SC/31/Doc 37

Preliminary Population Estimate for the California Gray Whale based upon Monterey Shore Censuses, 1967/68 to 1978/79

Stephen B. Reilly
Dale W. Rice
Allen A. Wolman

National Marine Mammal Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Bldg. 32, Seattle, Washington 98115

ABSTRACT

Annual shore censuses of southward migrating gray whales have been conducted for the past 12 years from points near Monterey, California by the National Marine Mammal Laboratory. To utilize these counts in an estimation of total population size, a series of experiments were conducted during the 1978/79 migration. Specific goals were to (1) determine what proportion of whales pass by out of sight offshore, and (2) identify and measure sources of observer bias in estimating the number of individuals in each group and its distance from shore. For 1, aircraft transects were flown perpendicular to the coast near the census stations, and distances of whales from shore were recorded. For 2, groups of experienced and naive observers made independent estimates of numbers within and distances to group of passing whales. A true count of number in each group was made from a circling aircraft, and a true measure of distance was made with an inclinometer. A preliminary application of the experimental results to the census data indicates a population size of at least 16,500 ± 2,900 gray whales.

INTRODUCTION

Gray whales (*Eschrichtius robustus*) now only occur in the North Pacific Ocean and adjacent waters of the Arctic Ocean. The species also existed in the North Atlantic until a few centuries ago (Fraser, 1970; Rice and Wolman, 1971; Mitchell and Mead, 1977). There are presently two geographically isolated stocks: an eastern Pacific stock, which migrates between Baja California and the Bering and Chukchi Seas, and a western Pacific stock, which migrates between South Korea and the Okhotsk Sea. These are designated as the California stock and the Korean stock, respectively. The efforts described in this paper were carried out in an attempt to evaluate the population status of the California stock.

The California stock spends the summer mostly in the Chukchi and northern Bering seas, although a small proportion remains scattered along the west coast as far south as Baja California, Mexico (Darling, 1977; Hatler and Darling, 1974; S. Swartz, pers comm.). This stock leaves the feeding grounds in October and migrates down the North American coast to winter along the west coast of Mexico (Rice and Wolman, 1971; Rugh and Braham, 1979).

Henderson (1972) concluded, after analyses of historical data, that the population of California gray whales did not exceed 15,000 prior to initiation of commercial exploitation in 1846, notwithstanding Scammon's (1874) estimate of 'probably not over 30,000' from 1853 to 1856. In 1885/96 Townsend (1887) estimated that only 160 gray whales migrated south past San Simeon, California. Howell and Huey (1930) doubted 'whether more than a few dozen individuals survived', but K. W. Kenyon (pers. comm.) stated that he commonly observed gray whales migrating past La Jolla, California during the 1930s, and calculations by Ohsumi (1976) suggest that the stock attained its lowest size of 4,400 in 1875.

Systematic shore counts of the southward migration were initiated at Point Loma in San Diego, California (32°40'N; 130 m above sea level), in 1952/53 and continued intermittently until 1977/78 (Gilmore, 1960; Rice, 1961; Wolman and Rice, 1979). These counts indicated a steadily increasing population until 1959/60 (Table 1), but by the mid-1960s offshore observations revealed that, due to the trend of the coastline, the

Table 1

Counts of southward-migrating gray whales, 1952/53 to 1978/79[a]

	Number of whales counted	
Season	Point Loma[b]	Yankee Point and Granite Canyon[c]
1952/53	982	
1954/55	1,646	
1956/57	1,839	
1959/60	2,344	
1967/68	1,324	3,120
1968/69	1,154	3,081
1969/70		3,064
1970/71		3,034
1971/72		2,588
1972/73		3,304
1973/74		3,492
1974/75		3,348
1975/76	2,822	3,797
1976/77	3,648	4,058
1977/78	5,122	3,127
1978/79		3,568

[a] Data for 1952/53 to 1956/57 from Gilmore (1960).
[b] Total counts.
[c] 'Comparison period' only – 18 December to 4 February, except for 25 December and 1 January. Count made at Yankee Point until 1973/74, and at Granite Canyon thereafter.

majority of whales passed too far offshore to be seen from land (Rice, 1965). Increasing boat traffic also appeared to be causing an increasing proportion to migrate far offshore.

Starting in 1967/68, a shore count has been made every winter, at Yankee Point (36°29′N; 23 m above sea level from 1967/68 to 1974/75), or at Granite Canyon (3.7 km south of Yankee Point, 21 m above sea level) from 1975/76 to 1978/79. Previous observations had shown that few whales pass out of sight of land at these sites, and boat traffic is at a minimum. As the data from this location form a continuous series, and are less complicated by geography and boat traffic than are the Point Loma data, the present analysis is concentrated on the Monterey data.

METHODS

Each year the whale watch was made from 0700 to 1700 each day by two observers who alternated five-hour shifts. Observers watched seven days a week. The exact duration of the census has changed slightly from year to year, but it usually began on or before 10 December, and ended on or after 6 February (59 days). The coastal topography is relatively uniform between the census locations and Point Lobos to the north, and Point Sur to the south, and we believe that any differences in counts between Yankee Point and Granite Canyon due to geography would be negligible.

In the actual census procedure, the observer watched to the north for southward migrating whales coming into view. When a whale or group of whales was first sighted, the time was recorded, and a first estimate of the number of animals present was noted, but not recorded. The whales were then kept under observation until they were directly offshore from the station, usually about one-half hour later. At that time a final estimate of the number of individuals present was made and recorded, along with the time, and an estimate of the distance of the animals' path from shore at that point. Binoculars (7×50) were used as a visual aid. Distance estimates were generally made to within one of seven intervals: 0–¼ miles; ¼–½; ½–¾; ¾–1; 1–1½; 1½–2; 2+. Wind direction, Beaufort wind force, and notes on visibility conditions (fog, glare, etc.) were recorded continuously throughout the day.

Occasionally, only one of the two times was recorded. Often when an observer came on duty at 0700 h, there were whales passing directly offshore or to the south of the station, and consequently no north time was recorded. Also, when an observer ended the afternoon watch at 1700 h, there were often whales sighted to the north which had not yet passed directly in front of the station. In order to account for these missing data, an average elapsed time between the two time records was calculated for each observer, and missing times generated from this average difference. The time when the animals were directly offshore was used to categorize sightings for time of day analysis. Only sightings with this time recorded between 0700 and 1700 were used for abundance estimation.

