the first ship survey to cover this region in late autumn and to survey systematically different depth strata out to 91 m (50 fathoms). The 1995 ship survey contrasts with previous NMFS ship surveys that were conducted earlier in the year along the 18-m isobath and that relied on models of porpoise density at different depths to calculate abundance (Barlow, 1988). We estimate porpoise abundance for two regions within California (Fig. 1): Bodega Bay to the California-Oregon border, hereafter referred to as “northern California,” and Point Sur to San Francisco Bay in central California, hereafter referred to as “region 2,” as delineated by Barlow (1988). We emphasize results from northern California because relatively little survey effort was conducted in central California. We compare statistically aerial and ship survey abundance estimates in 1995 with those from recent aerial surveys in northern California and region 2 in central California, using a confidence interval of differences (CI_d) method proposed by Lo (1994). We also describe the depth distribution of harbor porpoise in northern California from the 1995 ship survey sighting data.

Methods

Observers searched for marine mammals during daylight hours from the 53-m NOAA research vessel *McArthur*. Nine observers rotated through five duty stations on the flying bridge 10 m above sea level, spending 30 minutes at each station. Two observers at the periphery of the flying bridge scanned from the trackline to the ship's beam (0 to 90 degrees) with 7× binoculars and two inner observers scanned from the trackline to 45 degrees on each side. The middle observer recorded data into a laptop computer and searched for porpoise groups by naked eye. A sixth

independent observer opportunistically searched from the ship's bridge level (~7.5 m above sea level) to estimate the fraction of porpoise groups missed by the primary team of five observers.

A series of predetermined saw-tooth transect lines began at Point Conception, California (34°27'N) and ended at the California-Oregon border (42°00'N). Transect lines extended from approximately the 20-m isobath to the 91-m (50 fathom) isobath. Some depths greater than 91 m were surveyed, especially where the axes of submarine canyons intersected our transects. The ship could not routinely operate in water depths shallower than 20 m. The ship proceeded along the transect lines in passing mode, i.e. it did not deviate from course even when porpoise groups were sighted. The study area was divided into several *a priori* analysis regions (Fig. 1), the same as those used by Barlow (1988) and Barlow and Forney (1994). The region referred to as “northern California” incorporates region 4 and that part of region 5 that is south of the California-Oregon border (Fig. 1). Areas of each region were previously calculated by Forney.³

An event-driven data acquisition program (PPCRUISE) was used to record all sighting and effort data. The program was run on a laptop computer linked to the ship's GPS system to obtain geographic position data. For each harbor porpoise group sighted, bearing and distance from the ship were recorded. Observers obtained the bearing to harbor porpoise groups using mounted protractors on the flying bridge. Distance to harbor porpoise groups was read from calibrated reticle marks imprinted on the eyepiece of 7× binoculars (Barlow and Lee, 1994) or estimated by eye for some close groups. Depth soundings were recorded systematically every two minutes while the ship was underway. The position of each porpoise sighting was calculated to correct for differences between the position of the ship and porpoise groups. Depths at which porpoise were sighted were determined from National Ocean Service (NOS) hydrographic survey data⁴ by using a triangulated irregular surface model in Arc Info GIS.

To estimate abundance, we used transect data collected only during calm sea states, defined as Beaufort 0 through 2 (wind speeds up to 6 knots, no whitecaps present). Porpoise abundance was estimated out to the 91-m isobath. Effort segments in deeper water were excluded from line-transect analysis to allow direct spatial comparison with recent aerial survey results (Barlow and Forney, 1994; Forney¹). Porpoise abundance in region *i* was estimated

² Chivers, S. J. 1999. Personal commun. NMFS, Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA. 92038.

³ Forney, K. 1988. Contour mapping and the calculation of areas between 10m depth contours along the coasts of California, Oregon and Washington. Administrative report LJ-88-23, National Marine Fisheries Service, Southwest Fisheries Center, 18 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]

⁴ National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC). 1999. National Ocean Service (NOS) hydrographic survey data, U.S. coastal waters, version 4.0, available on CD-ROM. Website: <http://www.ngdc.noaa.gov/ngdc.html>

