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ESTIMATES OF LARGE WHALE ABUNDANCE OFF CALIFORNIA, OREGON WASHINGTON, AND BAJA CALIFORNIA BASED ON 1993 AND 1996 SHIP SURVEYS

by

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ABSTRACT

Visual sighting surveys on two ships in summer/fall 1993 and 1996 were used to estimate the abundance of large whales found within 555 km (300 nmi) off the coasts of California, Oregon, and Washington, U.S. and Baja California, Mexico. Surveys systematically covered 28,500 km of pre-determined transect lines within this study area. Line-transect methods were used on the surveys and in the analysis of these data. Abundance was estimated separately for four geographic strata: California Inshore, California Offshore, Oregon/Washington, and Baja California. Group size estimates for each observer were adjusted using calibration factors developed from aerial photographic counts. In addition, group size estimates for sperm whale pods that were observed for a short period of time were corrected for the systematic underestimation that has been shown in those circumstances. The most abundant large whales were sperm whales (3,047, CV=0.26), blue whales (2,528, CV=0.17), fin whales (1,851, CV=0.19), and humpback whales (1,177, CV=0.28). Bryde's whales and sei whales are rarely seen in this study area.

INTRODUCTION

Abundance has been estimated for most cetaceans off the coasts of California, Orgeon, and Washington from previous ship (Barlow 1995; Barlow and Gerrodette 1996; Barlow 1997) and aerial (Forney et al. 1995) line-transect surveys. These estimates are used in Stock Assessment Reports to determine the allowable number of human-caused mortalities. The current 2000 Stock Assessment Reports (Forney et al. 2000) use abundance estimates from ship surveys in 1991, 1993, and 1996. However, guidelines for the preparation of Stock Assessment Reports (Wade and Angliss 1997) state that abundance estimates should not be used if they are more than 8 years old. Stock assessment reports for sperm whales, fin whales, and humpback whales will be revised in 2001, and, therefore, new estimates of abundance that exclude the 1991 data are needed for these species. Here we present a re-analysis of the 1993 and 1996 surveys to estimate the abundance of all large whales for this time period. We use the same methods used in previous analyses of the 1991-96 data (Barlow 1997) with a slight change in the geographic stratification (subdividing California into inshore and offshore strata and adding a stratum for waters off the west coast of Baja California).

METHODS

Field Methods

The 1993 and 1996 surveys were conducted using two National Oceanographic and Atmospheric Administration (NOAA) research vessels: the 53 m *McArthur* and the 52 m *David Starr Jordan* (Mangels and Gerrodette 1994; Von Saunder and Barlow 1999). Teams of three observers searched from the flying bridge deck of both vessels using line-transect methods. Two observers searched through 25x pedestal-mounted binoculars while the third observer searched with unaided eyes and a 7x hand-held binocular. Observation height at eye level was approximately 10 m above the water's surface for both vessels. The third observer was also responsible for recording all data on searching effort and sightings on a lap-top computer. Often, a fourth "independent" observer also searched with unaided eyes and a 7x binocular to detect groups that were missed by the three primary observers; data from independent observers are not presented in this analysis. During daylight hours, the ships traveled at approximately 18 km/hr (10 kts) along a grid of pre-determined tracklines that uniformly covered the region between the coast and 555 km (300 nmi) from shore. At night, the vessels either remained in an area (to begin the next morning where effort was terminated the previous evening) or transited to a new transect line. Typically, groups of cetaceans were approached for species identification and group size estimation; however, approximately one third of search effort in 1996 was conducted in "passing mode" (Barlow 1997).

Each observer typically made three estimates group size ("best", "high" and "low" estimates) and estimated the percentage of each species present in multi-species aggregations. Estimates of group size and of the percentage of each species present were not discussed among observers and were recorded independently in personal notebooks. Estimates of group size and species percentages were transcribed into the computer record at the end of each day by the cruise leader.

Each observer team included at least one expert in species identification. Species were positively identified in the field only if the observers were certain of the species identification. For groups that could not be identified to the species level, observers recorded the lowest classification level of which they could be certain (eg. genus, family, "small whale", or "large whale"). Observers were required to describe and draw all diagnostic features used to identify species, and if a sighting could not be identified to species with certainty, they were asked to list the most likely species.