As the data were transcribed for computer analysis during 1978, a relative visibility code (1 = 'excellent' to 6 = 'unacceptable') was assigned to each observation in an attempt to quantify the effects of visibility on the census results. Beginning in 1978/79, a quantitative visibility code was assigned to each sighting by the observers.

The yearly gray whale censuses (along with the bowhead census) are unique in that they are attempts at a complete count of that proportion of the population which passes during daylight hours. Consequently, while extrapolations to account for whales missed are small relative to other whale population estimates that are based on censuses of vast water areas, they are still an important aspect of the estimation procedure.

In order to extrapolate from recorded counts to an estimate of total population size, it is necessary to determine:

(1) Is there a consistent observer bias in estimating the number of individual whales present in a group? If so, what is that bias?

(2) What proportion of the population, if any, passes beyond sight of the observers?

(3) Are there diel variations in migration rate? Can we use the daylight counts to estimate the number passing at night?

(4) How much effect does weather (= visibility) variation have on the census results?

A previous attempt at estimating observer bias in counting the number of whales in a group was made by Paul Sund of the Southwest Fisheries Center, NMFS (pers. comm.). In January 1977 he circled above migrating whales in a light aircraft (Cessna 172), and compared aerial counts with counts made by the observers at Granite Canyon for a total of 46 paired observations. While limited by small sample sizes, his results indicated the shore observer made a slight overestimate for single animals, and slight underestimates that increased with pod size for pods of two or more.

In an attempt to determine if a significant proportion of the population passes too far offshore to be seen, Rice and Wolman ran a transect in a small boat across the migration corridor on 18 January 1968. They began at Yankee Point and went to 37 kilometers offshore. Data from this single transect indicated that 24 of 33 whales sighted (73%) passed within 1.5 kilometers from the shore station (Rice and Wolman, 1971). Further, Sund and O'Connor (1974) reported estimated distances of 149 whales recorded off Monterey (Pt. Cypress to Pt. Sur) during January 1973. Their results agreed closely, indicating 94% within 1.6 kilometers.

Regarding diel variations in migration rate, Gilmore (1960) and Adams (1968) used arbitrary correction factors of 50% and 70%, respectively, to estimate nocturnal travel rates. Also, Hubbs and Hubbs (1967) as well as Ramsey (1968) believed there was some evidence of diel variation in rates. Cummings *et al.* (1968), IWC (1976 and 1977), and Rugh and Braham (1979) contrarily reported no apparent diel variations in migration rate. The data available for this study were examined for trends within the 10 hr (0700–1700) period of the censuses. Also, in an attempt to obtain further data on rate of passage at night, observation trails were made by Wolman with a Starlight Scope (1975; 1976), and night vision goggles (1977). Both were used under a variety of weather and lighting conditions. The binocular goggles do not magnify, but have a 40° field of view, in contrast to the monocular Starlight Scope which had only a 16° field of view. Very few whales were seen with either system. The few whales that were seen and tracked supported the hypothesis of animals moving at the same rate during night as they do during the daylight hours.

Direct measurement of observer biases. In order to test for bias in the observers' estimates of the numbers of animals in each group, and its distance offshore, it would ideally have been appropriate to have all past observers available for simultaneous experimental tests. The data recorded by each observer could then be corrected for that observer's individual biases. Since this was impossible, a group of 12 people (3 'experienced', 9 'naive') were used as a representative sample for such experiments.

At Granite Canyon on 30 and 31 December 1978, the 12 observers participated in the following experiments: For a total of 62 groups of whales passing offshore, each person made an independent estimate of distance to and number of individuals present in each pod. Simultaneously, Wolman circled above each group of whales in a Cessna 172 aircraft until an accurate count of the true number present was obtained. For a truth measure of the distance to each group, Reilly was positioned on a steep hill 200 m (660 ft) above and directly behind the census station, and used an inclinometer to measure the vertical angle to each group of whales as it passed directly offshore. From the angle, known elevation of the hilltop, and known distance to the water's edge, the distance of the whales from shore was calculated. The aircraft, census station, and inclinometer station were in radio contact to assure that they were all observing the same pod. Howard Braham coordinated the activity from the census station.

These experiments were conducted to measure bias *given* that a group of whales was sighted, which is equivalent to being recorded in past censuses. From these data, no estimates can be made of groups missed entirely.

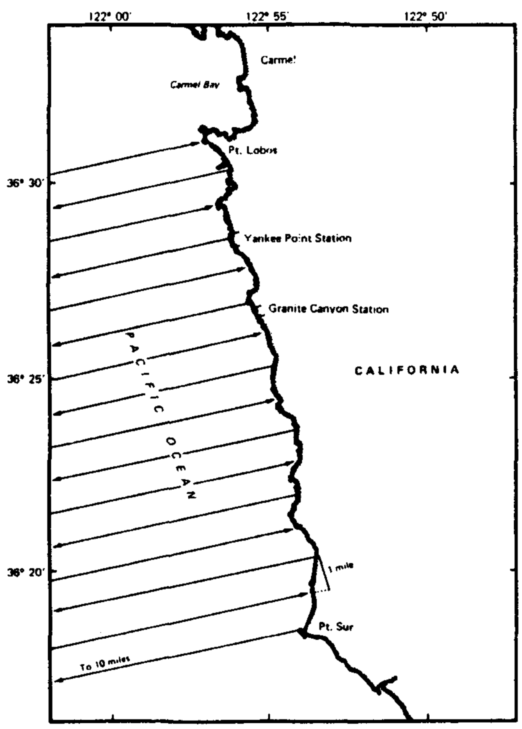

Fig. 1. Chart of California coast south of Monterey, showing census stations, and aerial transect lines.

Aerial transects of the migration corridor width. Flight transects were conducted to provide estimates of the corridor width, independent of the limited shore-based observers' estimates. Results from census studies based upon line transect and similar theory (Seber, 1973; Eberhardt, 1968, 1978) indicate that sighting efficiency decreases with increasing distance of an animal from the observer. A comparison of the observers' data on proportions of whales passing within each distance interval, with similar data from an 'unbiased' source should indicate the proportion of whales passing that are missed as a function of their distance from shore. A Cessna 172 aircraft flying at 300 m (1,000 feet) and 145 km/h (90 mph) altitude was used as this independent source. Although an observer in an aircraft will also miss a proportion of the whales passed over as a result of plane's elevation and speed, this proportion should be independent of the distance from shore. Consequently, while absolute counts from a plane will be biased, relative proportions of the total number seen per distance interval will be unbiased estimates of the true proportions, given sufficient sample sizes.