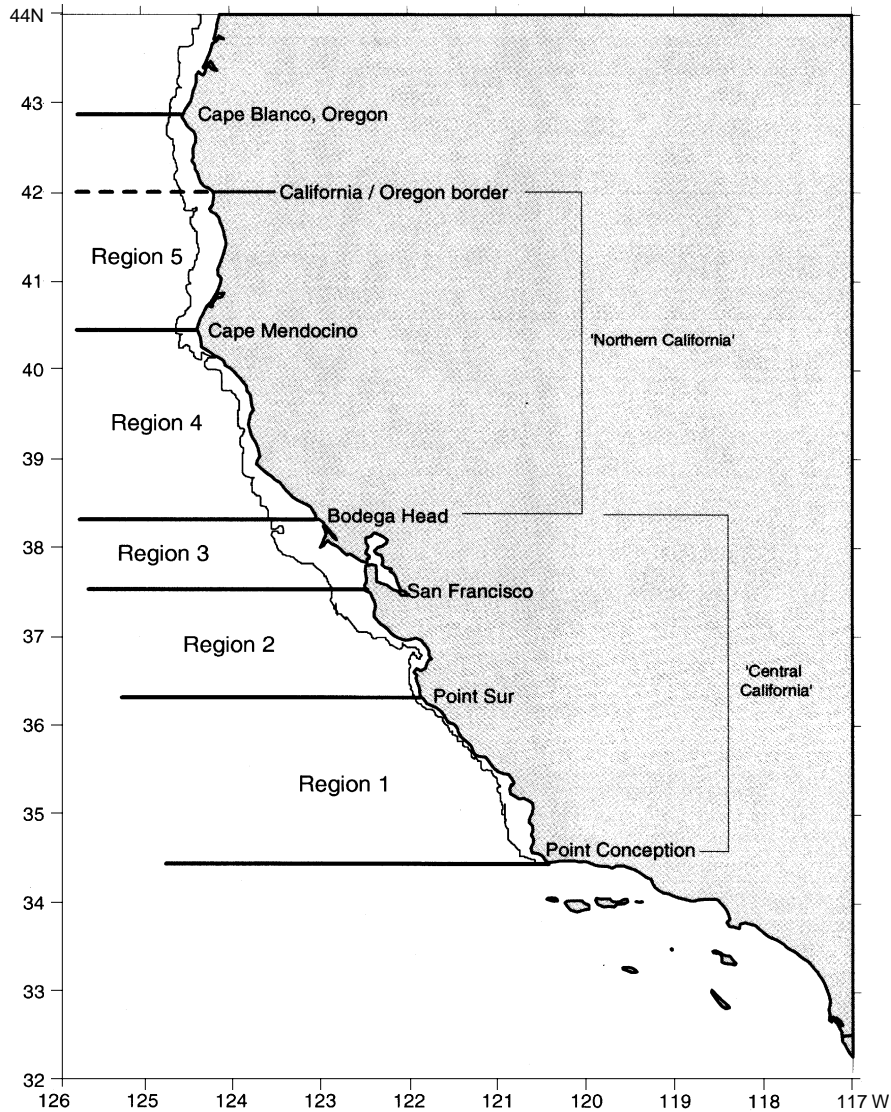


Figure 1

Study regions referred to in text. “Northern California” is defined as region 4 as well as part of region 5 south of the California-Oregon border. Central California includes regions 1–3. The thin line just offshore from Point Conception to Cape Blanco, Oregon, delineates the 91-m (50-fathom) depth contour.

by using standard line-transect methods (Buckland et al., 1993):

$$\hat{N} = \frac{A_i n_i S_i f(0)}{2 L_i g(0)}$$

where A_i = size of the study area (km²) in region i ;
 n_i = number of sightings in region i ;
 S_i = mean group size in region i ;
 $f(0)$ = sighting probability density (/km) at zero perpendicular distance
 L_i = length of transect line (in km) surveyed in region i , and

$g(0)$ = probability of seeing a porpoise group directly on the trackline.

The histogram of radial sighting distances revealed spikes at distances corresponding to whole and half-reticle binocular readings, which suggests that observers tended to round-off radial sighting distances. In the absence of rounding error, the distance interval between any two adjacent radial sighting distances should have been relatively equal for both near and distant sightings, but these intervals usually increase with distance because of reduced precision in reading reticles at greater distances. Theoretically, a linear regression of dis-

tance from the observer against the interval between adjacent radial sighting distances should have a slope of zero in the absence of rounding error. Following Barlow,⁵ we modeled the rounding error in radial sighting distances with this regression method, where the slope of the regression represents the percentage of rounding error. As a result, we smeared radial sighting distances by a random factor between $\pm 4\%$. Observers also showed a tendency to round bearing angles to the nearest 5 degrees; therefore we smeared angles by a random number between ± 5 degrees to further reduce the effects of rounding (Buckland et al., 1993).

We noted a problem in the recording of radial sighting distances when the ship was closer than 5.6 km (3 nmi) to shore. In these cases, the shoreline was closer than the true horizon and radial sighting distances were sometimes recorded by using the shoreline as the horizon (documented from database comments and inferred in other cases). The use of the shoreline as a false horizon introduces errors because resulting radial (and perpendicular) sighting distances are positively biased. Thirty sightings were identified for which shoreline bias probably resulted in positively biased distance readings. Frequency distributions of "shoreline-biased" and "unbiased" perpendicular sighting distances were significantly different (Kolmogorov-Smirnov test, $P < 0.001$) and the "shoreline-biased" distribution revealed a higher proportion of sightings beyond 400 m. To reduce this bias, we excluded the "shoreline-biased" sightings prior to data truncation and to fitting the detection function to the perpendicular distance data. Buckland et al. (1993) recommend truncation of 5% to 10% of the largest perpendicular distances prior to model fitting. We truncated all sightings beyond 1 km, which eliminated 10% of all sightings. Three models (hazard rate, half-normal, and uniform) were fitted to the perpendicular distance data by using the program DISTANCE (Laake et al.⁶) and the most parsimonious model was selected by DISTANCE based on minimizing Akaike's Information Criterion (AIC: Akaike, 1973; Buckland et al., 1993). We also fitted the above models by using other truncation distances and bin intervals to examine the sensitivity of abundance estimates to these values.

Because large porpoise groups are more likely to be detected at greater distances than single animals or pairs, it is possible to introduce bias into abundance estimates by overestimating mean group size. Truncation of distance data will reduce potential overestimation of group size because the largest groups are eliminated, thus minimizing this bias. An additional step to reduce overestimation is to test for dependence between group size and detection distance

by regressing the log of the observed group size against the detection probability at distance x [$\log(s_x)$ versus $\hat{g}(x)$], as recommended by Buckland et al. (1993). If the regression is significant at $\alpha = 0.15$, the mean group size is replaced with the regression-based estimate of mean group size at zero distance, where theoretically, group size bias should not occur. We used this regression method in the program DISTANCE to determine which group sizes to use for estimating abundance.

We tested the null hypothesis that harbor porpoise are randomly distributed with respect to depth by comparing the proportion of porpoise sightings to the proportion of survey effort within 20-m depth intervals. We used depth soundings as a measure of survey effort because soundings were taken at regular 2-minute intervals while the ship was underway. If harbor porpoise are randomly distributed by depth, then the proportion of porpoise sightings to depth soundings should be relatively equal for a given depth interval. Distributions were compared by using a nonparametric Kolmogorov-Smirnov goodness-of-fit test.

Precision of the abundance estimates was estimated with two methods. Log-normal confidence intervals were calculated analytically with formulae presented in Buckland et al. (1993). Bootstrap confidence intervals and coefficients of variation (CV) were calculated as follows. Effort and sighting data from region i were divided into 5-km effort segments (for Beaufort 0–2 sea states only). A TRUE-BASIC computer program (BOOTPORP) was written to randomly draw (with replacement) effort segments within each region until the number of kilometers drawn equaled the number of kilometers actually surveyed. A pseudo-abundance estimate was then calculated from this bootstrap sample and the process was repeated 2000 times. The CV of the point estimates were calculated as the standard error of the 2000 bootstrap estimates divided by the original point estimate. Bootstrap 95% confidence intervals were determined by identifying the 2.5th and 97.5th percentiles of the 2000 bootstrap estimates. For each bootstrap sample, the effective half-strip width [ESW or $1/f(0)$], was treated as a random variable drawn from a normal distribution with a mean and standard error equal to that obtained from the detection model fitted to the truncated perpendicular distances. The probability of detecting a trackline group of porpoise, $g(0)$, was estimated for each bootstrap as a random variable drawn from a binomial distribution with mean = 0.769 (SE=0.117). This $g(0)$ value was calculated by Barlow⁵ with independent observer methods, using a nearly identical vessel and the same observer configuration that we used. Owing to an insufficient number of sightings by the independent observers during our survey, we could not independently estimate a value for $g(0)$.

