APPENDIX I

Preliminary estimates of 2003-2004 Bering-Chukchi-Beaufort bowhead whale (*Balaena mysticetus*) abundance from photo-identification data

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ABSTRACT

Photographic surveys were conducted near Point Barrow during the spring migrations of the Bering-Chukchi-Beaufort Seas stock of bowhead whales in 2003 and 2004. The 2003 survey was the most complete photographic survey of the population conducted to date. Estimates of 2003-2004 bowhead abundance were computed from the photo-identification data using a closed population model and the modified Petersen estimate of Chapman (1951) for the number of naturally marked whales. This estimate was divided by estimates of the proportion of the bowhead population that is naturally marked to account for unmarked whales. If only the 2003 photographs are used to estimate the proportion marked, 2003-2004 bowhead abundance is estimated to be 11,836 with a CV of 0.29 and a 95% confidence interval from 6,795 to 20,618. The estimate of 11,836 is consistent with expectations based on the results of the ice-based count of bowheads in 2001. Further analyses which should lead to a more precise estimate of 2004 abundance are planned. Some of these depend on completing the matching of 2003-2005 photographs with photographs from earlier surveys. Completion of this matching is strongly recommended.

INTRODUCTION

Aerial photography projects conducted from 1981–2000 have provided much of the life history data that are available on the Bering-Chukchi-Beaufort (BCB) stock of the bowhead whale (Nerini *et al*., 1984; Koski *et al*., 1992, 1993, 2006; Miller *et al*., 1992; Rugh *et al*., 1992a; Zeh *et al*., 1993, 2002; Angliss *et al*., 1995; da-Silva *et al*., 2007). The last major photographic effort was conducted in 1992, although smaller scale photography projects were conducted during 1994 and 1998-2000. It was recognized that continuation of bowhead photography studies would provide information that would allow us to better define life history parameters of bowhead whales as has been done for other species of baleen whales such as right and humpback whales (Payne *et al*., 1990; Barlow and Clapham, 1997; Best *et al*., 2001; Cooke *et al*., 2001; Gabriele *et al*., 2007). Long gaps between surveys result in less precise estimates and difficulties in analysing data. Thus aerial photography studies were conducted near Point Barrow, Alaska, during the spring bowhead migration in 2003 and 2004 to continue collection of photographs that could be used for better definition of life-history parameters.

The earlier 1985 and 1986 photography projects also provided data that were used to make abundance estimates (da Silva *et al*., 2000; da-Silva, 2003; da-Silva *et al*., 2003; Schweder, 2003; da-Silva and Tiburcio, 2008) using closed population capture-recapture models. These estimates and their precision were similar to estimates from the ice-based censuses in 1985 and 1986 (da-Silva *et al*., 2000). The capture-recapture estimates were based on photographs of the midback zone of the whales of acceptable quality using the scoring system of Rugh *et al*. (1998). Zeh *et al*. (2000, 2002) developed a data screening method that allowed natural marks in all four zones (midback, rostrum, flukes and lower back) to be used without risking failure to recognize recaptures because different zones of the whale were visible in photographs taken on different sampling occasions. This screening method provides larger sample sizes of naturally marked whales and increased precision of estimates based on their photographs. It was used to estimate annual survival probability of bowheads by Zeh *et al.* (2002)

and da-Silva *et al.* (2007) using open population capture-recapture models; da-Silva *et al.* (2007) showed that accounting for heterogeneity in capture probabilities between moderately and highly marked whales improved precision of the survival estimate.

The 2003 data along with earlier data from the spring photographic surveys near Point Barrow were used by Schweder *et al.* (2007) to estimate abundances, population growth rate and mortality intensity. Their approach eliminated the need for data screening by modelling the probability of recognizing a recapture as a function of degree of marking of the whale and quality of the photographs.

Because of concerns that global warming and unstable shore-fast ice might prevent successful completion of future ice-based censuses, another important objective of the 2003 and 2004 aerial photographic surveys was to confirm that photographic data analyzed using capture-recapture methods can provide adequately precise abundance estimates to permit replacing ice-based with photographic surveys. The aerial photography approach to estimating abundance is less sensitive to vagaries in ice cover than is the ice-based survey but is sensitive to weather conditions suitable for conducting flights.