For this purpose a series of 16 transect lines were defined perpendicular to the coast at 1.6 km (1 mile) intervals between Point Sur and Point Lobos (Fig. 1). Each transect line extended from shore to 16 km (10 miles) at Sea.

Data from two previous shore censuses (1974/75 from Yankee Point; 1975/76 from Granite Canyon) were pooled, and used as a pre-sample of the proportions expected within each interval. The sample size requirement for the plane census was then determined by the formula (adapted from Cochran 1973):

$$N_T = \sum_{I=1}^{7} n_I = \sum_{I} \hat{p}_I \cdot \hat{q}_I \cdot (Z\alpha^2/d^2) \qquad (1)$$

where N_T = total sample required
n_I = sample required for interval I
$\hat{p}_I$ = estimate of the percent of the population in I from the past data
$\hat{q}_I$ = $(100 - \hat{p}_I)$
$Z\alpha$ = area under the normal curve for the required precision level
d = (100 − required precision level)

The method assumes that the estimates ($\hat{p}_I$) are normally distributed about the parametric values.

From (1) sample size requirements for 3 precision levels were determined (Table 2). Due to time and budgetary limitations, a 90 per cent precision level was accepted. Flights were continued until at least the minimum number of whales (330) assuring 90 per cent precision were recorded.

Table 2

Aerial transect sample size requirements for 3 levels of precision

	Precision level		
Number of	90%	92.5%	95%
Whales	330	582	1,311
Pods[a]	165	290	656

[a] Based upon an average approximately 2 per pod from pre-sample data.

Personnel for each flight included two observers and, when possible, a data recorder. On all flights, observations were also recorded on a cassette tape recorder through a microphone-headset system. Written data were verified by comparison with vocal data from the tapes.

The observer on each side of the plane concentrated on a 1.6 km (1 mile) strip of water, measured horizontally from the plane's track line by markings on the wing struts and windows. Left and right side duty were rotated between observers, and markings changed at each rotation to account for the different eye levels (and consequently different perspectives) of the observers.

Along each transect, whenever a group of whales was sighted within the one-mile strip, the number of animals was counted, and the elapsed time from the beginning of the transect to the moment when the animals were beneath the wing struts was recorded. The distance from shore was then calculated from the time difference between the sighting and the shore, and the plane's speed.

RESULTS

The Estimating Function

In its current state (June 1979) the estimating function begins with the i^{th} estimate of the number of animals present in a sighting, (n_i). This estimate is then corrected for bias in estimating the true number present by the function $f(n_i)$, the computation of which is described below (eg. 8). Then for each j^{th} day an average hourly rate is calculated. This is multiplied by 24 to produce an estimate for the entire day assuming a constant rate of migration throughout 24 hours. This daily estimate $(\hat{n}_j)$ is then:

$$\hat{n}_j = (\Sigma f(n_i)/t_j)\cdot 24 \tag{2}$$

where t_j is the total time watched on the j^{th} day.

In equations 2–7, the notation is as follows:

- n_i = original estimate of the number of animals present in the i^{th} of observation,
- $f(n_i)$ = the bias correction function for n − equation (8)
- t_j = time watched during the j^{th} day
- $\hat{n}_j$ = number estimated for 24 hr day j corrected for bias in $n_i = [(\Sigma f(n_i)/t_j)\cdot 24]$
- $\hat{p}_j$ = cumulative proportion of the population expected on the jth day,
- $h(k)$ = bias correction for each year (k^{th}) for proportion of whales missed offshore − equation (10)
- $\hat{N}_j$ = estimate of the total population made on day j
- $\hat{N}_l$ = estimate of the total population made on the last day of the census (j = l)

The next step is an estimation of the animals which pass by the station before and after the census period. This is done following a method developed to predict run size for migratory salmon (Mundy, 1979; Walters and Buckingham, 1975), in which a quantitative measure of the migratory timing is required: the cumulative proportion of the total 'run' expected on each day, calculated from past 'runs'. Their method basically, for each day j, estimates total population Nj by minimizing the least squares function

$$\Sigma_j (p_j - {}^{(\Sigma \hat{n}_j)}/_N)^2 \tag{3}$$

for N, according to Mundy (1979). This is solved for N by

$$\hat{N}_j = \Sigma_j(\Sigma \hat{n}_j)^2/(\Sigma \hat{n}_j \, . \, \hat{p}_j) \tag{4}$$

Major assumptions of the method are that data fit a normal cumulative distribution, and that the mean days for each year are not significantly different. For our purposes, the only $\hat{N}_j$ of interest is that calculated on the last day of the census, $N_{j=l}$

Finally, the $\hat{N}_l$ is corrected for animals missed as a function of their distance from shore by the correction function h(k), for each year k. h(k) is a result of the differences between recorded and predicted (from aerial transects) proportions in the distance intervals (see equation (10) in Results section). The final estimating function is then:

$$\hat{N}_k = N_l \cdot h(k) \tag{5}$$

The variance of N_k is estimated by the Delta Method, which is a Taylor series expansion with the higher order terms ignored (Seber 1973) as:

$$\text{est. Var}[\hat{N}_k] = \sum_{p=1}^{3} (\delta N_k/\delta x_p)^2\cdot \text{Var}[x_p] + 2\Sigma\Sigma \text{cov}(x_p,x_q)\cdot[\delta N_k/\delta x_p]\cdot[\delta N_k/\delta x_q] \tag{6}$$

where $x_1 = f(n_i)$; $x_2 = \hat{n}_j$; $x_3 = h(k)$.

Ninety-five percent confidence limits for the estimates are then:

$$\hat{N}_k \pm 1.96\sqrt{\text{Var}[N_k]} \tag{7}$$

The Data Base

Data from 12 consecutive annual censuses near Monterey are currently under study. The latest of these, 1978/79, was not fully prepared for analysis in time for this report.

For developing a population estimate from the census results, the most important statistics are rate of animals recorded per unit time, and those statistics describing if and how this rate is affected by variability between observers, times of day, and visibility conditions. Three time units were examined: one hour, 5 hours (a ½ day observer shift) and 10 hours (a full day's watch).