We statistically compared abundance estimates obtained from the 1995 ship survey with estimates from aerial surveys conducted 1 to 2 months earlier (Forney, 1999), using the "confidence interval of differences" approach proposed by Lo (1994) and adopted by Forney and Barlow (1998) for bootstrap confidence intervals. Commonly used comparative methods, such as those based on whether confidence intervals overlap or whether one population mean is in-

⁵ Barlow, J. 1987. Abundance estimation for harbor porpoise (*Phocoena phocoena*) based on ship surveys along the coasts of California, Oregon, and Washington. Administrative report LJ-87-05, National Marine Fisheries Service, Southwest Fisheries Center, 36 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]

⁶ Laake, J. L., S. T. Buckland, D. R. Anderson, and K. P. Burnham. 1996. DISTANCE user's guide, 82 p. Colorado Cooperative Fish and Wildlife Research Unit, Colorado State University, Fort Collins, CO 80523.

cluded within the confidence interval of a second mean, have been shown to be biased, because α levels do not approach the intended value of 0.05 (Lo, 1994). Therefore, we used a third method proposed by Lo (1994), based on the confidence interval of the difference (CI_d), between two population means. Through computer simulation, we generated 5000 log-normal pseudo-abundance estimates for the aerial and ship surveys (N^*), using the mean estimate and CV from each respective survey. The difference between ship and aerial pseudo-estimates was calculated as

$$d^* = N^*_{ship} - N^*_{air}$$

and a 95% confidence interval of the differences (CI_d) was calculated from the 5000 d^* values with the percentile method. Aerial and ship survey estimates were considered significantly different if the resulting CI_d did not include zero. Under the alternative hypothesis that abundance estimates were significantly different, we estimated the statistical power of this test by constructing one thousand 95% CI_d intervals through simulation, using the observed effect size and variance from the ship and aerial surveys in 1995. The probability of committing a type-II error β was calculated as the fraction of 1000 intervals that included zero (indicating no significant difference at $\alpha=0.05$). An initial power analysis at $\alpha = 0.05$ revealed that the power to detect a difference as large as the one observed between aerial and ship estimates was low ($=0.13$). We therefore generated a power curve in order to objectively reselect an α level for the CI_d test that would provide an approximate power of 0.80 (Cohen, 1988). This resulted in an α level = 0.10; therefore, all statistical comparisons between aerial and ship estimates were considered statistically significantly different if the 90% CI_d did not include zero. Following Forney and Barlow (1998), we estimated the significance level for this comparison by iteratively constructing a range of confidence intervals from the simulated data (i.e. 80%, 90%, 95%, 96%, 97%...) and we identified the threshold α level (two-tailed) where the CI_d just included zero.

Results

We surveyed a total of 594 km of transect in California during calm sea states (Beaufort 0–2) and detected 170 harbor porpoise groups within the truncation distance of 1 km (Figs. 2 and 3, Table 1). Most survey effort (377 km) occurred in northern California, where 153 groups of harbor porpoise were seen, mostly in the vicinity of Cape Mendocino. No harbor porpoise were seen within regions 1 and 3 in central California, but the amount of survey effort in these regions (60 and 91 km, respectively) was low. Owing to persistent coastal fog, transect coverage within region 3 was limited to the offshore area near the Farallon Islands. In region 2, only 17 porpoise groups were detected within the 1-km truncation distance, but only 91 km of trackline was surveyed.

The perpendicular distance data were best fitted with the half-normal model without adjustment terms and had

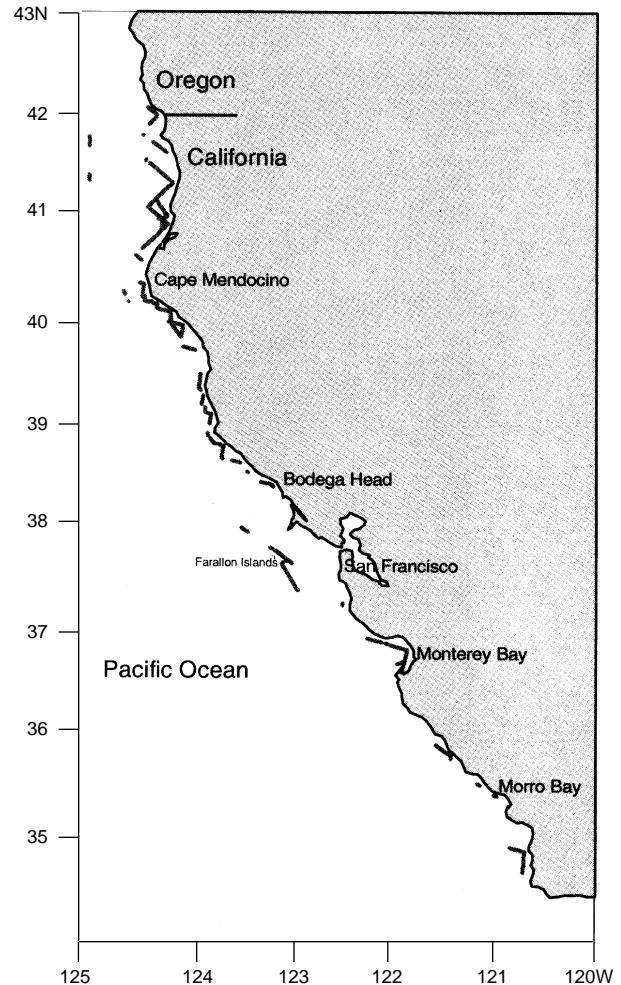


Figure 2

On-effort transect effort (594 km) shown as thick gray lines in central and northern California during calm (Beaufort 0–2) sea states.

the lowest AIC value of all competing models (χ^2 goodness-of-fit test, $P=0.84$, Fig. 4). Several truncation distances and interval groupings were explored when fitting a detection function to the distance data, and all fits resulted in estimates of abundance within 9% of each other. In general, the lowest abundances were obtained with hazard-rate models. Here, we report only the results obtained with the half-normal model with a truncation distance of 1 km. We used the observed mean group size of 2.45 for region 2 and 2.65 for northern California to estimate porpoise abundance because the regression of the log of observed group size versus $\hat{g}(x)$ was not significant ($r^2=0.11$, $P<0.89$), suggesting no school size bias within the truncation distance of 1 km.

