Eastern North Pacific gray whale abundance in the winter of 2006-2007

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ABSTRACT

The southbound migration of the Eastern North Pacific stock of gray whales [*Eschrichtius robustus*] was documented by the National Marine Fisheries Service's Alaska Fisheries Science Center (AFSC) from 12 December 2006 to 22 February 2007. Research protocol was essentially identical to that used in previous surveys. This involved single observers independently searching for whales and recording data on environmental conditions and the time, location, count, and direction of travel for each sighting. The counting system and observer performance were tested through paired, independent observational effort. The timing of the 2006-2007 southbound migration seemed to be 1 week later than in previous years, with the median date close to 21 January instead of 15 January. Most (80%) of the sightings occurred in January, 17% were in February and only 3% were in December. Counts of gray whales pods during fair to excellent visibility conditions totalled 1,770 pods during the 73 days (651.6 hr) of the standard census. The estimated abundance for 2006-2007 was 20,110 (SE = 1,766), which is similar to abundance estimates made in 2000-2001 (19,448; SE = 1,882) and 2001-2002 (18,178; SE = 1,780). The unweighted rate of increase for the period 1967/68 – 2006/07 was 0.016 (SE = 0.0031), and the weighted rate (based on the variance of each abundance estimate) was 0.019 (SE = 0.0030).

INTRODUCTION

The National Marine Fisheries Service (NMFS) has conducted shore-based counts of the Eastern North Pacific stock of gray whales (*Eschrichtius robustus*) 22 years from 1967 to 2001 (Table 1) at Granite Canyon (or nearby at Yankee Point), 13 km south of Carmel, in central California. Convenient access to the Granite Canyon research station (owned by NOAA but operated by the State of California Department of Fish and Game) and the narrowness of the whales' migratory corridor in this area (Shelden and Laake 2002) permitted an efficient counting process at this site. All counts were conducted during the 2-month southbound migration rather than the protracted 3-month northbound migration (Pike 1962). The routine nature of these counts and the consistency in research protocol lend themselves to inter-annual trend analyses.

The primary objective of the study in 2006-2007 was to provide another in the series of abundance estimates such that trend analysis could be continued. These estimates may provide the first documentation of a stock of large whales approaching carrying capacity (Wade and DeMaster 1998). An additional incentive to conduct this season's study was to assess the abundance after 2 years (1999 and 2000) in which unusually high counts of dead gray whales had been reported (LeBoeuf *et al*. 2000, Gulland *et al*. 2005) and after two censuses (2000-2001 and 2001-2002) in which abundance estimates were well below the expected trajectory (Rugh *et al*. 2005).

METHODS

Field procedures

Systematic counts of gray whales were conducted from 12 December 2006 to 22 February 2007, covering virtually the entire southbound migration past the Granite Canyon research station (36°26'N 121°55'W). Observation sheds provided a writing platform with some protection from the elements, and they helped observers concentrate on the viewing area. Average eye height above sea level was 22.5 m. Although the field of view covered >150°, observers generally searched through an arc of only 40-50° near the standard azimuth, which is a line perpendicular to the coastline that intersects the survey site at 241° magnetic. Three 3-hour standard-watch shifts covered the 9 daylight hours from 0730 to 1630. Observers were rotated to keep a balance of effort in each of the three shifts Standard-watch procedures were the same as those used in previous surveys (Rugh *et al*. 1990, 1993).

In addition to the primary watch (generally at the 'South Shed'), a second, independent watch was conducted (at the 'North Shed') one to three times daily from 6 January to 1 February 2007. The field of view and altitude of the two sheds were nearly identical. This provided paired, independent sighting records, allowing for comparisons between observers and an estimation of the number of whales missed within the viewing area (Rugh *et al*. 1993).

During censuses in 1988, 1993, 1994, and 1996, aerial survey results indicated only 1.28% of the gray whale population traveled beyond the viewing range of shore-based observers, which is approximately 3 nautical miles (nm) offshore (Shelden and Laake 2002). Therefore, no correction, other than for probability of detection by distance, has been calculated for whales migrating seaward of the viewing area.