1. Animals recorded per 5-hour shift. This was examined, within each census, for effects due to the observer on duty, the time of day (morning or afternoon) and average visibility code, by analysis of variance (ANOVA). Only periods which were exactly 5 hours were included in the analysis. There were differences between the two observers in only two censuses: 67/69 and 76/77. ($F = 3.932$, 3.908 respectively; data from these two censuses are currently under re-analysis to produce estimates which take these differences into account.) For the estimates produced in this report, data for the observers within each census are pooled. There were also no differences detected between periods with different visibility codes. This, however, could be a result of the elimination of periods shorter than 5 hours which were often those with bad visibility conditions. Another possible factor is that variability throughout the season resulting from the timing of the migration is probably great enough to overshadow any variability as a result of visibility. Consequently, this test is not conclusive, and further analysis is in progress.

This test does conclusively show that there were no differences between morning and afternoon periods in the numbers of animals recorded. Consequently, one-half day shifts were pooled for each day.

2. Number of animals per hour of day. Data for all censuses were pooled, then broken down into 10 one-hour groups (0700–1700), in order to test for indications of diel variation. Both an ANOVA of rate of animals recorded per hour, with hours of day as groups (F = 1.608, d.f. = 9, ∞: n.s. at $\alpha = .05$) and a plot of average hourly rate by hour (Fig. 2) fail to indicate any change in migration rate during daylight hours. With no evidence to suggest that migration rate changes at night, a constant rate for each day is assumed here.

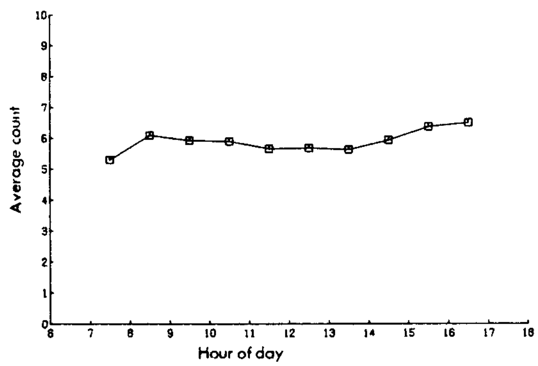

Fig. 2. Average number of gray whales recorded per hour at Monterey by hour of day for 0700–1700, from 11 annual censuses 1967/68–1977/78.

3. *Number of animals per 10-hour day.* The average hourly rate recorded per day is used as a basis for extrapolation over 24 hours for each day. The average hourly rate is used rather than the days sum to account for days in which less than 10 hours were watched.

4. *The migratory corridor: differences between locations.* In order to determine if the move to Granite Canyon in 1975/76 has had an effect on census results, data from each location were pooled, and broken down into relative proportions recorded within the seven intervals of distance from shore. A difference in the distances of animals from shore between the two locations could result in higher or lower counts. Table 3 lists a Chi-squared contingency test of differences between proportions per interval at the two locations. They are not significantly different at $\alpha = .05$. (Similarly, a t-test of differences in mean distance indicated no difference.) Consequently location difference between early and late censuses is not considered an important factor at this time.

5. *The migratory corridor: changes during each migration.* As we were only able to conduct verification experiments on the migratory corridor during the middle third of the migration, the census results were tested for

Table 3

Chi squared contingency test for differences in proportions of observations per offshore interval between Yankee Point and Granite Canyon

Distance increment	Yankee Point (8 yrs)	Granite Canyon (3 yrs)
0. –0.25	31.7	46.5
0.25–0.5	34.7	29.4
0.5 –0.75	15.9	12.2
0.75–1.0	11.5	7.1
1.0 –1.5	3.8	2.8
1.5 –2.0	1.8	1.6
2.0+	0.6	0.4

$\chi^2 = 10.567$ not significant at $\alpha = .05$.
$\chi^2_{.05,6} = 12.592$.

possible differences in distances of animals from shore during the migration. Data were divided into three approximately equal time segments: 'early' = 10 Dec–29 Dec; 'mid' = 30 Dec–18 Jan; 'late' = 19 Jan–6 Feb. While a χ^2 test of differences in proportions between the midseason results and those for the early and late seasonal periods indicated no significant differences (early $\chi^2 = 4.55$. Late $\chi^2 = 11.78$; compared to $\chi_{6,.05} = 12.592$) an ANOVA of mean distances of the three seasonal groups indicated they were significantly different (Table 4). A multiple classification analysis (Nie *et al.* 1975) indicates that early and late seasons are not different, but together they are different from the midseason, the whales being recorded farther from shore, on average, at that time. As there was a disagreement between test results, the conservative route was chosen, and only the mid-season data used for comparison with results from aerial transects of the migration corridor.

Table 4

ANOVA of distance of observations from shore, with early, middle and late season as groups

Season	$\bar{X}$	SD	n
Early	.5093	.3302	3.980
Mid	.5897	.4357	10.616
Late	.4825	.3835	4.878
All	.5463	.4076	19.474

Source of variation	DF	Mean square	F
Between groups	2	15.2284	92.9788**
Within groups	19.472	0.1638	

** Significant at $\alpha = .01$.

The Verification Experiments

1. *Estimation of the number of whales present in each group.* Data for this experiment were collected over the course of two days, involving estimates for 62 groups of whales. The observations from the first morning (12) were thrown out, being considered an orientation exercise. Of the remaining 50, the plane was present to make a truth count for 34. In these a total of 381 estimates were recorded. An analysis of variance of errors in estimating the true number of whales present per group with people (12) and true number (4) as groups (Table 5) shows that both factors are significant, as is the interaction between them. That is, there were significant differences between observers not only in their overall bias, but in their relative biases for each group size. Also, overall, there are

Table 5

Analysis of variance for errors in estimating the number of whales present per observation with observers (12) and pod sizes (4) as groups.

Source	SS	DF	MS	F
Mean	169.088	1	169.088	(74.700)
People	85.796	11	7.799	3.446**
Group size	137.717	3	45.905	20.281**
People × group size	165.629	33	5.019	2.217**
Error	785.449	347	2.263	
Total	1.343.449	395		

** Significant at $\alpha = .01$.

differences in bias for different numbers of whales per group. An estimation of the average bias for each estimate n, was calculated as (bias of n) = (estimated number (n) − ave. true number). As indicated in Table 6, estimates of 1 and 4 or more were significantly below the true value, while those for 2 and 3 were not significantly different from the true values.