Abundance of harbor porpoise in northern California was estimated at 5686 (log-normal 95% CI=3498–9242; bootstrap CV=0.29, bootstrap 95% CI=2760–8394) out to the 91 m isobath, based on 377 km of transect effort and 153 porpoise sightings in calm sea states (Beaufort 0–2). A statistical comparison of our estimate with the aerial

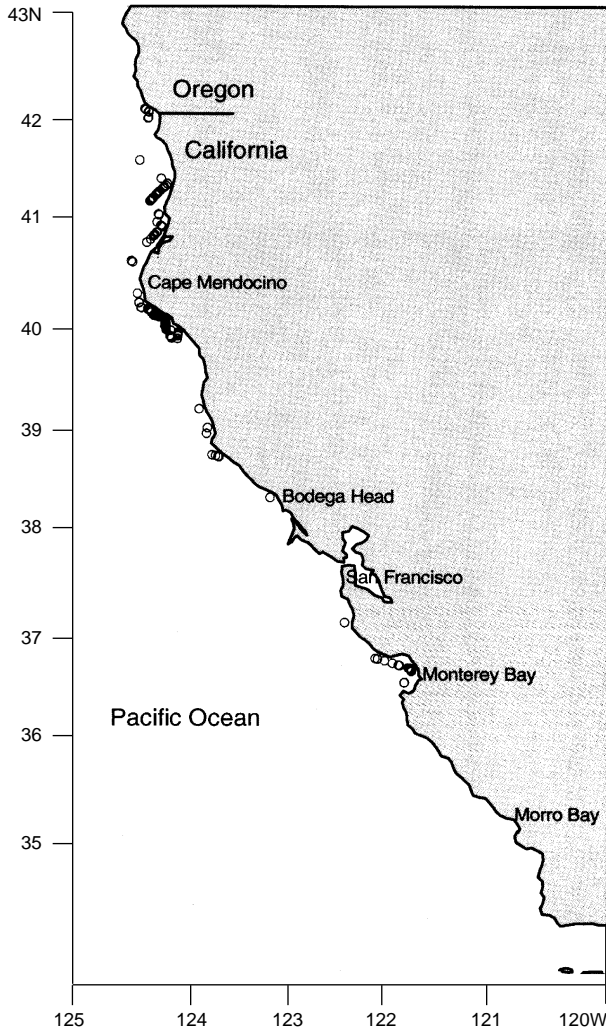


Figure 3

On-effort sightings of harbor porpoise recorded in central and northern California during calm (Beaufort 0–2) sea states.

survey estimate obtained 1–2 months earlier ($N=13,145$ $CV=0.39$)¹ revealed that the 90% confidence interval of differences (CI_d) did not include zero, indicating that aerial and ship abundance estimates were significantly different at $\alpha = 0.10$ (90% $CI_d = -17,275$ to -257 , $P=0.08$, Fig. 5, A and B). Porpoise abundance for region 2 was estimated at 1041 (log-normal 95% $CI=559$ – 1941 ; bootstrap $CV=0.44$, bootstrap 95% $CI=587$ – 4138), based on 91 km of survey effort and 17 porpoise sightings. Our estimate for region 2 was significantly different (90% $CI_d = -4084$ to -162 , $P=0.07$, $\alpha=0.10$) from an estimate obtained with aerial surveys 1 to 2 months earlier in the year ($N=2861$ $CV=0.39$)¹.

In northern California, harbor porpoise were not distributed randomly with respect to water depth (Kolmogorov-Smirnov test, $P<0.001$; Fig. 6A). High proportions of porpoise sightings with respect to survey effort were found between 20 to 60 m, and fewer porpoise than expected were found in waters deeper than 60 m. Because calm

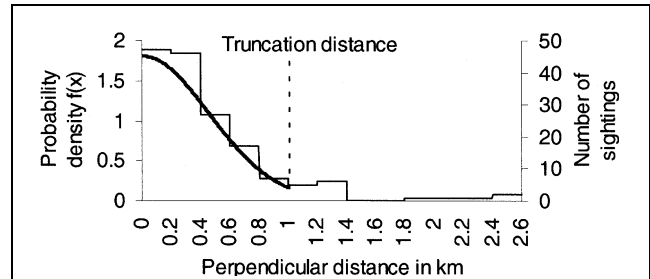


Figure 4

Half-normal model fit to the perpendicular distance data. Data were truncated at 1 km, which eliminated 10% of all observations. The model fitted the data well, as determined by a chi-square goodness-of-fit test ($P=0.84$).

sighting conditions often occur in nearshore shallow waters where porpoise densities are relatively high (Barlow, 1988), we also examined relative abundance at depth for rough sea states (Beaufort 3–4) to see if the overall depth patterns held. The depth distribution of porpoise was similar in rough sea states: more porpoise than expected occurred between 20 to 40 m and fewer porpoise than expected were seen at depths of 40 to 120 m (Kolmogorov-Smirnov test, $P<0.002$, Fig. 6B). During our survey, the area from shore to the 20-m isobath went largely unsurveyed because of the ship's draft and the presence of local navigational hazards. Owing to an insufficient number of sightings within region 2 ($n=25$, depth range=20 to 93 m), we did not attempt to statistically describe the depth distribution of harbor porpoise for that region.

Discussion

Abundance of harbor porpoise off northern California

Our estimate of porpoise abundance for northern California (5686, log-normal 95% $CI=3498$ – 9242) is considerably lower than estimates for the same area from 1988 to 1993 aerial surveys (9250, 95% $CI=5943$ – $14,397$; Barlow and Forney, 1994). Barlow and Forney (1994) estimated 2.05 porpoise/ km^2 in northern California from aerial surveys (corrected for missed groups), whereas we estimated 1.26 porpoise/ km^2 (also corrected for missed groups). From 1984–85 ship surveys conducted in September, Barlow (1988) estimated 12,700 porpoise (2.09 porpoise/ km^2) from Bodega Head, California to Cape Blanco, Oregon, an area approximately 23% larger than our study area in northern California. From aerial survey data collected 1 to 2 months prior to our ship survey, Forney¹ reported a preliminary estimate of 13,145 porpoise ($CV=0.39$, log-normal 95% $CI=6316$ – $27,357$; 2.92 porpoise/ km^2) for northern California. This aerial estimate is significantly different from our ship survey estimate, as determined by the confidence interval of differences test (90% $CI_d = -17,275$ to -257 , $P=0.08$, $\alpha=0.10$). Had we used the traditional α level

of 0.05, these two estimates would not have been significantly different, but the power to detect such a difference was low (0.13). This result highlights recent criticisms of statistical significance testing (Johnson, 1999) and underscores the importance of estimating statistical power to aid in decision-making. Regardless, real differences exist between aerial and ship estimates obtained in 1995, as evidenced in Figure 5, A and B, which may be due to a number of factors.