Analysis

Population abundance calculations from the observer counts follow the analytical procedures described in Hobbs *et al*. (2004). These methods account for: 1) whales that passed during periods when there was no observational effort (prior to and after the census season, at night, or when visibility was poor); 2) whales missed within the viewing range during on-effort periods; 3) differential sightability by observer, pod size, distance offshore, and various environmental conditions; 4) errors in pod-size estimation; 5) covariance within the corrections due to variable sightability by pod size; and 6) differential diel travel rates of whales. Although the methods used here are essentially the same as used in the past, the only significant change is a new correction factor for night travel rate (see below) based on a study conducted by Perryman *et al*. (1999). The recorded sighting time and location closest to the standard azimuth (usually within a few degrees of 241°) were converted to estimate the time and offshore distance at which each pod crossed this line. This was based on the assumption that southbound migrating gray whales travel at 6km/hr and maintain a course parallel to shore (c.f. Swartz *et al*. 1987). The time from the beginning to the end of the survey season was partitioned into effort periods (time between 0730 and 1630 with visibility 4 or better and an observer on effort) and non-effort periods. Each sighting was assigned to the effort or non-effort period into which it fell as a function of the calculated time it crossed the standard azimuth. Whale sightings were eliminated from the analysis if they crossed this line prior to the start of an effort period or if they had not crossed the line by the end of an effort period.

Corrections for whale pods missed within the viewing area during a systematic effort are estimated from the paired, independent observation records. These paired records provide capture-recapture data that were used to estimate the total number of pods passing the station while observations were underway. A scoring algorithm (established by Rugh *et al*. 1993) defined matches between records based on time, offshore distance, and pod size. Iterative logistic regression (Buckland *et al*. 1993) was used to identify significant covariates to the probability of detecting a pod and to estimate the detection probability associated with each recorded pod. Possible covariates were observation site (North or South shed), effort period (1, 2, or 3), day, observer, distance offshore, pod size, sea state (Beaufort scale), wind direction, and whales per hour averaged over each day. After establishing the matching record, all covariates were examined individually as binned categorical data. All covariates were then entered into the model, and a backward step-wise model selection was followed until no step decreased the Akaike Information Criterion (AIC). Once the best model with main effects was determined, interactions between each possible pair of the retained covariates were considered.

The logistic regression model was used to compare $\hat{p}_{ei}$, the detection probability of the i^{th} pod of size e passing during the effort periods of the survey. The total number of pods of size e passing during the effort periods of the survey, $\hat{M}_e$ and its variance were estimated as:

$$\hat{M}_e = \sum_{i=1}^{m_e} \frac{1}{\hat{p}_e}, \qquad Var\left(\hat{M}_e\right) = \sum_{i=1}^{m_e} \frac{1-\hat{p}_{ei}}{\hat{p}_{ei}^2} + D_\beta\left(\hat{M}_e\right)^T \hat{\Sigma}_\beta D_\beta\left(\hat{M}_e\right)$$

where m_e is the number of pods assigned size *e* sighted from the primary site,

$D_\beta\left(\hat{M}_e\right)$ is the vector of partial derivatives of $\hat{M}_e$ with respect to the vector of parameters β estimated in the logistic regression evaluated at $\hat{\beta}$, the vector of parameter estimates, and $\hat{\Sigma}_\beta$ is the estimated variance-covariance matrix of $\hat{\beta}$ (c.f. Borchers 1996).

The estimated total number of pods passing the field site while systematic efforts were underway, $\hat{M}$, is then

$$\hat{M} = \sum_{e=1}^{E} \hat{M}_e, \qquad Var\left(\hat{M}\right) = \sum_{e=1}^{E} Var\left(\hat{M}_e\right) + 2\sum_{j=1}^{E-1}\sum_{k=j+1}^{E} D_\beta\left(\hat{M}_j\right)^T \hat{\Sigma}_\beta D_\beta\left(\hat{M}_k\right)$$

where *E* is the largest observed pod size.

Bias in the recorded pod size resulting from under-estimation of pod size by observers is removed by an additive correction which has been estimated for each pod size, *e*, from data collected during earlier surveys (Laake *et al*. 1994), with the variances and covariances calculated in Hobbs *et al*. (2004).

The total number of whales (W_e) passing the observation site during effort periods represented by pods recorded as size *e*, was estimated as:

$$\hat{W}_e = \hat{M}_e\left(e + b_e\right) \qquad Var\left(\hat{W}_e\right) = Var\left(\hat{M}_e\right)\left(e + b_e\right)^2 + \hat{M}_e^2 \hat{\sigma}_{b_e}^2$$

where b_e is the estimated additive bias correction for pods estimated as size *e* from Laake *et al*. (1994), and $\hat{\sigma}^2_{b_e}$ is the bootstrap estimate of the variance of b_e.

