A calf index for monitoring reproductive success in the Bering-Chukchi-Beaufort Seas bowhead whale (*Balaena mysticetus*) population

W.R. Koski*, J. Zeh+ and J.C. George #

Contact e-mail: bkoski@lgl.com

ABSTRACT

The percentage of calves in a whale population can provide information on whether a population is increasing, stable or decreasing and is an input to population models. In this paper a method for estimating the percentage of calves in the Bering-Chukchi-Beaufort Seas (B-C-B) bowhead whale population in any given year by obtaining information on the percentage of calves passing Point Barrow, Alaska, during the last three weeks of the spring migration is presented. The method incorporates information on the timing of the migration with the percentage of calves detected during calf index surveys conducted during weekly periods from 14 May to early June. Historic data provide the different proportions of the migration during the weekly periods during low, medium and high calf years. The index is adjusted to allow for calves passing before 14 May and calves that are born after their mothers pass Point Barrow. The calf index was calculated for eight years using data from aerial photographic surveys near Point Barrow from 1985 to 2004 and the mean percentage of calves in the sampled years was 6.1%. Power analyses indicate that nine years of calf index data are required following a decline to detect a 60% reduction in the calf index. Additional calf index surveys prior to a decline would increase the power to detect a decline. This method can provide a robust estimate of the percentage of calves in the population each year with a modest aerial survey or photographic effort at Point Barrow. The data would be valuable in evaluating whether calving rates are within the range tested for the purpose of reviewing the B-C-B bowhead whale *Strike Limit Algorithm*.

KEYWORDS: ARCTIC; BEAUFORT SEA; CHUKCHI SEA; BOWHEAD WHALE; CALVES; PHOTOGRAMMETRY; POPULATION PARAMETERS; REPRODUCTION; SURVEY-AERIAL; NORTHERN HEMISPHERE; BIRTH RATE

INTRODUCTION

The Bering-Chukchi-Beaufort (B-C-B) population of bowhead whales (*Balaena mysticetus*) has increased at a rate of 3.4% per annum (95% CI=1.7-5.0%) from 1978 to 2001 (George *et al*., 2004b; Zeh and Punt, 2005) despite a subsistence harvest conducted under a quota administered by the International Whaling Commission (IWC). Under the current management agreement a new population estimate is obtained at least every 10 years to confirm population trends, but because the confidence intervals around these estimates are broad, changes in population trends cannot be confirmed by a single estimate. Therefore, a cost effective technique is needed to gauge the health of the population across shorter time intervals. This could be done by monitoring calving success through a complete calving cycle, which is thought to be 3-4 years (George *et al*., 2004a; Koski *et al*., 1993). Such data would also be valuable to evaluate whether calving rates were within the range tested for the purposes of reviewing the bowhead whale *Strike Limit Algorithm* (*SLA*) and would provide data for evaluating the effect of environmental variability on calving rates. The latter has been identified by IWC (2009) as an important input to future stochastic operating models for evaluating effects of harvests on stocks such as the B-C-B bowhead whale.

Changes in sea ice cover have been found to impact marine mammals in different ways. Species that avoid ice, such as gray whales (*Eschrichtius robustus*), have lower calf production and are in poorer condition during years when ice lingers late into the summer feeding season (Perryman *et al*., 2002; Perryman and Lynn, 2002). Species that rely on ice as a feeding or resting habitat, such as walruses (*Odobenus romarus*) and polar bears (*Ursus maritimus*), have reduced reproductive success when ice cover is reduced (Cooper *et al*., 2006; Stirling *et al*., 1999; Stirling and Parkinson, 2006). Concerns that reductions in ice cover in the Arctic might affect bowhead whale reproductive success because of their strong affiliation with sea ice and that increased oil and gas exploration activity might impact the population further motivate development of a more frequent and economical measure of reproductive success for this population.