Capture-recapture analysis of the 2003–2004 photographic survey data provides a completely independent abundance estimate to compare to the best available estimate from visual counts and acoustic recordings made by ice-based observers near Point Barrow in 2001 (George *et al*., 2004; Zeh and Punt, 2005). Comparison of independent estimates permits an evaluation of the two survey methods. If the CV obtained from the photography data is "acceptable", the estimate may be used in the AWMP strike-limit algorithm (SLA) for giving management advice (IWC, 2003).

METHODS

The 2003–2004 aerial photographic studies were conducted jointly by LGL Limited (LGL), the North Slope Borough Department of Wildlife Management (NSB-DWM) and the National Marine Mammal Laboratory (NMML) with support from the Minerals Management Service (MMS). The field and laboratory methods were similar to those of earlier studies (Koski *et al*., 1992; Angliss *et al*., 1995) and are described in Koski *et al.* (2006).

Following the 2003 and 2004 field seasons, the film was developed, labelled, duplicated and stored in acid-free archive sheets for future analyses. The data documenting each photograph were entered into an Excel spreadsheet for future integration into the "Bowhead Whale Photography Database" described in Koski *et al*. (2006). Images obtained in 2003 and 2004 were digitized at 4000 dots per inch; most of the digitized images were cropped and printed to nearly fill 12.7cm × 17.8cm (5in. × 7in.) colour prints, which are suitable for comparing photographs to identify matches (Rugh *et al*., 1992b). All printed images were checked against the original film transparencies and the data files to ensure that all were scanned and printed.

Researchers at LGL and NMML have shared all tasks. NMML researchers have taken the lead on scoring images for photo quality and identifiability (as per Rugh *et al*., 1998). LGL researchers have taken the lead on within-year matching for 2003–2004 studies, assembling the database, and measuring whales. NMML researchers did within-year matching of images from 2004 for verification of the same effort at LGL. Researchers at both NMML and LGL provided final determination of within-year matches. LGL and NMML researchers independently identified between-year matches. After both groups completed their matching efforts, match results were compared and discussed and final match determinations made.

Photographs were screened using the method of Zeh *et al.* (2000, 2002) to determine whether they were of acceptable quality for use in capture-recapture analyses and, if so, whether they were of naturally marked or unmarked whales. Quality is scored as 1+ (best), 1-, 2+, 2- or 3 (worst) in each of four zones on the whale's body: midback, rostrum, flukes and lower back. If a zone is scored as 3, it is not acceptable for use in defining the whale as marked or unmarked for capture-recapture analyses. Identifiability in each zone is scored as H+ (highly marked), H-, M+ or M- (moderately marked); U+, U- or U (unmarked); or X meaning the zone is not depicted clearly enough in the photo to determine mark status. Scores of X almost always correspond to quality 3. In defining the whale (as opposed to the zone) as marked, whales marked in the midback zone are first defined as marked. Then whales with at least one quality 2+ midback photo that were never scored as marked in the midback zone are defined as marked if they are marked on the rostrum. Whales are added to the list of marked whales similarly if they are marked on the flukes or lower back and unmarked in the zones already considered. Photographs of acceptable quality of whales not on the list of of marked whales are considered to be of unmarked whales.

This screening method leads to heterogeneity in capture probabilities that should be accounted for in analyses, but we have not yet completed such analyses. Our approach was to begin with simple analyses using two-sample closed population models that could produce independent estimates of 1985-1986 abundance and

2003-2004 abundance. Both could be compared to ice-based census estimates and the estimates of Schweder *et al.* (2007). The 1985-1986 estimate could also be compared to the estimates of da Silva *et al.* (2000), da-Silva (2003), da-Silva *et al.* (2003), Schweder (2003), and da-Silva and Tiburcio (2008). We describe our methods using 2003-2004 as an example.