The variance consists of two summands representing the estimation errors in $\hat{M}_e$ and b_e.
The total number of whales, *W*, passing the site during usable effort periods was estimated as:

$$\hat{W} = \sum_{e=1}^{E} \hat{W}_e,$$

$$CV\left(\hat{W}\right) = \frac{1}{\hat{W}} \sqrt{\sum_{e=1}^{E} Var\left(\hat{W}_e\right) + 2\sum_{j=1}^{E-1} \sum_{k=j+1}^{E} \left[\left(j+b_j\right) D_\beta\left(\hat{M}_j\right)^T \hat{\Sigma}_\beta\, D_\beta\left(\hat{M}_k\right)\left(k+b_k\right) + \hat{M}_j \hat{M}_k \hat{\sigma}_{b_{jk}}\right]}$$

where *E* is the maximum observed pod size, and $\hat{\sigma}_{b_{jk}}$ is the bootstrap estimated covariance of b_j and b_k.

Corrected pod sizes were summed by effort period with the sum rounded to the nearest integer so they could be used in the FORTRAN program *GWNORM* (Buckland 1992), which fits a normal distribution function to count data and adds polynomial terms to the model to improve the fit. In earlier gray whale analyses, estimated numbers of pods passing during each effort period were used with *GWNORM* to estimate the passage rate of pods; however, since 1997 and in the present analyses, the estimated number of whales passing during each effort period is used and the result is the passage rate of whales rather than pods. The rate of whales passing the site through time was modeled by a normal distribution with Hermite polynomials added to adjust for skewness, kurtosis, and higher moments (Buckland 1992, Buckland *et al*. 1993). The model defines a bell-shaped rate function, *q*(*t*), of expected whales per day that was integrated to correct for periods when no search effort was underway. The correction factor, f_t, was defined as the ratio of the area under *q*(*t*) integrated over the entire survey period, *Q*, to the area under *q*(*t*) integrated only over effort periods. Although the histograms used to portray the seasonal distribution of sighting rates averaged data through each day, the model used to interpolate the generalized distribution was based on each effort period down to a minimum effort period of 3 minutes. No corrections were applied for whales passing prior to or after the apparent start and end of the migrations based on the distribution of sighting rates for the respective season, and no correction was included for whales traveling beyond the viewing range of the shore-based observers because these factors appear to involve very few whales without satisfactorily quantifiable estimates.

The computer program *GWNORM* fitted Hermite polynomials to the estimated number of animals passing in each effort period and provided output for five nested polynomial models, starting with the normal distribution model and adding additional terms. The best-fitting model was chosen based on the AIC criterion:

$$\text{AIC} = -2\mathrm{L}\,(\hat{\theta}) + 2k,$$

where L is the log-likelihood, $\hat{\theta}$ are the maximum likelihood estimates of the Hermite polynomial parameters and *k* is the number of parameters estimated.

The night passage rate, f_n = 1.020 (SE = 0.023), used by Buckland *et al*. (1993), was based on data from three radio-tagged gray whales recorded by Swartz *et al*. (1987) during both day and night hours (hr) near Granite Canyon; they excluded data from six other whales that were followed either during the day or the night. To further study diurnal variations in gray whale travel rates, Perryman *et al*. (1999) recorded thermal imagery of whales at Granite Canyon while the census of the southbound migration was underway in January 1994, 1995, and 1996 (total sample size = 116 hr by day; 146 hr by night). As with the tagging results, the imagery showed elevated travel rates at night, or put more accurately, depressed rates during the day, perhaps related to increases in non-migratory behavior in daylight hours after the middle of the migration, on 15 January (Perryman *et al*. 1999)[1]. That is, prior to the middle of the migration, it appears that the day and night rates are the same. For calculations of abundance, we elected to use median sighting dates instead of 15 January, because the median date was thought to be more representative of the whales' behavior than a calendar date. Accordingly, we have applied a multiplicative

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[1] To confirm that there was a change in whale behavior midway through the migration, our primary observational effort was searched for milling whales and whales seen going north before 13 February 1998, 15 February 2001, and 18 February 2002, dates on which it appeared the northbound migration had started. Of 37 gray whales seen deviating from their migration south throughout the respective southbound migrations, 30 (81%) were after 15 January.

correction factor f_n^* = 1 + 0.28 (0.5) (15/24) = 1.0875 (Perryman *et al*. 1999)[2], where 0.5 is the fraction of total whales migrating after the median date and 15/24 is the fraction of night time hours in January with SE = 0.116 (0.5) (15/24) = 0.0363 and CV(f_n^*) = 0.0334.