Aerial photogrammetry studies of bowhead whales have been conducted near Point Barrow, Alaska, during their spring migration from the Bering Sea toward summer feeding areas in the Beaufort Sea and Amundsen Gulf. Data from these studies have been used to document the length-frequency distribution of the population and hence the percentage of calves in the population (Koski *et al*., 2006). The migration past Point Barrow is size structured (Angliss *et al*., 1995; Koski *et al*., 2006; Withrow and Angliss, 1992; 1994). Few calves are seen before mid-May, so annual recruitment can be estimated by monitoring the numbers of calves migrating past Point Barrow from mid-May to early June, the latter part of the spring bowhead whale migration. Note that the gray whale spring migration off California is also monitored for calves only during the latter half (Perryman *et al*., 2004).

In this paper a method of monitoring the reproductive success of B-C-B bowhead whales is described. Mothers and calves passing Point Barrow during the mid-May to

---

* *LGL Limited, environmental research associates, 22 Fisher St., PO Box 280, King City, Ontario L7B 1A6, Canada.*
+ *University of Washington, Statistics, Box 354322, Seattle WA 98195-4322, USA.*
# *Department of Wildlife Management, North Slope Borough, Box 69, Barrow, AK 99723, USA.*

early June period were counted or photographed and these data integrated with historic data on the proportion of the migration passing during weekly periods, with the weekly proportions varying among low, medium and high calf years. This permits an estimate of the percentage of calves in any given year without sampling the entire migration if calves born later in the season than surveys are conducted or after their mothers pass Point Barrow are accounted for (Koski *et al.*, 2004; 2006). If the data that are collected include information on whale lengths obtained from photogrammetry, the size structure of the sampled whales permits evaluation of whether the season is a typical or unusual season with respect to the timing of the migration.

METHODS

Aerial photogrammetry surveys

Aerial photogrammetry surveys were flown near Point Barrow, Alaska, in each of 1985-87, 1989-92, 1994 and 2003-04 by the National Marine Mammal Lab (NMML), Alaska Fisheries Science Center, NOAA Fisheries Service and/or LGL Limited. All of these years except 1987 and 1994 covered the latter part of the spring migration well. The methods employed build on the approach used by Koski *et al.* (2006) to estimate the length-frequency distribution of B-C-B bowhead whales by combining information on the proportion of the population passing during weekly periods with the length structure of the population during those same periods. This approach minimised biases caused by low sampling rates during some weekly periods. The calf index is an extension of this approach and does not require sampling during the first four weekly periods because no or few calves pass Point Barrow before 14 May (fig. 3 of Koski *et al.*, 2006).

The weekly proportions of the migration passing Point Barrow late in the season vary among low, medium and high calf years with a higher proportion of the migration passing later in the season during years when higher numbers of calves are present. Although the mean weekly proportions used by Koski *et al.* (2006) were appropriate when averaging several years of data, year-specific proportions are necessary to compute an unbiased calf index for a specific year. Visual, acoustic and aerial survey data from the ice-based surveys of bowhead whales in 1985, 1986, 1988, 1993 and 2001 (George *et al.*, 2004b; Zeh and Punt, 2005) were analysed to estimate the proportion of the migration that passed Point Barrow during the periods 14-20 May, 21-27 May and >27 May. These were the years when ice-based effort supplemented by aerial surveys spanned the entire migration. Based on earlier studies, 1986 and 2001 were categorised as high calf years (Angliss *et al.*, 1995; George *et al.*, 2004b) and 1985 and 1988 as low calf years (Angliss *et al.*, 1995; George *et al.*, 1995). Based on number of calves seen as a percentage of number of whales seen by the ice-based survey (George *et al.*, 1995; 2004b) it is likely that 1993 was a medium calf year. The low survey proportions after 13 May in 1993 compared to those in the high calf years 1986 and 2001 (Table 1) also suggest that 1993 was not a high calf year.

Calculation of calf index

The calf index is calculated by multiplying the proportion of the migration estimated to pass Point Barrow during a weekly period by the percentage of calves detected during that same period and then summing the resulting products for the last three weekly periods of the season (i.e. 14-20 May, 21-27 May and >27 May). The percentage of the calves during each period can be obtained either from aerial surveys or from photogrammetry studies. If aerial surveys are used, each whale sighted should be circled to confirm whether or not it has a calf. Calves can be very difficult to detect during aerial surveys because they are small and frequently travel below their mothers (Davis *et al.*, 1983).