Animals may have moved out of the study area between the time of the two studies. Seasonal movements of harbor porpoise are known to occur on the Atlantic coast (Polacheck et al., 1995), and in Glacier Bay, Alaska (Taylor and Dawson, 1984). In California, the situation is less clear because pollutant evidence suggests limited latitudinal movement along the coast (Calambokidis and Barlow, 1991) and genetic stock structure remains unresolved (Chivers²). Several researchers have reported highest porpoise densities during late summer and autumn throughout California (Barlow, 1988, Monterey Bay; Calambokidis et al.⁷, central California; Dohl et al.⁸, California-wide; Goetz, 1983, northern California; Sekiguchi, 1995, Monterey Bay). Barlow (1988) and Sekiguchi (1995) observed the lowest harbor porpoise densities in Monterey Bay during winter. Forney (1995, 1999) reported harbor porpoise abundance was negatively correlated with positive sea-surface temperature anomalies in the Monterey Bay region in autumn, a finding that suggests that animals move in response to changing oceanographic conditions. Pyle and Gilbert (1996) reported harbor porpoise sightings near Southeast Farallon Island in central California only from March to November, even though observers searched year-round over a ten-year period (1982–92). Collectively, the data suggest small-scale seasonal movement of harbor porpoise along the California coast. Most cetacean species in California show seasonal trends in distribution and abundance (Forney and Barlow, 1998) and despite the restriction of harbor porpoise to neritic habitat

⁷ Calambokidis, J., C. Ewald, G. H. Steiger, S. M. Cooper, I. D. Szczepaniak, and M. A. Webber. 1990. Harbor porpoise studies in the Gulf of the Farallones. Final contract report CX 8000-8-0001 to the Gulf of the Farallones National Marine Sanctuary, 57 p. Fort Mason Center, Bldg. 201, San Francisco, CA 94123.

⁸ 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. Contract rep. 14-12-0001-29090, p. 135–152. Pacific OCS Region, Minerals Management Service, U.S. Department of the Interior, Washington D.C.

Table 1

Estimates of harbor porpoise abundance, precision, and effort from the most recent ship and aerial surveys in California waters. Sizes of study areas and transect lengths are given in kilometers. Effective half-strip widths (ESWs) are given in meters. Regions are shown in Figure 1. Bold rows indicate regions under comparison between the two studies.

Study	No. of groups n	Mean group size	Area (km ²)	Transect length (km)	ESW (meters)	g(0)	Porpoise density (no. of porpoise/m ²)		Abundance (no. of individuals)	CV	Lower 95% CI	Upper 95% CI
							g(0)	CV				
1995 ship (our study)												
Central California	17	2.45	6951	217	554	0.769	—	—	—	—	—	—
Region 1	0	—	1985	60	554	0.769	—	—	—	—	—	—
Region 2	17	2.45	1917	91	554	0.769	0.54	1041	0.44	559	1941	—
Region 3	0	—	3049	66	554	0.769	—	—	—	—	—	—
Northern CA	153	2.65	4504	377	554	0.769	1.26	5686	0.29	3498	9242	—
1995 aerial ¹												
Central California	101	—	6951	2035	197	0.292	0.86	6007	0.27	3584	10,067	—
Region 1	13	2.08	1985	858	197	0.292	0.27	542	0.48	222	1326	—
Region 2	62	2.00	1917	720	197	0.292	1.49	2861	0.40	1353	6048	—
Region 3	26	1.73	3049	457	197	0.292	0.85	2604	0.43	1166	5814	—
Northern California	85	1.62	4504	374	197	0.292	2.92	13,145	0.39	6316	27,357	—

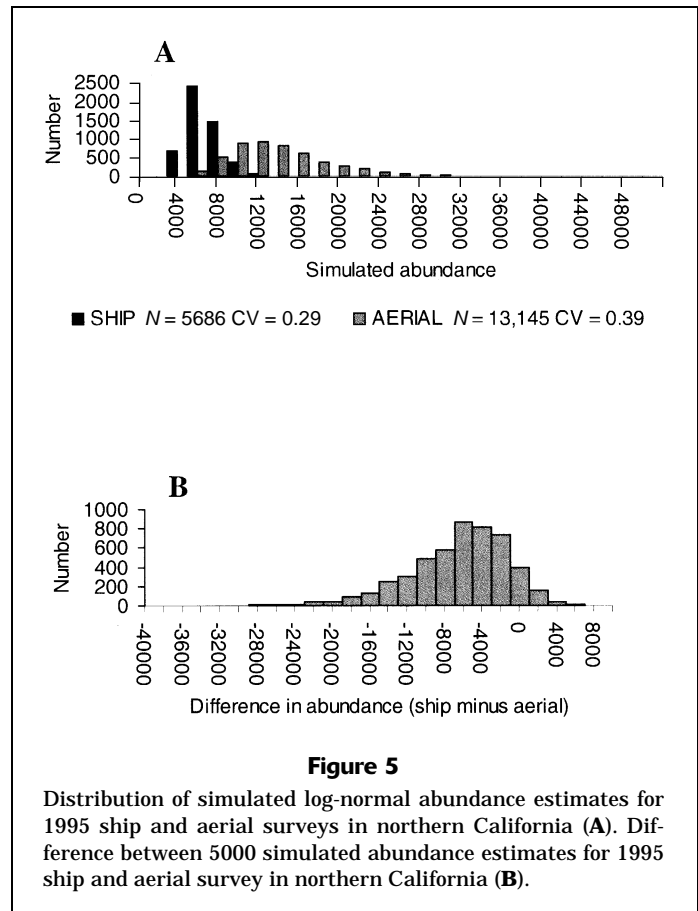
¹ Forney, K. A. 1999. The abundance of California harbor porpoise estimated from 1993–97 aerial line-transect surveys. Administrative report LJ-99-02, National Marine Fisheries Service, Southwest Fisheries Science Center, 16 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]

along the California coast, they probably respond to seasonal or interannual oceanographic changes.