The total number of whales passing through the viewing area at Granite Canyon during effort periods, *W*, was multiplied by corrections for whales passing when no search effort was in effect (including periods with poor visibility), f_t, and differences in diurnal/nocturnal travel rates, f_n^*. Accordingly, the total abundance estimate was calculated as:

$$\hat{N} = W \cdot f_t \cdot f_n^*$$

The coefficient of variation, *CV*, was estimated by:

$$CV\left(\hat{N}\right) = \sqrt{\frac{\chi^2/df}{W} + CV^2\left(f_t\right) + CV^2\left(f_n^*\right) + CV^2\left(W\right)}$$

where χ^2/df is a variance inflation factor from fitting a Hermite polynomial to the sighting rates.

The rate of increase from 1967 to 2007, based on an exponential model ($N_t = N_0 e^{rt}$), was estimated by GLM using a log link (family = quasi-poisson) and weights equal to $1/\operatorname{var}\left(\log\left(N\right)\right)$, where $\operatorname{var}\left(\log\left(N\right)\right) \approx cv^2\left(N\right)$. In addition, a discrete logistic model was fit to the abundance data (generalized logistic):

$$N_t = N_{t-1} + R_m N_{t-1}\left(1 - \left(N_{t-1}/K\right)^z\right) - C_{t-1}$$

Where N_t is the abundance at the start of time period *t*, R_m is the rate of increase, *K* is the carrying capacity, *z* is the density dependent exponent and C_{t-1} is the catch during time period *t*-1 (catches take place after the shore census).

To compare models using AIC the data must be on the same scale (the GLM model uses a log scale) so a nonlinear least squares fit to the data with an exponential rate of increase model $\left(N_t = N_0 e^{rt} + \varepsilon_t\right)$ was carried out. The small sample size version of AIC was used: AIC$_c$ = $n\log\left(\hat{\sigma}^2\right) + 2kn/\left(n-k-1\right)$, where $\hat{\sigma}^2$ = $\sum \hat{\varepsilon}_i^2/n$, *n* is the sample size and *k* is the number parameters estimated (including $\hat{\sigma}^2$).

RESULTS

Sample size

The 2006-2007 gray whale census was conducted for 73 days from 12 December 2006 to 22 February 2007 (Fig. 1), a period similar to previous years (Table 1). Observers in the primary (South) shed recorded 1,861 pods of gray whales, of which 1,770 were seen during excellent to fair conditions (visibilities 1-4). Watches were maintained for a total of 651.6 hr on the primary watch (542.3 hr in visibilities 1-4), 111.7 hr on the secondary watch (during paired, independent counting efforts, n = 758 pods), and 19.7 hr on the fixed, high-powered binoculars (n = 110 pods).

Visibility

Of the six subjective categories of visibility, little time was spent in the best (category 1: 2.0 hr) and worst (category 6: 9.3 hr) conditions, but intermediate categories 2-5 were well represented, with 80 to 240 hr each, respectively (Table 2).

Migratory timing

The 2006-2007 study included almost the entire southbound migration of gray whales because sighting rates were very low (<1/hr) for the first 16 days (until 27 December) and for the last 8 days (after 15 February) of the study (Fig. 1). Typical of most southbound migrations of gray whales observed from Granite Canyon, sighting rates rose

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[2] In Perryman *et al*. (1999), the standard error equation SE = 0.116 (14/24) should have been SE = 0.116 *f* (15/24), corrected here by including the *f* term, using 15 night hours instead of 14, and by including the fraction of the migration (0.5) that should be adjusted for night rates (J. Laake, National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, Seattle, Washington, 98115, USA. pers. commun.).

from late December until mid-January and then gradually declined until mid-February, approximating a normal distribution. However, the migration seemed to be later than usual in 2006-2007. The mean sighting date in 2006-2007 was 21 January (day 52, with day 1 = 1 December), approximately a week later than the expected mean date of 15 January (Rugh *et al*. 2001).

Abundance estimate

The uncorrected count (*m*) of southbound gray whale pods seen by observes during periods of adequate visibility (<5) during the primary effort was 1,770 for 2006/07 (Table 2). This count was multiplied by the corrected pod sizes to give the number of whales ($W = 6{,}207$). Pod sizes were corrected for bias in pod size determination as well as for missed pods (Table 3). Significant covariates to the probability of detecting a pod and to estimate the detection probability associated with each recorded pod were: observer, pods size, Beaufort number and pods per hour. Model selection was based on stepwise AIC (Akaike Information Criterion) by iterative logistic regression (Tables 4 and 5). The estimated number of whales seen during effort periods (raw count corrected for pod-size bias and missed-pod bias) was fit with the Hermite polynomial model (Fig. 3). The AIC statistics for each Hermite polynomial model are shown in Table 5. It is clear that model 5, with 6 parameters, is the best-fitting model with an Akaike weight of 70%. The abundance estimate was 20,110 (SE = 1,766, lognormal confidence interval 16,936 to 23,878) (Table 6).