An estimate N of 2003-2004 bowhead abundance can be computed from photo-identification data using the modified Petersen estimate N^m of Chapman (1951) for the number of naturally marked whales and accounting for unmarked whales by dividing by an estimate p^* of the proportion of the bowhead population that is naturally marked. This abundance estimate is

$$N = N^m / p^*. \tag{1}$$

See p. 72 of Seber (1982) or equation (1) of da Silva *et al.* (2000). A rough estimate of the variance of N can be derived using the delta method if N^m and p^* are statistically independent (Seber, 1982). It can be written as

$$V(N) = N^2\,[V(N^m) / (N^m)^2 + (1-p^*) / (np^*)] \tag{2}$$

where n is the number of photographs on which p^* is based. See equation (2) of da Silva *et al.* (2000). This is only a rough estimate because the assumption that binomial sampling was used to obtain p^* does not hold, and N^m and p^* are not statistically independent if some of the same photographs are used in computing both N^m and p^*. Nevertheless, equation (1) provides an estimate of bowhead abundance, and the square root of the right-hand side of equation (2) provides a preliminary estimate of its standard error (SE). Calves are not included in computing either N^m or p^*, so N is an estimate of the size of the 1+ population.

The estimate N^m is

$$N^m = (n_1 + 1)\,(n_2 + 1) / (m_2 + 1) - 1 \tag{3}$$

where n_1 is the number of naturally marked whales photographed in 2003, n_2 the number photographed in 2004 and m_2 the number photographed in both years. The variance $V(N^m)$ of N^m is estimated by v^*, p. 60 of Seber (1982):

$$v^* = [(n_1 + 1)\,(n_2 + 1)\,(n_1 - m_2)\,(n_2 - m_2)] / [(m_2 + 1)^2\,(m_2 + 2)]\ . \tag{4}$$

Equations (3) and (4) assume that the population of naturally marked bowheads is closed, i.e. the effects of emigration, immigration, mortality and recruitment on the size of the marked population are negligible so that this size can be assumed to be constant over the period during which the data are collected. This bowhead population has a high survival rate (Zeh *et al*., 2002), a modest annual rate of increase (George *et al*., 2004; Zeh and Punt, 2005), a consistent migration pattern that brings it past Point Barrow and into the Beaufort Sea each spring which makes it easy to photograph (Braham *et al*., 1984; Moore and Reeves, 1993) and stable natural markings that permit the whales to be identified over periods of many years (Koski *et al*., 1992; Rugh *et al*., 1992a,b, 2007). Thus the closed population assumption when a two-year period is considered seems reasonable and has been shown via simulation by da Silva *et al.* (2000) not to lead to biased estimates.

The estimate p^* is based on all photographs with adequate quality for capture-recapture analyses in at least one of the four zones except those with the midback scored as X. The data screening procedure of Zeh *et al.* (2000, 2002) that we use results in the majority of marked whales being marked on their midbacks, and to qualify for the list of marked whales on the basis of marks in another zone, they must be unmarked on their midbacks. Therefore photographs scored X in the midback zone do not contribute in any way to defining whales as marked or unmarked After the restriction to the photographs just described, each photograph is given a weight. That weight is 1.0 for the vast majority of the photographs. However, following Koski *et al.* (2006), photographs of cows accompanied by calves are given a weight of 0.407 because of increased effort to photograph cow-calf pairs and the greater amount of time spent at the surface by calves. Cows and yearlings travelling together are given weight 0.685 because, like cows with calves, increased effort is made to photograph them. Then p^* is given by

$$p^* = (\text{sum of weights of photographs of marked whales}) / (\text{sum of weights of all photographs})\ . \tag{5}$$

Aerial photographic studies of bowheads were conducted in 1981-87, 1989-92, 1994, 1998-2000 and 2005 as well as 2003 and 2004. Use of data from these studies for computing p^* is considered below.