Large swells (3 m) during our ship survey may have caused observers to miss more porpoise groups on the trackline than is accounted for by our $g(0)$ correction factor. The independent observer recorded an insufficient number of sightings during our survey; therefore we could not independently estimate $g(0)$. Instead, we adopted the $g(0)$ value of 0.769 (SE=0.117) estimated by Barlow⁵ who used the same searching method and vessel type as we did. During our survey, the largest swells (3 m) occurred in northern California, where porpoise densities are highest. Further, swell height increased with latitude in California and the slope of the regression was significant (Zar, 1984; ANOVA, $P < 0.005$). Even in calm sea states, porpoise groups may be easily missed because animals surface behind large swells and thus are not observed. Our transect lines frequently were oriented directly into the prevailing northwest swell or directly down-swell as a consequence of our sampling design, possibly contributing to more groups being missed on the transect line than expected. If swells were considerably larger during 1995 survey than during the 1980s surveys, then Barlow's $g(0)$ value may not reflect the fraction of trackline groups missed and our estimate of abundance would be negatively biased by an unknown, but nontrivial, amount. Larger winter swells may also help explain why porpoise densities from winter vessel surveys are generally lower than those from summer and autumn surveys (Goetz, 1983; Barlow, 1988; Sekiguchi, 1995; Calambokidis et al.⁷).

Abundance in northern California may be underestimated because the area inshore of the 20-m isobath, known to have relatively high porpoise densities, was not routinely surveyed. Only 2% of all survey effort and 4% of all sightings occurred at depths shallower than 20 m. Shallow water effort is included in our abundance estimate, thus we implicitly assume that porpoise density from shore to 20 m is equal to that in the remainder of our study area. Depth data from aerial surveys conducted from 1988 to 1997 support this assumption. Porpoise encounter rates (weighted by effort for each depth stratum) are nearly equal for the area from shore to 90 m (0.33 porpoise/km) and from 20 to 90 m (0.32 porpoise/km) (NMFS⁹). However, these data were collected primarily during September and October and may not reflect the depth distribution of harbor porpoise in November. During our survey, if porpoise densities were significantly higher from shore to 20 m than from 20 to 90 m, our estimate of porpoise abundance would be negatively biased by an unknown amount. The same bias might result if significant numbers of harbor porpoise moved into waters deeper than 90 m between the time of the aerial and ship surveys.

⁹ NMFS (National Marine Fisheries Service). 1999. Unpubl. data. Protected Resources Div., Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA. 92038.



The distribution of harbor porpoise in northern California is highly clustered, especially near Cape Mendocino, where densities are highest, and our level of survey effort may not have fully captured the spatial heterogeneity in porpoise densities in northern California. The bootstrap CV of ship abundance estimate was not extremely precise (0.29) and reflects the spatial variability in porpoise encounter rates in northern California on small (5-km bootstrap unit) scales. The estimated number of transect effort in kilometers needed to attain higher levels of precision for the northern California estimate, following the method described in Buckland et al. (1993, p. 303–304) were approximately 800 and 3200 km, respectively, to obtain CVs of 0.20 and 0.10 (we surveyed 377 km). These effort estimates assume a Poisson distribution of porpoise, and are probably conservative. Repeated sampling of our transect lines over a longer period may have yielded an estimate of abundance more similar to recent aerial surveys. An adaptive sampling method, as used by Palka and Pollard (1999), would be useful on future surveys to increase sampling effort in known high-density regions.

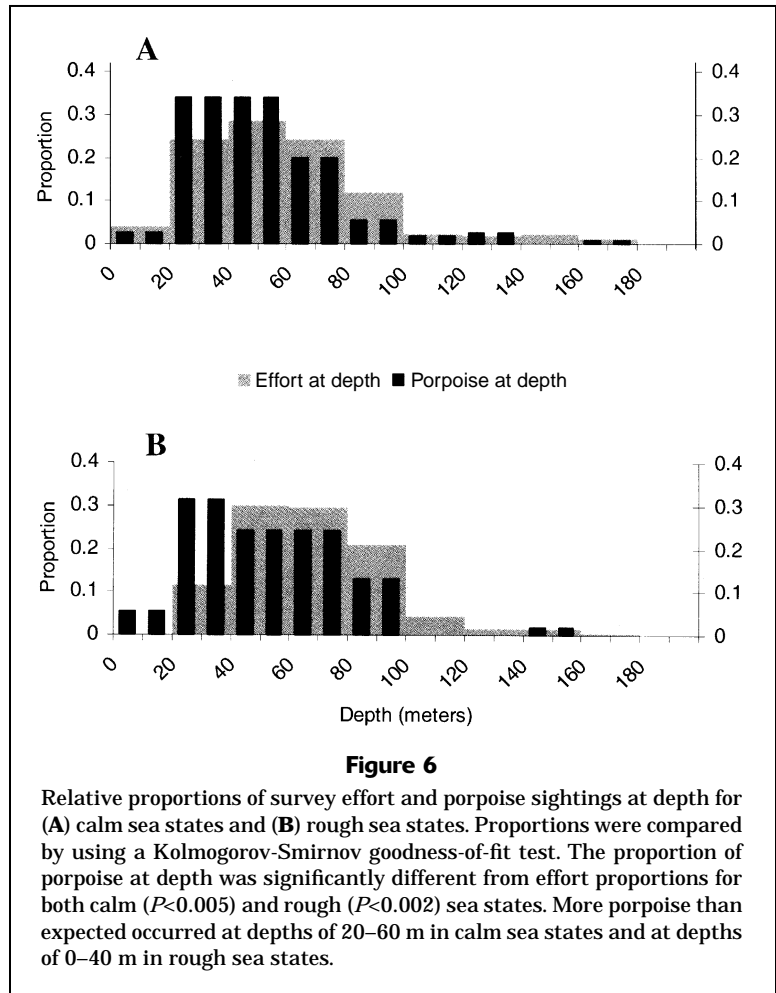
Abundance of harbor porpoise off central California

Region 1 has the lowest densities of harbor porpoise in California (Barlow, 1988; Forney et al., 1991; Dohl et al.³) and we did not detect any porpoise during 60 km of survey

effort. The most recent estimate of porpoise abundance for region 1 is 627 (CV=0.452) from a 1997 aerial survey (Forney¹).

Our estimate of porpoise abundance for region 2 is 1041 (log-normal 95% CI 559–1941, CV=0.44). This is less than the 1778 porpoise (95% log-normal CI=1096–2885, CV=0.25) estimated by Barlow and Forney (1994) from 1988–93 aerial surveys, and 1459 porpoise (CV=0.61) estimated from 197 km of ship survey effort in 1984–85 (Barlow, 1988). Our estimate is statistically significantly different (90% CI_{90%}=−4084 to −162, $P=0.07$, $\alpha=0.10$) from an aerial survey estimate made 1–2 months earlier (2861, 95% CI=1353–6048, CV=0.39).¹ To obtain abundance CVs of 0.30, 0.20, and 0.10 for the 1995 ship survey in region 2 would have required approximately 175, 400, and 1600 km of transect effort respectively (we surveyed 91 km).