Rate of Increase

The unweighted rate of increase (*r*) based on GLM was 0.016 (SE = 0.0031) and the weighted rate of increase (using the inverse of the variance of each abundance estimate) was 0.019 (SE = 0.0030) (Table 7). The fitted trajectories are shown in Fig. 2. Nonlinear least-squares parameter estimates for the discrete logistic model, with the density dependent exponent *z* fixed at 1 and for the case where z was estimated are given in Table 7. Note that the estimate of *z* is rather large (corresponding to relative MSYL = 0.86) and has very poor precision. The estimates of *K* are similar (23,686 and 22,325) but the estimates of R_m are quite different. A negative correlation exists between R_m and *z*, therefore combinations of high *z* and low R_m can produce trajectories similar to those for low *z* and high $R_{m.}$. The fitted generalized logistic trajectories (for $z = 1$ and $z = 20$) are shown in Fig. 3.

The AIC_c for the exponential model was 379.1 and for the generalized logistic ($z = 1$) 373.4, indicating that the logistic provides a better fit to the data. AIC_c for the case where *z* was estimated was 370.4 (Table 7).

DISCUSSION

The number of gray whale pods seen in 2006-2007 was similar to counts recorded in 2000-2001 and 2001-2002 but lower than in previous years (Table 1). There was a 2.6% per annum increase in abundance from 1967-1968 to 1997-1998 (Rugh *et al*. 2005), but then abundance dropped. Recorded rates of >270 dead gray whales seen in 1999 (LeBoeuf *et al*. 2000, Gulland *et al*. 2005) and >300 in 2000 (Gulland *et al*. 2005) were much higher than the average rates of 41/yr from 1995-1998 (Gulland *et al*. 2005), indicating there may have been a large die-off in this population.

It does not seem that observer experience, shifts in the migratory corridor, or visibility can adequately explain why abundance estimates have been lower since 1997-1998. However, we have not yet fully tested the theory that inconsistent proportions of the population migrate as far south as Granite Canyon. In most years, the timing of the gray whale migration has been phenomenally regular (Rugh *et al*. 2001). Unexpectedly low encounter rates occurred in 1992-1993, yet that season was followed by several seasons with much higher estimates (Table 1). One of the primary explanations for the low abundance estimate in 1992-1993 was that various proportions of the gray whale population remain north of Granite Canyon each year, and in 1992-1993 more whales than usual stayed north of this site (Laake *et al*. 1994). Perhaps in 2000-2001, 2001-2002 and 2006-2007, as in 1992-1993, many whales did not migrate as far south as Granite Canyon. However, the many dead whales seen in 1999 and 2000, and the consistency of abundance estimates since 2000 strongly suggest that the abundance did drop after 1997-1998 and has since stabilized again.

A slowing in the recorded rise in abundance from 1967-1968 to 1997-1998 has been anticipated (Reilly 1992, Wade 1997); but, until 2000-2001, there was only a suggestion of density-dependence beginning to occur (Wade and DeMaster 1998). If the most recent abundance estimates are representative, it could be the first indication this stock of whales has reached the carrying capacity of its environment. We may anticipate that abundance will fluctuate as this population approaches equilibrium and adjusts to environmental limitations.

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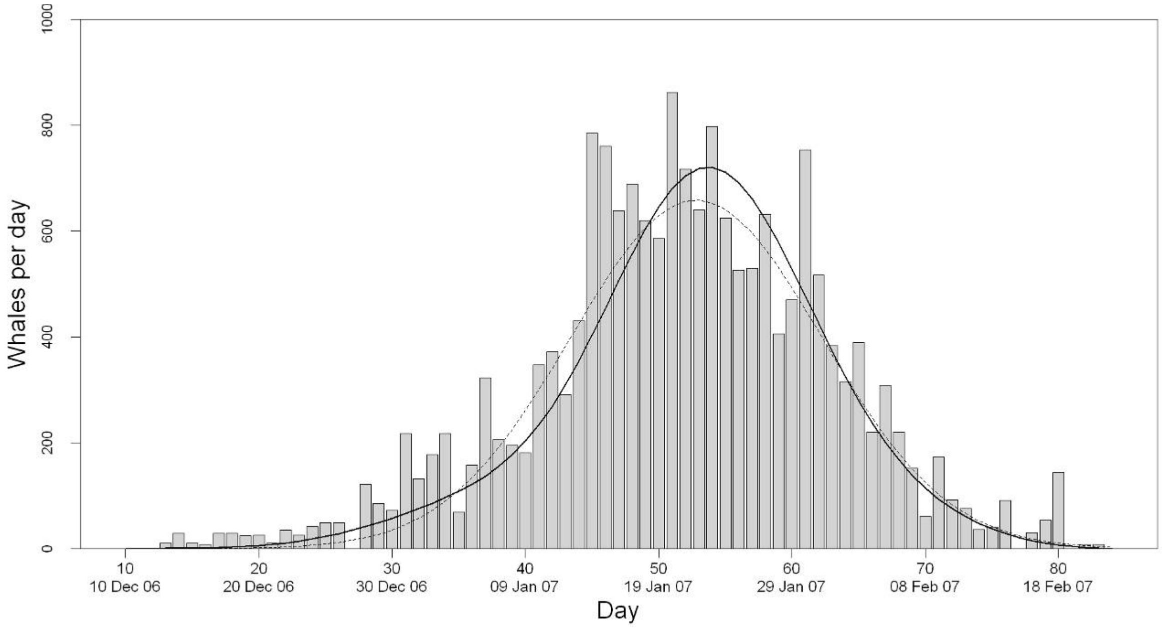