Analytical Methods

Cetacean abundance was estimated using line-transect methods (Buckland et al. 1993). The study area was divided into four geographic strata: inshore waters off California (261,700 km^2, corresponding to the aerial survey stratum of Forney et al. 1995), offshore waters off California (557,100 km^2), waters off Oregon and Washington (323,700 km^2), and waters off the west coast of Baja California, Mexico (953,200 km^2) (Figure 1). Sightings were stratified by group size to account for differences in detectability and to avoid size bias (Buckland et al. 1993, p. 77). The density, D_{aij}, for species j within geographic stratum a and group-size stratum i was estimated as

$$D_{aij} = \frac{n_{aij}\ s_{aij}\ f_{ij}(0)}{2\ L_a\ g_{ij}(0)} \qquad (1),$$

where n = number of sightings,
S = mean group size,
$f(0)$ = sighting probability density at zero perpendicular distance,
L = length of transect line completed,
$g(0)$ = probability of seeing a group directly on the trackline.

Passing and closing modes were pooled to estimate abundance. To facilitate comparisons with earlier estimates, we used the same group size strata that were used by Barlow (1995), Barlow and Gerrodette (1996), and Barlow (1997). In estimating f(0), geographic strata were pooled, and all species of large whales (Table 1) were pooled. Search effort was included when the sea state was Beaufort 0 to 5. We estimated f(0) using options for hazard-rate and half-normal key functions with cosine adjustments using the program DISTANCE (Laake et al. 1994). Akaike Information Criterion (AIC) was used to select the best model. We used the same critical truncation distances (5.56 km for large whales) as used by Barlow and Gerrodette (1997) to eliminate distant sightings before estimating f(0). Estimates of g(0) for these species and group size strata (Table 2) were taken from Barlow (1995) for baleen whales, from Barlow and Sexton (1996) for sperm whales, and from Barlow (1999) for Baird's beaked whales.

Mean group size, S, was estimated as the geometric mean of the "best" estimates of group size made by all observers (Barlow et al. 1998). If no "best" estimate of group size was made by any observer, the mean of the "low" estimates was substituted. Group size estimates were calibrated based on individual calibration factors (Barlow et al. 1998). Most of the observers on the 1993 survey were directly calibrated by comparing their estimates of group size with counts made from aerial photographs taken from a helicopter on the Jordan during the southern segments of that survey. The same calibration factors were used for the directly calibrated observers who participated in the 1996 survey. New observers in 1996 were calibrated against other calibrated observers using a method developed by Barlow et al. (1998). In addition to these adjustments to group size, the size of some sperm whale groups was adjusted for a known systematic underestimation (see Sperm Whale Group Size, below).

The total abundance for species j in area a, (N_{aj}), is estimated as the sum of the densities in all s strata times the size of the study area, A_a ,

$$N_{aj} = A_a \sum_{i=1}^{s} D_{aij}$$

The coefficient of variation (CV) of the abundances were estimated as the square root of the sum of the squared CVs of f(0), g(0), and the encounter rate ($n \cdot S/L$). The CV of the encounter rate was estimated empirically by breaking the transects into 75 nmi segments and calculating the standard error among segments (Buckland et al. 1993, p. 110). The CV of f(0) was estimated by the program DISTANCE using an information matrix approach. The CV of g(0) was estimated using an analytical formula for most species (Barlow 1995, Appendix) and was estimated from a simulation model based on search behavior and dive times for sperm whales and Baird's beaked whales (Barlow and Sexton 1996; Barlow 1999).

Sperm Whale Group Size

In 1997, a dedicated effort was made to survey sperm whales in the eastern temperate Pacific. Sperm whale groups most often consist of a large, asynchronously diving group, which may span several miles, composed of smaller synchronously diving clusters of individuals that surface together in close proximity. Typical dive times for clusters are 30-50 minutes. During the 1997 study, detailed behavioral observations were made for at least 90 minutes on all sperm whale groups that were seen, and surface time and position of every cluster was recorded. Using these data, we estimated the minimum number of individuals (making all plausible linkages between surfacing clusters) and the maximum number of individuals (not linking clusters when it was plausible they were different). We also determined how many individuals would be seen had the group been observed for only ten minutes (which is the typical length of time that sperm whale groups have been observed on past Southwest Fisheries Science Center cetacean surveys). As expected, we found that the 10-minute counts underestimated the actual number of sperm whales present, because many of the clusters did not surface during a 10-minute period of observation. We developed a correction factor for 10-minute counts by linear regression of the maximum 10-minute estimate against the minimum 90-minute estimate, which gives a minimum correction factor. The regression was forced to go through zero and resulted in a slope of 1.25 ($r^2 = 0.85$, $p < 0.001$). We conclude that, on average, the size of sperm whale groups that are observed for only 10 minutes are underestimated by at least 25%.