We surveyed 66 km in region 3 in the Gulf of the Farallones during calm sea states and did not detect any harbor porpoise. Harbor porpoise are known to be abundant in this area, where a total of 552 sightings were recorded during small-vessel studies conducted between 1977 and 1985 (Szczepaniak and Webber¹⁰). However, a majority of these sightings were 10–20 km west of the mouth of San Francisco Bay and only a small number of sightings were recorded within 10 km of the Farallon Islands, where nearly all of our survey effort in region 3 occurred (Fig. 2). Calambokidis et al.⁷ conducted year-round surveys in the Gulf of the Farallones and found high porpoise densities within 10–20 km of San Francisco Bay but sighted no porpoise offshore near the Farallon Islands. Szczepaniak¹¹ found the same pattern during autumn surveys. No specimens were reported from the Farallon Islands in the 208 stranding records of harbor porpoise from 1915 to 1985 summarized by Szczepaniak.¹¹ Further evidence of low porpoise densities in this area comes from studies at Southeast Farallon Island, where over the ten-year period 1982–92, observers stationed year-round at the island detected only 68 groups of harbor porpoise (Pyle and Gilbert, 1996). The collective evidence suggests that harbor porpoise are uncommon in the immediate vicinity of the Farallon Islands, where water depths generally range from 55 to 75 m. In California, this depth range is



characterized by relatively low porpoise densities, as discussed in the next section.

Depth distribution of harbor porpoise

In northern California, we found that higher numbers of harbor porpoise than expected occurred at depths of 20 to 60 m and fewer porpoise than expected in waters deeper than 60 m (Fig. 6, A and B). Barlow (1988) found the abundance of harbor porpoise along the California, Oregon, and Washington coasts to be roughly constant from shore to 55 m, declining linearly with depth, and he found that no harbor porpoises were detected in waters deeper than 110 m. We encountered 19 porpoise groups in waters deeper than 91 m (range 101 to 215 m) over submarine canyons near Cape Mendocino, where deep canyons intersect shallow water habitat characterized by higher porpoise densities. Our observed depth distribution of harbor porpoise is similar to that of Calambokidis et al.,⁷ who found porpoise only at depths <70 m, but who surveyed to depths of 120 m. In contrast, near the Northern San Juan Islands, Washington, porpoise occur more often than expected at depths >100 m and fewer than expected occur at depths <75 m (Raum-Suryan, 1995; Raum-Suryan and Harvey,

¹⁰ Szczepaniak, I. D., and M. A. Webber. 1985. Status of the harbor porpoise (*Phocoena phocoena*) in the eastern north Pacific, with an emphasis on California. Final report to Center for Environmental Education, 52 p. Washington, D.C. 20004.

¹¹ Szczepaniak, I. D. 1987. Abundance and distribution of harbor porpoise (*Phocoena phocoena*) in the Gulf of the Farallones National Marine Sanctuary. Final report to National Park Service, 48 p. Point Reyes National Seashore, Point Reyes, CA 94956.

1998). We attribute these differences in depth distribution between California and the San Juan Islands to habitat: porpoises near the San Juan Islands occupy an inland waterway characterized by numerous islands with steep bathymetry, whereas the open coastline of California has relatively gentler bathymetry. In both areas harbor porpoise do not occur far from land. Along the outer coasts of Oregon and Washington, Green et al.¹² reported approximately 25% of all harbor porpoise at depths of 100 to 200 m; further, the depth distribution of harbor porpoise changed seasonally, in summer, 56% of porpoise were inshore of the 100-m isobath and during winter, this proportion increased to 86%.

Much of what we know about harbor porpoise abundance and depth distribution in California comes from aerial and ship data collected in late summer and early autumn, largely because weather conditions are more favorable at this time of year. For northern California, in particular, there is a bias towards collection of autumn data: the depth distribution model of Barlow (1988) contained only September data and past abundance surveys have relied on summer and autumn data (Barlow, 1988; Forney, 1995; 1999). The exception to this seasonal collection of data are year-round aerial surveys conducted by Dohl et al.⁸ off central and northern California. However, Dohl's surveys were not ideally suited to estimate porpoise abundance because their transect lines were oriented perpendicular to the shoreline and most survey effort occurred far offshore of known porpoise habitat. Additional winter and spring aerial surveys are needed in California to investigate seasonal differences in harbor porpoise distribution and abundance. To permit direct seasonal comparisons, we suggest that winter-spring surveys use existing transect lines from past summer-autumn aerial surveys. We recommend aerial surveys over ship surveys because they permit coverage of shallow water areas where larger research vessels cannot operate; are more cost-effective for surveying large areas, thus maximizing data collection during brief fair-weather periods; and reduce the influence of large ocean swells that compromise the effectiveness of a ship line-transect survey.

Acknowledgments

We thank the marine mammal observers who spent many hours collecting the sightings and effort data: W. Armstrong, M. Donahue, B. Hanson, B. Odom, D. Outram, K. Raum-Suryan, R. Rowlett, (and S.J.C. and B.L.T.). We also thank the officers and crew of the NOAA ship *McArthur* for all their support. Charles Stinchcomb assisted in identifying shoreline-biased sightings. Karin Forney provided

unpublished data on harbor porpoise encounter rates at depth from previous aerial surveys and patiently reviewed the CI_d method. Tim Gerrodette provided a FORTRAN subroutine used to correct sighting positions in relation to vessel positions. Rich Cosgrove provided NOS bathymetric data used to determine the depth distribution of porpoise. This survey was funded by the NMFS Office of Protected Resources. Lastly we thank Jay Barlow, Debbie Palka, Kim Raum-Suryan, and two anonymous reviewers for their critiques of the manuscript. An earlier draft of this manuscript served as working paper 98-PSRG-5 at the November 1998 Pacific Scientific Review Group meeting in Seattle, WA.