Figure 1. Histogram ow whales per day (corrected by pod size bias and missed pod size correction factors) with fitted Hermite polynomial curve (solid curve) and normal distribution (dashed line)

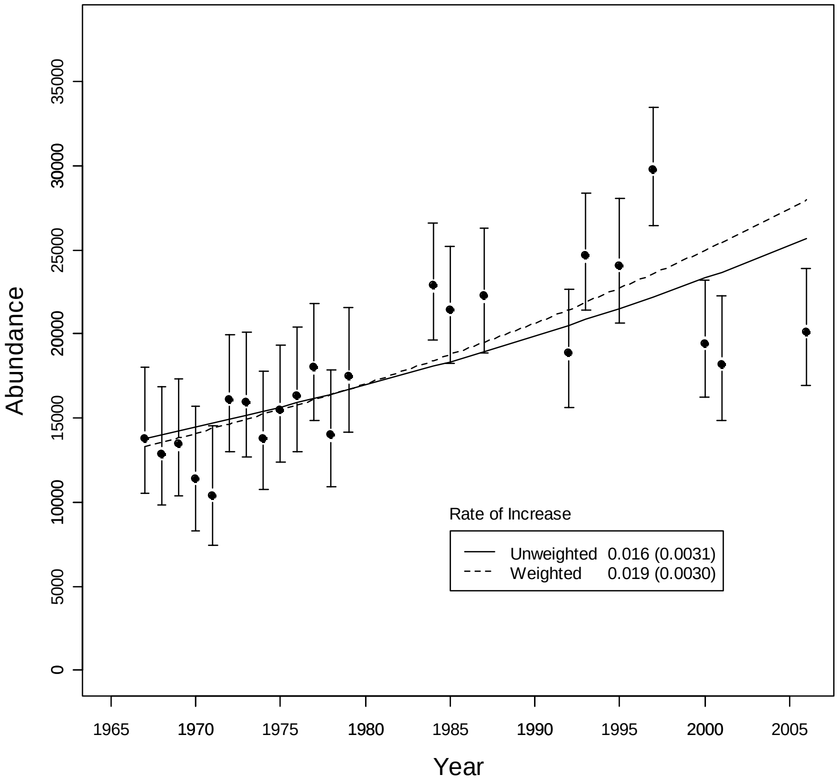

Figure 2. Gray whale abundance estimates and lognormal confidence intervals, 1967/68 – 2006/07, including weighted and unweighted rate of increase model fits.