The method of Buckland (1992) is used to compute a 95% confidence interval (CI) for either N^m or N. For example, a 95% CI for N is

$$(N / C,\ N\times C)\text{ , where } C = \exp\,[1.96 \times \sqrt{\log_e(1+ V(N) / N^2)}]\ . \tag{6}$$

RESULTS and DISCUSSION

The method of data screening used in Zeh *et al*. (2000, 2002) for estimating survival rate from bowhead photo-identification data was used to identify naturally marked whales. It produced a sample with n_1 = 150 marked whales in 2003 and n_2 = 210 in 2004, with m_2 = 9 whales captured in both years. Equation (3) gives N^m = 3,185 and equation (4) its SE = 906, the square root of v^*. Because there were summer as well as spring surveys in 1985 and 1986, there were n_1 = 253 marked whales in 1985 and n_2 = 162 in 1986, with m_2 = 19 of the 1985 whales recaptured in 1986, leading to more precise estimates of N^m and N, as shown in Table 1.

Table 1 presents two different estimates N for total 2003-2004 1+ bowhead abundance, corresponding to two different choices of the years to use for computing p^*. Neither of these includes 2005 because, unlike any of the earlier surveys, the 2005 survey was designed to photograph well marked whales in the Bering Sea in early spring and near Barrow in early fall to determine whether these same whales had been photographed in other years during spring migration past Point Barrow or during summer in the Beaufort Sea. Since marked whales were targeted and unmarked whales avoided in 2005, the 2005 data are not suitable for estimating the proportion of the population that is marked.

Table 1. Estimated abundances N^m of the marked population and N of the total 1+ population and their precision for 1985 – 1986 and 2003 – 2004. The estimate p^* of the proportion of the population that is naturally marked and the years and number of images on which it is based are also shown.

	N^m	SE (N^m)	p^* years	n	p^*	N	SE (N)	CV (N)	95% CI
1985 – 1986	2,069	406	1981 – 1987	4,083	0.2916	7,095	1,403	0.1977	4,833 – 10,415
2003 – 2004	3,185	906	1989 – 2004	4,887	0.3303	9,643	2,750	0.2852	5,574 – 16,681
2003 – 2004	3,185	906	2003 only	1,052	0.2691	11,836	3,420	0.2889	6,795 – 20,618

The choice of years for the first 2003-2004 estimate in Table 1 was based on dividing the number of 1981-2004 photos considered in our analyses roughly in half and using the first half for 1985-1986 and the second half for 2003-2004. The division is a rough one to avoid using images from the same year in both estimates. It resulted in using 1981-87 data to compute p^* for the 1985-1986 estimate and 1989-2004 data for the 2003-2004 estimate; there was no photographic survey in 1988. Since no data are used in computing both the 1985-1986 and the 2003-2004 values of N, these estimates are independent of one another. In addition, splitting the data in this manner allows for some change in the proportion of naturally marked whales over time. Another advantage of this approach is that there is less dependency between N^m and p^* than there would be if only years for which abundance is being estimated were included. Finally, using multiple years may average out biases in the proportion of marked whales photographed in particular years and provides a larger sample of photographs, leading to better accuracy and precision of the estimates N.

In Table 2, we show the number of marked whales by year for all the survey years with photographs usable for estimating p^* except 2000, which had no marked whales. The captures by year in the first row make clear that the only years with large enough samples for capture-recapture analyses are 1985-1986 and 2003-2004. The cumulative captures in the second row show that roughly half the captures of marked whales occurred before, and half after, 1988. This is consistent with the split of photographs used for obtaining independent estimates p^* for the 1985-1986 and 2003-2004 estimates in Table 1.

Table 2. Number of naturally-marked whales captured by year (first row) and cumulatively (second row).

1981	1982	1983	1984	1985	1986	1987	1989	1990	1991	1992	1994	1998	1999	2003	2004
22	64	5	63	253	162	24	88	60	69	61	16	18	23	150	210
22	86	91	154	407	569	593	681	741	810	871	887	905	928	1078	1288

The second 2003-2004 abundance estimate in Table 1 uses only 2003 data for computing p^*. The advantage of using 2003 only is that it constitutes the most complete photographic survey of the population conducted to date (Koski *et al*., 2007) and should therefore be representative in terms of the proportion of the population that was naturally marked during 2003-2004. The same could be said about using 2003 and 2004 except that there was poorer coverage in late 2004 than in late 2003 (Koski *et al*., 2007), so the 2004 data could be less representative. The disadvantages of restricting the photographs to the years for which N is being computed are that dependency between N^m and p^* is exacerbated and the smaller sample size reduces the precision of p^*, although comparison of the CVs of the 2003-2004 estimates in Table 1 suggests that the loss of precision is not too great. The 1985-1986 row of Table 1 has a p^* value between those of the 2003-2004 rows, so there is no indication that the proportion of the population that is naturally marked has changed over the period from 1981 through 2004.