To correct past data for this measured bias, the function f(n) is defined

$$E[n] = f(n) = n + b_n = \begin{cases} n + .350 & n = 1 \\ n + \emptyset & n = 2, 3 \\ n + .333 & n \geq 4 \end{cases} \qquad (8)$$

with variance estimated as

$$\mathrm{Var}[f(n)] = \begin{cases} .464 & n = 1 \\ \emptyset & n = 2, 3 \\ \cancel{.333}\ .612 & n \geq 4 \end{cases} \qquad (9)$$

Table 6

Bias of estimates of numbers present per observation, from 1973 verification experiment

Estimate	$\bar{X}$ Truth count	Standard deviation	n	t	Bias
1	1.350	0.6812	225	7.709*	−0.350
2	2.178	0.9316	101	1.921	0
3	3.035	1.290	28	0.144	0
4 or more[a]		0.7825	27	2.210*	−0.333

* Significant at $\alpha = .05$.
[a] The data for observations of 4 or more were compared individually to their true counts. The 'bias' listed above is the average residual of these 27 observations.

Table 7

Analysis of variance for errors in estimating the true distance interval in which a group of whales passes, with people (12) and true intervals (4) as groups

Source	SS	DF	MS	F
People	238.664	11	21.696	13.839*
True interval	22.338	4	5.585	3.562*
People × true interval	132.514	44	3.012	1.921*
Error	755.679	482	1.568	
Total	1,149.195	572		

* Significant at $\alpha = .05$.

2. *Estimation of distances of groups of whales from shore.* After an initial orientation period, 542 estimates were made for 50 occurrences of whales passing offshore. For each of these 50 there was an inclinometer truth measurement taken. Data from both the estimates and the truth measurements were classified into the seven distance intervals. An analysis of variance of errors in estimating the true distance interval in which a pod of whales is passing, with people (12) and true interval (4) as groups (Table 7) shows that both factors are significant, as is the interaction (just as with number estimation). That is, not only are people different in their ability to accurately estimate distances, but they differ also in where they make significant errors in estimating distances. Table 8 lists the average true distance for estimates of each of the seven intervals. For all intervals except 1–1.5 miles the true interval was on average significantly different from that estimated. Both within the area from shore to 1 mile out, and within the area beyond 1.5 miles, there are serious

Table 8

Results of distance estimation bias experiments from Granite Canyon 30, 31 December 1978

Estimated distance	1 (0–.25)	2 (25–.5)	3 (.5–.75)	4 (.75–1.0)	5 (1.0–1.5)	6 (1.5–2.0)	7 (2.0+)
Number of observations	18	55	101	183	114	47	24
Relative frequency	.033	.101	.186	.337	.210	.086	.04
Average true distance	0.556	0.683	0.871	0.995	1.250	1.350	1.208
Sd	0.137	0.244	0.303	0.259	0.306	0.371	0.319
t	13.385*	11.397*	8.159*	6.267*	0	7.392*	12.285*

* Significant at $\alpha = .05$.

Table 9

Data from aerial transects of migrating gray whales between Point Sur and Point Lobos, California during January 1979

Number	Date	Elapsed air time (hr)	Number of observations	Number of animals	Comments
1	2 Jan 79	3:00	16	27	200 + *Grampus*; 50–75 sea lions; 3–10 unident. porpoise
2	4 Jan 79	2:52	18	31	
3	4 Jan 79	2:55	26	45	
4	5 Jan 79	2:40	25	46	130 *Grampus*; 50+ *Phocoenoides*
5	6 Jan 79	2:35	26	40	80+ unident. porpoise
6	6 Jan 79	2:42	28	66	12 *Grampus*; 80± unident. porpoise
7	7 Jan 79	1:24	5	99	5 *Phocoenoides*
8	9 Jan 79	0:55	3	4	abort due to poor visibility: wind and chop
9	9 Jan 79	1:00	0	0	abort due to fog
10	10 Jan 79	2:20	21	36	2 *Phocoenoides*
11	12 Jan 79	1:00	0	0	abort due to equipt. malfunction
12	12 Jan 79	2:47	21	38	50+ *Grampus*
13	13 Jan 79	2:37	22	57	10± 2 sea lion; 8 unident. porpoise; 15 *Lagenorhynchus*
14	13 Jan 79	2:52	20	40	100+ *Lagenorhynchus*; 2 *Zalophus*; mixed group stellar sea lions (50+) and *Lagenorhynchus* (75+)

misclassification problems. Unfortunately during the experimental period, no whales actually passed within the closest and farthest intervals (1, 7).

3. *Aerial estimation of the migration corridor.* A total of 14 flights were taken during the period 2 January 1979 and 13 January 1979 (Table 9). Of these, two were aborted before actually beginning the transects (9, 11) and two others were aborted after only a few legs (8, 10). In general, data were collected during periods of 'good' to 'excellent' visibility.

Data on distances of whales from shore were examined for effect of side of planes and leg number (1–16), while data on number of whales sighted were examined for effects of observer, side of plane, and morning vs. afternoon flight.

Table 10

ANOVA of estimated distance of whales from the airplane, with sides of plane and transects legs as groups (raw data)

Source	SS	DF	MS	F
Sides	1.886	1	1.886	7.7*
Legs	26.106	15	1.740	7.1*
Sides × legs	14.985	15	0.999	4.1*
Error	94.186	384	0.245	

* Significant at $\alpha = .05$.

An ANOVA of distance estimates with side of plane and legs as groups (Table 10) indicates that both factors are significant. The differences between sides is to be expected, as the person on the left sat behind the pilot, while the person on right sat next to the pilot, resulting in differing perspectives for identifying the time at which the wing strut passed over an object. In fact, the mean distance estimates for the two sides (1.405 miles left; 1.205 miles right) are different by exactly 0.2 miles, which corresponds to 8 seconds of flight at 90 mph. To account for this difference, left side estimates were adjusted by −0.2 miles (−8 sec), under the assumption that right side estimates were accurate, as that side afforded the greater visibility. A second ANOVA (Table 11), with these adjusted data, shows no significant difference between sides. Data were consequently pooled from both sides. The differences between legs are possibly due to very small samples per leg (in fact only when all legs are pooled

Table 11

ANOVA of estimated distances of whales from the airplane, with sides of plane and transect legs as groups (left side data adjusted by −.2 mi)

Source	SS	DF	MS	F
Sides	0.1155	1	.116	0.5 n.s.
Legs	26.106	15	1.740	7.1*
Sides × legs	14.985	15	0.999	4.1*
Error	94.186	384	0.295	

* Significant at $\alpha = .05$.

are there enough data for even 90 per cent precision). Another possibility is that the whales are responding to the relatively slight variations in coastal geography along the stretch of coast surveyed. As there aren't sufficient observations per leg to test this quantitatively, a qualitative examination of the location of observations in relation to varying bottom contours is in progress. For the present, data from all legs are pooled.