During the 1993 survey the average time spent on sperm whale sightings was 14.7 minutes, and, therefore, many groups are likely to be underestimated. In contrast, all sperm whale groups in 1996 were observed for longer than 60 minutes and therefore do not require such correction. The group size estimates for 1993 were corrected if they met the following criteria: 1) the behavior was clearly asynchronous diving and was not described as rafting or traveling, 2) the time spent with the group was less than 20 minutes, and 3) the observation was not a part of a series of observations that were close to one another in time and space. Of the 56 sperm whale sightings made in 1993, 27 were corrected using a correction factor of 1.25. Unfortunately, the correction factor assumes that the observers are viewing the group as a whole, which may cover several miles between the most distant clusters. There were several cases in 1993 where multiple sightings were recorded from clusters within one group. Although it is likely that group size was still underestimated in such situations, the correction factor developed does not match this situation and was therefore not used (criterion 3 above).

RESULTS

Transects in Beaufort sea states 0 to 5 almost uniformly covered the defined geographic strata (Figure 1). A few planned transect lines were not covered, including an area of persistent fog along the coasts of northern California and southern Oregon. Transects completed in Beaufort 0-5 totaled 5,632 km in the Inshore California stratum, 11,046 km in the Offshore California stratum, 4,353 km in the Oregon/Washington stratum, and 7,524 km in the Baja California stratum. A total of 493 large whale sightings were made during the survey in Beaufort sea states 0-5.

Effective Search Widths

Truncation at 5.56 km excluded approximately the most distant 12% of sightings. The best fits to the observed distributions of perpendicular distance were obtained using a half-normal model with cosine adjustments (for both group size strata). The estimated effective search widths (ESW=1/f(0), Eq. 1) were much narrower for small groups of 3 or fewer whales (2.48 km) than for larger groups (3.85 km) (Table 2). More than half the larger groups were sperm whales or Baird's beaked whales.

Abundance Estimates

Estimates of 1993/96 cetacean abundance in the California and Oregon/Washington strata are given in Table 3.

DISCUSSION

Group Size Estimates

The estimates of whale abundance in this paper differ from previous analyses of these data (Barlow 1997) in using group size calibration factors (Barlow et al. 1998). Their use is not unequivocally justified for large whales, because those factors were developed primarily using aerial photographs of dolphins schools. Here we have implicitly assumed that observers' tendencies to over or under estimate dolphin schools reflects the way that they estimate groups of whales. Although whales typically occur in much smaller groups, the study by Barlow et al. (1998) showed that tendencies to over or under estimate typically held for an individual observer over 2 orders of magnitude in dolphin group size. We believe that, it is better to assume the same relationship for large whales than to assume that all observers are unbiased estimators of large whale abundance.

The group size bias correction for sperm whales (+25%) changed the overall sperm abundance estimate by only 7%. This is because it did not appropriately apply to any of the 1996 sightings (all of which were observed for a least 60 minutes) and applied to only about half of the 1993 estimates. Furthermore, the estimate of 25% was a minimum estimate based on easily justified criteria. It is likely that sperm whale group size is still underestimated to some degree. Although it would be possible to estimate the other end of the spectrum of sperm whale group size corrections (ie. the maximum conceivable correction factor), it is not possible, with available data to make a statistically defensible "best" estimate.

"Probable" Species Identifications

Our whale abundance estimates also differ from previous estimates in using "probable" species identifications when species could not be unequivocally determined in the field. In many cases, observers can make a very good guess at what species they are seeing without being absolutely certain. Since 1991, observers have recorded these impressions in their field notes with comments such as "probably", "likely", and "very likely". These probable identifications were previously used only for unidentified small whales and unidentified beaked whales (Barlow 1997). These notes have now been entered into the computer record as a single category of "probable identification" to facilitate their use. Using these data reduces the number of whales in the categories of "unidentified large whale" and "unidentified rorqual", and we believe that using these data results in a more accurate estimate of abundance for each species, albeit, with some unquantifiable loss of precision. The alternative of prorating the unidentified categories to the other species categories would certainly be less precise than using the field observers' best guesses.

Abundance Estimates

As expected, most estimates of large whale abundance from the pooled 1993/96 surveys in the two California strata (pooled) are intermediate between the estimates from 1991/93 alone (Barlow and Gerrodette 1996) and the estimates for 1996 alone (Barlow 1997). The Oregon/Washington stratum (surveyed in 1996) adds appreciable numbers of fin whales and sperm whales. The Baja California stratum (surveyed in 1993) adds appreciable numbers of blue whales and sperm whales. Based on what is known about eastern North Pacific blue whales, the blue whales seen off Baja California in summer/fall are almost certainly part of the same population that is also found off California at that time (Calambokidis et al. 1990; Mate et al. 1999). The sperm whales found off the coast of Baja California may be part of the same population as those found off California; however, Mesnick et al. (1999) found significant genetic differences between sperm whales sampled off California/Oregon/Washington in 1993-99 and those killed by Japanese whalers approximately 300 to 500 nmi offshore of Baja California in 1978.

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Table 1. Species for which abundance was estimated and which were pooled to estimate *f(0)* and *g(0)*.