The values of N and their CI shown in Table 1 are consistent with our expectations concerning bowhead abundance based on completely independent ice-based census data (George *et al*., 2004; Zeh and Punt, 2005). George *et al.* (2004) estimated 2001 population size as 10,470 with CV = 0.13 and 95% CI 8,100 to 13,500. They estimated the annual rate of increase for the population as 3.4% (95% CI 1.7% to 5%). The estimates of Zeh and Punt (2005) are 10,545 (CV = 0.13) for 2001; 5,762 (CV = 0.25) for 1985 and 8,917 (CV = 0.22) for 1986. The 1985-1986 value of N in Table 1 lies between the 1985 and 1986 abundance estimates of Zeh and Punt (2005) and is more precise than either of them.

Turning from ice-based census estimates to other photographic data analyses, Schweder *et al.* (2007) estimated 1984 abundance as 6,868; 2001 abundance as 10,450 and annual rate of increase as 2.7% with a rough 95% CI from the likelihood profile that was contained within the CI of George *et al.* (2004). The estimates of 1985-1986 abundance given by da Silva *et al.* (2000) range from 4,719 to 7,331. Estimates in Schweder (2003) and in the other papers authored or coauthored by da-Silva are also in that range, as is our Table 1 1985-1986 N. Our 1985-1986 N also lies between the 1984 and 2001 abundance estimates given by Schweder *et al.* (2007).

Our main interest is in 2003-2004 abundance. The studies cited above that estimated 2001 abundance agreed that it was approximately 10,500, and the ice-based census estimates are very precise. If we project this value forward to 2004 using the estimated rate of increase from George *et al.* (2004) and its 95% confidence limits, the resulting estimated abundance in 2004 is 11,600 (11,000 to 12,200). Both 95% CI for 2003-2004 abundance in Table 1 contain the interval 11,000 to 12,200. The 2004 abundance estimate of 11,600 derived from the ice-based census data is well within a standard error of each of the 2003-2004 values of N in Table 1.

Both Table 1 values of CV(N) for 2003-2004 are approximately 0.29, larger than the CVs of the ice-based census estimates cited above, primarily because there were only nine recaptures in 2004. CV(N) for 1985-1986 in Table 1 is less than the corresponding CVs from Zeh and Punt (2005), primarily because summer photographic surveys in the Beaufort Sea in those years increased the number of captures and recaptures. The 2003-2004 results suggest that if only spring surveys are done, the photographic effort must be larger than in 2003 and 2004 to obtain precise estimates. This is feasible with a modest increment to the survey cost by increasing the survey effort during periods when large numbers of bowheads are passing Barrow. Alternatively, photographic surveys in summer and/or during fall migration would need to be added to the spring surveys.

Several steps can be taken to obtain a more precise estimate of 2004 abundance without further surveys:

1) Account for heterogeneity in capture probabilities among whales as a function of such potential predictors as best identifiability score in any zone, best quality score for zone with marks, number of zones with marks and maximum number of photos of a whale per sampling occasion. The results of da-Silva *et al.* (2007) suggest that this will improve the precision of N.

2) Compute N^m using appropriate open or closed population models including 2005 data. This will increase the number of captures and recaptures and thus improve the precision of N.

3) At present, the photographs from 2003-2005 have all been examined for photographic recaptures in 2004 and 2005, but not for matches that represent recaptures in 2003-2005 of whales first photographed in 1981-2000. When the matching effort is complete, there should be many more recaptures in 2003-2005. Then abundance for any year of interest can be estimated using an open population model (e.g., Schweder *et al.*, 2007). Completion of the matching should therefore be given high priority.

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