Flight data on number of whales sighted per flight were examined by factorial ANOVA for differences in sighting efficiency due to observer (skill), side of plane and morning vs afternoon flights (Table 12). There were no significant differences due to these factors, indicating that over 14 flights, neither differences in observers, side of plane or time of day significantly affected this aspect of the plane census results.

Table 12

ANOVA of number of whales sighted per flight during aerial transects of the gray whale migration corridor, 2–13 January 1979. Groups are sides of plane, observers, and period (morning vs afternoon)

Source	SS	DF	MS	F[a]
Sides	63.375	1	63.375	0.5
Observers	117.042	1	117.042	1.0
Sides × observers	155.042	1	155.042	1.3
Periods	57.042	1	57.042	0.5
Sides × periods	9.375	1	9.375	0.1
Observers × periods	126.042	1	126.042	1.1
Sides × observers periods	45.375	1	45.917	0.4
Error	1886.667	16		

[a] None significant at $\alpha = .05$.

Table 13

Relative and cumulative frequencies of observations in distance increments for the mid-season (29/12–18/01). 11 years. Compared to 'best estimate' from aerial transects

Distance interval		Plane transect predicted	67/68	68/69	69/70	70/71	71/72	72/73	73/74	74/75	75/76	76/77	77/78
1	rel.	3.4%	29.7	40.5	27.6	28.0	14.4	15.6	25.6	13.3	51.8	49.1	62.8
	cum.	(3.4)	(29.7)	(40.5)	(27.6)	(28.0)	(14.4)	(15.6)	(25.6)	(13.3)	(51.8)	(49.1)	(62.8)
2		8.7	37.6	49.4	36.7	31.7	27.6	35.5	25.9	17.9	29.9	35.0	25.8
		(12.1)	(67.3)	(89.9)	(64.3)	(59.7)	(42.0)	(51.1)	(51.5)	(31.2)	(81.7)	(84.1)	(88.6)
3		9.9	17.2	5.1	23.1	23.9	14.9	25.1	18.9	21.6	11.6	11.4	7.5
		(22.0)	(84.5)	(95.0)	(87.4)	(33.6)	(56.9)	(76.2)	(70.4)	(52.3)	(93.3)	(95.5)	(96.1)
4		17.3	7.6	4.4	7.8	11.1	27.4	13.8	19.0	24.4	4.8	3.1	2.8
		(39.3)	(92.1)	(98.0)	(95.2)	(94.7)	(84.3)	(90.0)	(89.4)	(77.2)	(98.1)	(98.6)	(98.9)
5		35.6	2.8	0.5	2.4	2.9	14.0	4.9	5.5	12.5	1.1	1.0	1.0
		(75.4)	(94.9)	(99.5)	(97.6)	(97.6)	(98.3)	(94.9)	(94.9)	(89.7)	(99.2)	(99.6)	100.0
6		17.08	3.0	0.0	0.2	1.9	1.1	3.7	3.9	8.0	0.7	0.5	0.0
		(93.2)	(97.9)	(99.1)	(97.8)	(99.5)	(99.3)	(98.6)	(98.9)	(97.7)	(99.9)	(100.0)	0.0
7		7.0	2.1	0.1	0.1	0.5	0.7	1.4	1.1	2.4	0.1	0.0	0.0
		(100.0)	(100.0)	(99.6)	(97.9)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	0.0	0.0

All aerial data pooled, broken down into proportions within the seven distance increments, were compared with the same data from the midseason (30 Dec–10 Jan) of each individual census (Table 13). Chi-squared tests indicate that all years are significantly different from the aerial predictions ($X^2 > 300$ for all : $\alpha = 0.1$). (Significant differences beyond 90 per cent are not meaningful here, as this was the sampling efficiency of the aerial census).

An estimator of the function h(k) (see methods section) from both the misclassification bias and from the differences between predicted and observed corridor distance interval proportions is in progress. At present, as a temporary approximator, data are pooled in two classes: 'inshore' (from shore to 1.5 miles), and 'offshore' (beyond 1.5 miles). Justification for the break at 1.5 miles comes from misclassification bias being a significant problem on both sides of the interval 1–1.5 miles, while there is no apparent bias within this interval. A necessary assumption is that in the 'inshore distance interval, virtually all groups of whales that passed were sighted. A simple function, then, for each year (k) is:

$$h(k) = C_p/c_s \qquad (10)$$

where C_p = cumulative proportion inshore predicted from aerial censuses

c_s = cumulative proportion inshore observed for the year h

The variance of h (k) is estimated by the Delta method (Seber, 1973) as:

$$\text{est. Var}[h(k)] = [-C_p/c_s^2]^2 \text{Var}[C_p] + (1/C_p)^2 \text{Var}[s_s] \qquad (11)$$

$$\text{where } \text{Var}[C_p] = (C_p).(1-C_p)/n_p \qquad (12)$$

$$\text{and Var}[c_s] = (c_s).(1-c_s)/n_s \qquad (13)$$

Values of h (k) are listed in Table 14.

Table 14

Values estimated for the correcting function h(k), for k = 1, 11

Year	h(k)
1967/68	1.26
1968/69	1.32
1969/70	1.29
1970/71	1.29
1971/72	1.31
1972/73	1.26
1973/74	1.26
1974/75	1.19
1975/76	1.31
1976/77	1.32
1977/78	1.33
1978/79	1.29

Migratory timing and estimation of whales passing following the census

The cumulative proportions of the whales seen each day during the period 10 Dec–6 Feb (all years combined) as fit by the cumulative normal (estimated by the logistic) are shown in Fig. 3 (taken from Table 15). As the fit is very good the major assumption of equality of mean days over years is however, not met by the data (median test T = 2,745 x $^2 10_j$,05). As the effect of this violation on the final population estimate is minor, the adjustment for migration tails was conducted assuming equality.