Species
sperm whale (Physeter macrocephalus)
Baird's beaked whale (Berardius bairdii)
Bryde's whale (Balaenoptera edeni)
Bryde's or sei whale (Balaenoptera edeni/borealis)
fin whale (Balaenoptera physalus)
blue whale (Balaenoptera musculus)
humpback whale (Megaptera novaeangliae)
unidentified rorqual whale
unidentified large whale

Table 2. Values of f(0), effective strip width (ESW=1/f(0)), and g(0) (the probability of detecting a trackline group of animals), and their estimated coefficients of variation (CV) used for the 1993/96 abundance estimates. Values of g(0) for sperm whales were estimated from a simulation model (Barlow and Sexton 1996); values of g(0) for other species were estimated using conditionally independent observer methods (Barlow 1995). [Note: CV is not defined when g(0) = 1.0, so g(0) was treated as a constant in those cases.]

Species Group Size Strata	f(0) km^{-1}	ESW km	CV(f(0))	g(0)	CV(g(0))
Sperm whales					
Group size 1-3	0.403	2.48	0.073	0.87	0.08
Group size 4+	0.260	3.85	0.124	0.87	0.08
Baird's beaked whales					
Group size 1-3	0.403	2.48	0.073	0.96	0.23
Group size 4+	0.260	3.85	0.124	0.96	0.23
Other large whales					
Group size 1-3	0.403	2.48	0.073	0.90	0.07
Group size 4+	0.260	3.85	0.124	1.00	0.00

Table 3. Abundance for large whales in Inshore California, Offshore California, Oregon/Washington, and Baja California strata estimated from the pooled 1993 and 1996 survey data. Abundances are based on values of f(0) and g(0) given in Table 2.

Species Geographic Strata	Number of Groups n	Mean Size of Groups S	Pop. Size N	C.V. N
sperm whale				
CA Inshore	10	8.9	622	0.74
CA Offshore	10	5.6	447	0.47
OR/WA	4	7.4	338	0.63
Baja California	19	3.9	1,640	0.34
CA/OR/WA Total			1,407	0.39
US/Mexico Total			3,047	0.26
Baird's beaked whale				
CA Inshore	6	16.4	617	0.53
CA Offshore	0		0	n/a
OR/WA	3	1.7	78	0.74
Baja California	0		0	n/a
CA/OR/WA Total			695	0.48
US/Mexico Total			695	0.48
Bryde's whale				
CA Inshore	0		0	n/a
CA Offshore	0		0	n/a
OR/WA	0		0	n/a
Baja California	4	1.0	113	0.45
CA/OR/WA Total			0	n/a
US/Mexico Total			113	0.45
Bryde's or sei whale				
CA Inshore	0		0	n/a
CA Offshore	1	1.0	11	1.00
OR/WA	0		0	n/a
Baja California	3	1.7	148	0.90
CA/OR/WA Total			11	1.00
US/Mexico Total			159	0.84
fin whale				
CA Inshore	67	2.0	1,189	0.23
CA Offshore	27	1.7	468	0.39
OR/WA	9	1.3	194	0.64
Baja California	0		0	n/a
CA/OR/WA Total			1,851	0.19
US/Mexico Total			1,851	0.19

Species Geographic Strata	Number Groups n	Mean Size of Groups S	Pop. Size N	C.V. N
blue whale				
CA Inshore	89	1.5	1,337	0.19
CA Offshore	34	1.3	470	0.34
OR/WA	0		0	n/a
Baja California	21	1.2	721	0.42
CA/OR/WA Total			1,807	0.17
US/Mexico Total			2,528	0.17
humpback whale				
CA Inshore	73	1.7	1,118	0.29
CA Offshore	1	2.3	26	1.00
OR/WA	2	1.0	33	0.71
Baja California	0		0	n/a
CA/OR/WA Total			1,177	0.28
US/Mexico Total			1,177	0.28
unidentified rorqual				
CA Inshore	22	1.6	308	0.28
CA Offshore	7	1.1	80	0.41
OR/WA	2	1.0	33	0.71
Baja California	6	1.1	164	0.34
CA/OR/WA Total			421	0.23
US/Mexico Total			585	0.19
unidentified large whale				
CA Inshore	13	1.4	177	0.28
CA Offshore	2	1.0	23	0.71
OR/WA	1	1.0	17	1.00
Baja California	2	1.0	57	0.71
CA/OR/WA Total			217	0.25
US/Mexico Total			274	0.25

Figure 1. Transect lines surveyed during Beaufort sea states of 0 to 5. Bold lines indicate the boundaries of the Inshore California, Offshore California, Oregon/Washington, and Baja California strata. Abundances were not estimated for the Gulf of California.