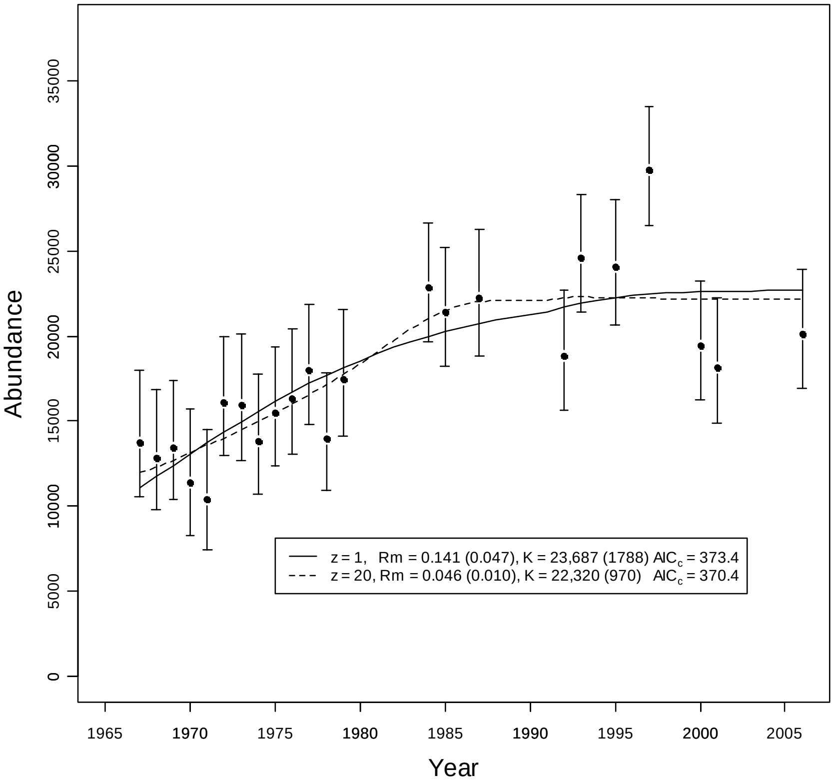

Figure 3. Gray whale abundance estimates and lognormal confidence intervals, 1967/68 – 2006/07, and discrete logistic model fits for z = 1 and z = 20.

Table 1. Duration of survey effort conducted by the National Marine Fisheries Service during counts of the southbound migration of gray whales at Granite Canyon, California. Uncorrected counts of whale pods (without hours of effort indicated) and the published abundance estimates are shown. Although abundance estimates presented here used the same method each year, standard errors since 1995 were adjusted to incorporate sources of variance not documented in previous years.

Start dates		End dates		Count	Abundance	SE	Source
1967	18 Dec	1968	3 Feb	903	13,776	1,082	1
1968	10 Dec	1969	6 Feb	1,079	12,869	708	1
1969	8 Dec	1970	8 Feb	1,245	13,431	758	1
1970	9 Dec	1971	12 Feb	1,458	11,416	590	1
1971	18 Dec	1972	7 Feb	857	10,406	614	1
1972	16 Dec	1973	16 Feb	1,539	16,098	834	1
1973	14 Dec	1974	8 Feb	1,496	15,960	872	1
1974	10 Dec	1975	7 Feb	1,508	13,812	781	1
1975	10 Dec	1976	3 Feb	1,187	15,481	930	1
1976	10 Dec	1977	6 Feb	1,991	16,317	818	1
1977	10 Dec	1978	5 Feb	657	17,996	1,249	1
1978	10 Dec	1979	8 Feb	1,730	13,971	753	1
1979	10 Dec	1980	6 Feb	1,451	17,447	984	1
1984	27 Dec	1985	31 Jan	1,756	22,862	1,379	1
1985	10 Dec	1986	7 Feb	1,796	21,444	1,120	1
1987	10 Dec	1988	7 Feb	2,404	22,250	1,115	1
1992	10 Dec	1993	7 Feb	1,180	18,844	1,190	2
1993	10 Dec	1994	18 Feb	1,864	24,638	1,475	2
1995	13 Dec	1996	23 Feb	2,151	24,065	1,393	3
1997	13 Dec	1998	24 Feb	2,853	29,758	3,122	4
2000	13 Dec	2001	5 Mar	1,684	19,448	1,882	4
2001	12 Dec	2002	5 Mar	1,712	18,178	1,780	4
2006	12 Dec	2007	22 Feb	1,770	20,110	1,766	5

Sources:

1 = Buckland and Breiwick (2002)
2 = Laake *et al*. (1994)
3 = Hobbs *et al*. (2004
4 = Rugh *et al*. (2005)
5 = Current document

Table 2. Rates of sightings of gray whale pods (encounter rates) as a function of visibility code.

Visibilities	Codes	Effort (hr)	Number of pods	Encounter rates	SE	Average pod size	SE pod size
Excellent	1	3.0	8	2.67	2.40	3.25	0.82
Very Good	2	80.2	397	4.95	0.54	2.13	0.08
Good	3	218.8	746	3.41	0.31	2.05	0.06
Fair	4	240.4	619	2.58	0.24	1.99	0.07
Poor	5	100.3	90	0.90	0.15	1.66	0.13
Useless	6	9.2	1	0.11	0.12	1.00	-
All Effort	1-6	651.8	1,861	2.86	0.16	2.03	0.04
Usable Effort	1-4	542.3	1,770	3.26	0.19	2.05	0.04

Table 3. Estimation of total number of whales passing during systematic observational periods (visibility <5) in 2006/07.