Table 15

Monterey gray whale census. Number of animals sighted per day (adjusted number—see text), relative frequency (adj) and cumulative frequency (adj)

	Date	Adjusted count	Per cent	Cumulative per cent
1	10 Dec	12.905	.13	.13
2	11 Dec	21.563	.21	.33
3	12 Dec	30.953	.30	.63
4	13 Dec	37.286	.36	.1.00
5	14 Dec	44.804	.43	1.43
6	15 Dec	47.772	.46	.1.89
7	16 Dec	45.397	.44	.2.33
8	17 Dec	46.495	.45	.2.78
9	18 Dec	65.217	.63	3.42
10	19 Dec	76.887	.75	4.16
11	20 Dec	84.739	.82	4.98
12	21 Dec	83.784	.81	5.79
13	22 Dec	117.214	1.14	6.93
14	23 Dec	143.658	1.39	8.32
15	24 Dec	150.503	1.46	9.78
16	25 Dec	151.203	1.47	11.25
17	26 Dec	161.880	1.57	12.82
18	27 Dec	207.556	2.01	14.83
19	28 Dec	205.425	1.99	16.82
20	29 Dec	185.356	1.80	18.62
21	30 Dec	224.817	2.18	20.80
22	31 Dec	280.459	2.72	23.52
23	1 Jan	290.003	2.81	26.53
24	2 Jan	284.557	2.76	29.09
25	3 Jan	363.821	3.53	32.61
26	4 Jan	420.755	4.08	36.69
27	5 Jan	371.890	3.60	40.30
28	6 Jan	402.371	3.90	44.20
29	7 Jan	382.179	3.70	47.90
30	8 Jan	287.085	2.78	50.68
31	9 Jan	276.636	2.68	53.37
32	10 Jan	333.840	3.24	56.60
33	11 Jan	314.091	3.04	59.65
34	12 Jan	278.278	2.70	62.34
35	13 Jan	303.374	2.94	65.28
36	14 Jan	271.297	2.63	67.91
37	15 Jan	254.513	2.47	70.38
38	16 Jan	235.295	2.28	72.66
39	17 Jan	247.296	2.40	75.06
40	18 Jan	190.440	1.85	76.91
41	19 Jan	215.155	2.09	78.99
42	20 Jan	204.857	1.99	80.98
43	21 Jan	213.319	2.07	83.04
44	22 Jan	198.859	1.93	84.97
45	23 Jan	197.393	1.91	86.89
46	24 Jan	162.597	1.58	85.46
47	25 Jan	158.802	1.54	90.00
48	26 Jan	149.114	1.45	91.45
49	27 Jan	149.140	1.45	92.89
50	28 Jan	125.544	1.22	94.11
51	29 Jan	23.427	.23	94.34
52	30 Jan	91.619	.89	95.22
53	31 Jan	82.017	.80	96.02
54	1 Feb	81.478	.79	96.81
55	2 Feb	71.358	.69	97.50
56	3 Feb	45.740	.44	97.95
57	4 Feb	47.491	.46	98.41
58	5 Feb	30.714	.30	98.71
59	6 Feb	36.534	.35	99.06

Mean day = 31.
Variance = 137.89.

Table 16 lists values of the original counts ($\Sigma \hat{n}_i$), counts adjusted for 24 hours and whales missed per pod seen ($\Sigma \hat{n}_j$), and the $\Sigma \hat{n}_j$ adjusted for whales passing after the census ($\hat{N}_I$). The average numbers of animals seen per day over the eleven years are plotted in Fig. 4.

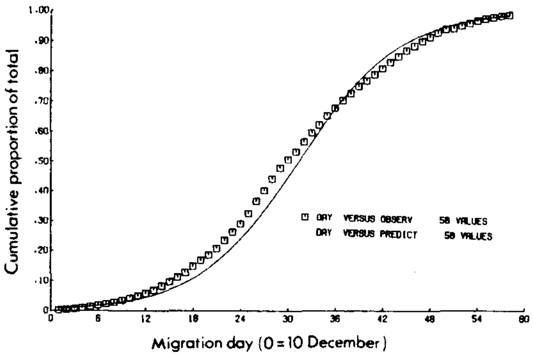

Fig. 3. Cumulative proportion of total count by day for 11 years (averaged) fit to the logistic, as an approximation to the cumulative normal.

Table 16

Sums of daily counts. Σn_i = raw data. $\Sigma \hat{n}_i$ = raw data adjusted for 24 hour and number estimate bias: $\dot{N}_i$ = adjusted for tails of migration

Year	Σn_i	$\Sigma \hat{n}_i$	$\dot{N}_i$
67/68	3,077	8,373	8,545
68/69	3,265	8,514	8,624
69/70	3,399	8,990	9,107
70/71	3,264	8,605	8,717
71/72	2,667	7,248	7,357
72/73	3,684	10,316	10,450
73/74	3,889	10,193	10,325
74/75	3,836	10,012	10,142
75/76	4,295	11,165	11,397
76/77	4,720	12,348	12,508
77/78	3,717	10,106	10,259
78/79	3,927	10,317	10,450

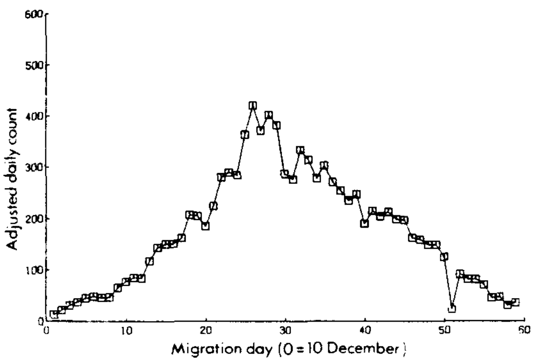

Fig. 4. Average daily counts of gray whales from Monterey, California, 1967/68–1977/78. Counts are adjusted for number estimation bias, and for the full 24 hour day.

Final estimates and their variances

Final estimates for each census are obtained by multiplying N_i by h(k) to complete the entire estimation process (as of this date).

The final form of the variance equation for the population estimator (Var[N_k]) was computed with the assumption that the covariances (6) were zero.

Table 17

Estimates of the population size of the California stock of the gray whale, and their variances and confidence limits, from 11 consecutive annual censuses at Monterey, California

Year	Estimate ($\dot{N}_k$)	Var [$\dot{N}_k$]	C.I.
1967/68	10,767	1,034,843	(8,773, 12,761)
1968/69	11,384	1,214,051	(9,224, 13,544)
1969/70	11,748	1,223,782	(9,579, 13,916)
1970/71	11,245	1,198,525	(9,099, 13,390)
1971/72	9,637	831,332	(7,851, 11,424)
1972/73	13,167	1,516,403	(10,753, 15,581)
1973/74	13,010	1,501,919	(10,608, 15,412)
1974/75	12,069	1,411,499	(9,746, 14,398)
1975/76	14,930	1,777,799	(12,316, 17,543)
1976/77	16,511	2,163,435	(13,628, 19,394)
1977/78	13,644	1,550,369	(11,204, 16,084)
1978/79	13,460	1,525,210	(11,039, 15,880)

CONCLUSIONS

Table 17 lists the final estimates, their variances and 95 per cent confidence limits.