Literature cited

- Akaike, H.
1973. Information theory and an extension of the maximum likelihood principle. *In* International symposium on information theory, 2nd ed., (B. N. Petran and F. Csáaki, eds.), p. 267–281. Akadèmiai Kiadó, Budapest, Hungary.
- Barlow, J.
1988. Harbor porpoise (*Phocoena phocoena*) abundance estimation in California, Oregon, and Washington: I. Ship Surveys. *Fish. Bull.* 86:417–432.
- Barlow, J., and K. A. Forney.
1994. An assessment of the 1994 status of harbor porpoise in California. U.S. Dep. Commer., NOAA Technical Memo., NOAA-TM-NMFS-SWFSC-205, 17 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]
- Barlow, J., K. A. Forney, P. S. Hill, R. L. Brownell Jr., J. V. Carretta, D. P. DeMaster, F. Julian, M. S. Lowry, T. Ragen, and R. R. Reeves.
1997. U.S. Pacific marine mammal stock assessments: 1996. U.S. Dep. Commer., NOAA Technical Memo., NOAA-TM-NMFS-SWFSC-248, 223 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]
- Barlow, J., and D. Hanan.
1995. An assessment of the status of harbour porpoise in central California. *Rep. Int. Whal. Comm.* (special issue) 16:123–140.
- Barlow, J., and T. Lee.
1994. The estimation of perpendicular sighting distance on SWFSC research vessel surveys for cetaceans: 1974 to 1991. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-SWFSC-207, 46 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]
- Barlow, J., P. S. Hill, K. A. Forney, and D. P. DeMaster.
1998. U.S. Pacific marine mammal stock assessments: 1998. U.S. Dep. Commer., NOAA Technical Memo., NOAA-TM-NMFS-SWFSC-258, 40 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]
- Buckland, S. T., D. R. Anderson, K. P. Burnham, and J. L. Laake.
1993. Distance sampling: estimating abundance of biological populations. Chapman and Hall, London, 446 p.
- Calambokidis, J., and J. Barlow.
1991. Chlorinated hydrocarbon concentrations and their use in describing population discreteness in harbor porpoises from Washington, Oregon, and California. *In* Marine Mammal Strandings in the United States (J.E. Reynolds

¹² 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. Chapter 1 *in* Oregon and Washington marine mammal and seabird surveys (J. J. Brueggeman, ed.), p. 1–140. Final report to OCS (Offshore Continental Shelf) Study MMS 91-0093. [Available from Ebasco Environmental, 10900 NE 8th St., Bellevue, WA 98004.]

- and D.K. Odell, eds.), p. 101–110. U.S. Dep. Commer., NOAA Technical Report NMFS 98.
- Cohen, J.
1988. Statistical power analysis for the behavioral sciences. Lawrence Erlbaum Assoc. Publ., Hillsdale, NJ, 567 p.
- Forney, K. A.
1995. A decline in the abundance of harbor porpoise, *Phocoena phocoena*, in nearshore waters off California, 1986–93. *Fish. Bull.* 93(4):741–748.
- Forney, K. A.
1999. Trends in harbor porpoise abundance off central California, 1986–95: evidence for interannual changes in distribution? *J. Cetacean Res. and Manage.* 1:73–80.
- Forney, K. A., and J. Barlow.
1998. Seasonal patterns in the abundance and distribution of California cetaceans, 1991–1992. *Mar. Mamm. Sci.* 14(3): 460–489.
- Forney, K. A., D. A. Hanan, and J. Barlow.
1991. Detecting trends in harbor porpoise abundance from aerial surveys using analysis of covariance. *Fish. Bull.* 89:367–377.
- Forney, K. A., M. M. Muto, and J. Baker.
1999. U.S. Pacific marine mammal stock assessments: 1999. U.S. Dep. Commer., NOAA Technical Memo., NOAA-TM-NMFS-SWFSC-282, 62 p. [Available from Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]
- Goetz, B. J.
1983. Harbor porpoise (*Phocoena phocoena*) movements in Humboldt Bay, California and adjacent waters. M.A. thesis, Humboldt State Univ., Arcata, CA, 118 p.
- Johnson, D. H.
1999. The insignificance of statistical significance testing. *J. Wildl. Manage.* 63(3):763–772.
- Julian, F., and M. Beeson.
1998. Estimates for marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990–95. *Fish. Bull.* 96:271–284.
- Lo, N. C. H.
1994. Level of significance and power of two commonly used procedures for comparing mean values based on confidence intervals. *Calif. Coop. Oceanic Fish. Invest. Rep.* 35:246–253.
- Palka, D., and J. Pollard.
1999. Adaptive line transect survey for harbor porpoises. *In* Proceedings of the symposium on surveys, status and trends of marine mammal populations, Seattle, Washington, USA, February 25–27 1998, (G. W. Garner, S. C. Amstrup, J. L. Laake, B. F. J. Manly, L. L. McDonald, and D. G. Robertson, eds.), p 3–11. A.A. Balkema Publishers, Rotterdam, Netherlands.
- Polacheck, T., F.W. Wenzel, and G. Early.
1995. What do stranding data say about harbor porpoises? *Int. Whal. Comm.* (special issue) 16:169–179.
- Pyle, P., and L. Gilbert.
1996. Occurrence patterns and trends of cetaceans recorded from Southeast Farallon Island, California, 1973 to 1994. *Northwestern Naturalist* 77:1–8.
- Raum-Suryan, K. L.
1995. Distribution, abundance, habitat use, and respiration patterns of harbor porpoise (*Phocoena phocoena*) off the Northern San Juan Islands, Washington. M.S. thesis, Moss Landing Marine Laboratory, San Jose State University, San Jose, CA, 77 p.
- Raum-Suryan, K. L. and J. T. Harvey.
1998. Distribution and abundance of and habitat use by harbor porpoise, *Phocoena phocoena*, off the northern San Juan Islands, Washington. *Fish. Bull.* 96:808–822.
- Rosel, P. E., A. E. Dizon, and M. G. Haygood.
1995. Variability of the mitochondrial control region in populations of the harbour porpoise, *Phocoena phocoena*, on interoceanic and regional scales. *Can. J. Fish. Aquat. Sci.* 52:1210–1219.
- Sekiguchi, K.
1995. Occurrence, behavior and feeding habits of harbor porpoises (*Phocoena phocoena*) at Pajaro Dunes, Monterey Bay, California. *Aquat. Mamm.* 21(2):91–103.
- Taylor, B.L. and P.K. Dawson.
1984. Seasonal changes in density and behavior of harbor porpoise (*Phocoena phocoena*) affecting census methodology in Glacier Bay National Park, Alaska. *Rep. Int. Whal. Comm.* 34:479–483.
- Zar, J.H.
1984. Biostatistical analysis, 2nd ed. Prentice Hall. Englewood Cliffs, NJ, 718 p.