Pod size	Number of recorded pods	Average correction for missed pods	Bias-corrected pod size	$\hat{M}_e$	$\hat{W}_e$	$CV\left(\hat{W}_e\right)$
1	852	1.483	1.941	1,264	2,452.5	14.5
2	484	1.253	2.646	606	1,604.6	10.3
3	215	1.121	3.607	241	869.4	11.6
4	109	1.071	4.25	117	496.3	16.4
5	42	1.036	5.25	44	228.5	14.1
6	24	1.026	6.25	25	153.8	12.7
7	17	1.011	7.25	17	124.6	11.4
8	11	1.006	8.25	11	91.3	10.9
9	4	1.004	9.25	4	37.1	12.9
10	3	1.002	10.25	3	30.8	12.8
11	1	1.002	11.25	1	11.3	18.5
13	1	1.000	13.25	1	13.3	15.4
14	2	1.000	14.25	2	28.5	10.6
15	1	1.000	15	1	15.3	13.3
16	1	1.000	16.25	1	16.3	12.5
20	1	1.000	20.25	1	20.3	10.0
Total	1,768			2,339	6,194[1]	

[1] This number differs from that in Table 6 (6,207) due to rounding errors.

Table 4. Statistical model for GLM analysis of matched sighting data and stepwise Akaike Information Criterion (AIC) values.

Variables used in the starting model:

seen ~ stat + wat + obs + ps + beau + vis + pphr + dist + dist^2 + dist:obs + wdir.sin + wdir.sin^2 + beau:wdir.sin + beau:wdir.sin^2 + offset(off)

AIC = 739.89

Ending model:

seen ~ obs + ps + beau + pphr + offset(off)

AIC = 706.84

Variable	Definition
Stat	station
Wat	watch period
Obs	observer
Ps	pod size
Beau	Beaufort number
Vis	visibility code
Pphr	pods per hour
Dist	distance
dist:obs	observer interaction term (similarly for other x:y terms)

Coefficients	Results	z	Pr(>|z|)
(Intercept)	0.351	0.793	0.428
Obs A	18.883	0.013	0.989
Obs B	0.046	0.132	0.895
Obs C	18.852	0.107	0.986
Obs D	19.324	0.008	0.993
Obs E	18.728	0.017	0.986
Obs F	-0.681	-2.559	0.010*
Obs G	-0.478	-1.617	0.106
Obs H	-0.172	-0.428	0.669
Ps	0.641	5.364	8.2e-8 ***
Beau	-0.199	-2.844	0.004 **
Pphr	0.095	3.046	0.002 **

Codes for levels of statistical significance: 0 ***, 0.001 **, 0.01 *

Table 5. Akaike Information Criterion (AIC) statistics for the five Hermite polynomial models considered.

Model	Log likelihood	Number of parameters (k)	AIC	ΔAIC	Akaike weights
5	-2005.143	6	4022.29	0.00	0.696
3	-2008.330	4	4024.66	2.37	0.213
4	-2008.182	5	4026.36	4.07	0.091
2	-2030.463	3	4066.93	44.64	0
1	-2063.835	2	4131.67	109.38	0

Table 6. Estimated abundance and intermediate parameters for the Eastern North Pacific stock of gray whales counted at Granite Canyon, December 2006 – February 2007.

Parameter	Estimate	SE	CV (%)
Total number of pods recorded by primary observers during effort periods with visibility ≤4 (*m*):	1,768	–	–
Mean recorded pod size:	2.05	0.039	1.90
Corrected mean pod size:	2.79	0.034	1.22
Estimated number of whales passing during effort periods (*W*):	6,207	522	7.66
Correction for pods passing outside effort periods (f_t)	2.979257	0.0036	0.209
Estimated total number of whales without night travel correction (*Q*)	18,492	501	2.71
Correction for night travel (f_n)	1.0875	0.0363	3.34
Estimated number of whales passing Granite Canyon ($\hat{N}$):	20,110	1766	8.78
95% CI	(16,936, 23,878)	–	–

Table 7. Parameter estimates from fitting models to the time series of abundance estimates (standard errors are in parentheses).

Model	$\hat{N}_0$	$\hat{R}_m$	$\hat{r}$	$\hat{K}$	$\hat{z}$	AIC$_c$
GLM (unweighted)	13,780 (903)		0.016 (0.0031)	–	–	
GLM (weighted)	13,317 (738)		0.019 (0.0030)	–	–	
Exponential	14,107 (1,029)		0.015 (0.0032)	–	–	379.1
Generalized Logistic (fixed z = 1)	11,109 (1,478)	0.141 (0.047)		23,686 (1,788)	1	373.4
Generalized Logistic	11,981 (1,276)	0.046 (0.015)		22,326 (1,176)	19.64 (69.3)	370.4