The population estimates presented here must be considered tentative until such time as: (1) the function correcting for whales offshore as a result of the aerial transect results (h(k)) can be estimated more accurately; (2) night travel rates can be more accurately substantiated; and most importantly (3) the effects of variability of weather (visibility) conditions on census results can be quantified in some form. Research is in progress on all 3 areas.

These estimates are most likely below the actual values, since no correction has been made for poor visibility (which certainly has an effect on an observer's ability to accurately census passing whales) and because the approximation to h(k) used here is the most conservative reasonably possible at this time. Consequently, the highest estimate produced (16,511 for 1976/77) is probably the best estimate available at this time. Further, that year was a 'drought' year in California, with an exceptionally clear and stormless winter, during which weather variability would be expected to be low.

The very lowest estimate (9,637 in 1971/72) came from a year which reportedly was 'stormier than usual', and its low value could be due to this in part.

While no attempt has been made to fit a line through the estimates presented, there is some indication that the population has been increasing during the period from 1967 to 1978. When the data from 1979/80 are analyzed, this estimate (in addition to the quantification of visibility) should help to define any trends which have possibly occurred in population size.

ACKNOWLEDGEMENTS

The following individuals manned the counting stations: Stephen Treacy (1970/71; 1972/73–1978/79), Nancy Severinghaus (1972/73–1974/75; 1977/78), Richard Strawn (1969/70–1970/71), Geoffry Carroll (1978/79), Larry Dickson (1967/68), R. G. Fletcher (1971/72), Ken Fuhs (1976/77), James Houk (1969/70), Sally Marquis (1975/76), Jeffrey Rochin (1967/68), James Rote (1968/69), Cathy Short (1968/69), and Ella Zeman (1971/72). Paul Sund gave valuable logistic advice and assistance. Melvin Jasper piloted the aircraft. We also wish to thank Howard Braham of the National Marine Mammal Laboratory, and the many volunteers from Greenpeace, Hopkins Marine Station, Merrill College, and Moss Landing Marine Laboratories who assisted in the verification experiments.

REFERENCES

Adams, L. 1968. Census of the gray whale, 1966–67. *Norsk Hvalfangsttid.* 57(2): 40–3.

Cochran, W. G. 1973. *Sampling Techniques*. John Wiley and Sons.

Cummings, W. C., Thompson, P. O. and Cook, R. 1968. Underwater sounds of migrating gray whales, *Eschrichtius glaucus* (Cope). *J. Acoust. Soc. Am.* 44(5): 1278–81.

Darling, J. 1977. The Vancouver Island gray whales. *Waters* 2(1): 5–19.

Eberhardt, L. L. 1978. Transect methods for population studies. *J. Wildl. Manage.* 42(1): 1–31.

Eberhardt, L. L. 1968. A preliminary appraisal of line transects. *J. Wildl. Manage.* 32: 82–8.

Fraser, F. C. 1970. An early 17th century record of the California grey whale in Icelandic waters. *Invest. Cetacea* 2: 13–20.

Gilmore, R. M. 1960. A census of the California gray whale. *U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish.* 342, 30 pp.

Hatler, D. F., and Darling, J. D. 1974. Recent observations of the gray whale in British Columbia. *Can. Field-Nat.* 88: 449–59.

Henderson, D. A. 1972. *Men and Whales at Scammon's Lagoon.* Dawson's Book shop. Los Angeles, 313 pp.

Howell, A. B., and Huey, L. L. M. 1930. Food of the gray and other whales. *J. Mammal.* 11(3): 321–2.

Hubbs, C. L., and Hubbs, L. C. 1967. Gray whales censuses by airplane in Mexico. *Calif. Fish Game* 53(1): 23–7.

International Whaling Commission. 1977. United States – progress report on whale research – June 1976 to March 1977. *Rep. int. Whal. Comm* 28: 125–9.

Mitchell, E. D., and Mead, J. G. 1977. History of the gray whale in the Atlantic Ocean. *Proc. (Abstracts) Second Conf. Biol. Mar. Mamm.* p.11.

Mundy, P. 1979. A quantitative measure of migratory timing illustrated by application to the management of commercial salmon fishing. PhD dissertation, U. of Washington, College of Fisheries.

Nie, N. H., Hull, C. H., Jenkins J. G., Steinbrenner, K. and Bent, D. H. 1975. *Statistical Package for the Social Sciences*, 2nd edition. McGraw-Hill. 675 pp.

Ohsumi, S. 1976. Population assessment of the California gray whale. *Rep. int. Whal. Commn* (Sci. Rep.) 26: 250–9.

Ramsey, D. H. 1968. Diurnal fluctuations in censuses of migrating California gray whales. *Norsk Hvalfangsttid.* 5: 101–5.

Rice, D. W. 1965. Offshore southward migration of gray whales off southern California. *J. Mammal.* 46(3): 500–1.

Rice, D. W., and Wolman, A. A. 1971. The life history and ecology of the gray whale (*Eschrichtius robustus*). *Am. Soc. Mammal., Spec. Publ.* 3: 1–142.

Rugh, D. J., and Braham, H. W. 1979. California gray whale (*Eschrichtius robustus*) fall migration through Unimak Pass, Alaska, 1977. *Rep. int. Whal. Commn* 29: 315–20.

Scammon, C. M. 1874. *The Marine Mammals of the Northwestern Coast of North America.* John H. Carmany Co., San Francisco, 319 pp.

Seber, G. A. F. 1973. *The Estimation of Animal Abundance and Related Parameters.* Griffin, London, 506 pp.

Sund, P. and O'Connor, J. C. 1973. Aerial observations of gray whales during 1973. *Mar. Fish. Rev.* 36(4): 51–2.

Townsend, C. H. 1887. Present condition of the California whale fishery. *Bull. U. S. Fish. Comm.* 6: 340–50.

Walters, C. J., and Buckingham, S. 1975. A control system for intraseason salmon management. Intl. Inst. Appl. Syst. Analysis: Proc. Workshop on Salmon Manag., Feb 24–28, 1975.

Wolman, A. A., and Rice, D. W. 1979. Current status of the gray whale. *Rep. int. Whal. Commn* 29: 275–9.