Koski *et al.* (2004; 2006) noted that the spring photography data are positively biased towards larger numbers of mother-calf pairs than other whales for two reasons. First, calves which are recently born in the spring, have much shorter dive times than non-calves and so the calves (and hence their mothers) are approximately 1.69× (SE=0.14) more likely to be detected than non-calves (Koski *et al.*, 2004). Thus, when calculating the percentage of calves during each weekly period from survey data, the weekly counts of mothers and calves should be divided by 1.69. Second, researchers conducting photographic studies made extra effort to photograph mothers and calves (including mothers accompanied by yearlings), resulting in 1.46× (SE=0.17) more photographs of mothers and calves than of other whales (Koski *et al.*, 2006). Thus, when photographs provide the data for calculating the calf index, as in this paper, the number of images of mothers and calves seen together in each week needs to be divided by 1.69 × 1.46=2.47. The 1.46 factor also needs to be applied to mother-yearling pairs in spring to avoid giving them too much weight when estimating the percentage of calves because extra effort was also made to photograph mother-yearling pairs. However, the dive times of yearling bowheads whales are much longer than spring-born calves and so the 1.69 correction factor is not applied to mother-yearling pairs.

To accomplish these corrections, each image of a whale was given a weight. The single image of an unaccompanied calf identified by a post-survey length measurement was given a weight of 1/1.69. All other images of calves were given weights of 1/2.47, as were the images of their mothers. Images of a mother-yearling pair were given a weight of 1/1.46. All other images had weights of 1. Thus, summing the weights of the images of calves and of other whales during a given week of a given year and computing the percentage of calves as

$$100 \times (\text{sum of calf weights}) / (\text{sum of calf weights + sum of other whale weights})$$

is equivalent to counting the images requiring each correction factor, dividing by the correction factor and computing the percentage of calves from the corrected counts.

Compared to previous estimates based on aerial and ice-based surveys and photogrammetry studies, a relatively accurate and fully-corrected estimate of the percentage of calves in the population can be obtained by applying corrections for calves that pass before 14 May or are born after their mothers pass Point Barrow to the raw calf index described above. No calves were seen before 14 May during photogrammetry studies in years with low calf production (1985 and 1992, raw calf index <2%). Thus no correction for calves that passed before 14 May was made for low-calf years. During years with medium (2-5%) or high (>5%) calf production (1986, 1989-91 and 2003-4), an augmented calf index including a weekly period covering calves seen before 14 May was computed. The mean (augmented calf index)/(raw calf index) over these years is 1.046 (SD=0.054). Koski *et al.* (1993) compared the length-frequency distribution of mothers photographed at Point Barrow in spring with that of mothers in the summering

Table 1

The proportion of the migration estimated to pass Point Barrow, Alaska, during each weekly period as estimated from ice-based survey data from 1986, 1988, 1993 and 2001. Calf production was high in 1986 and 2001, relatively low in 1988 and 1993.

Years	<23 Apr.	23-29 Apr.	30 Apr.-6 May	7-13 May	14-20 May	21-27 May	>27 May
1986	0.0065	0.1110	0.1536	0.3144	0.2386	0.1025	0.0734
1988	0.0850	0.1554	0.2186	0.4030	0.0829	0.0104	0.0448
1993	0.0302	0.1701	0.2378	0.3417	0.1135	0.0719	0.0350
2001	0.0757	0.1275	0.2593	0.2192	0.1501	0.0821	0.0861
Mean proportions:							
All years	0.0494	0.1410	0.2173	0.3196	0.1463	0.0667	0.0598
High calf years	0.0411	0.1193	0.2065	0.2668	0.1944	0.0923	0.0798
Low calf years	0.0576	0.1628	0.2282	0.3724	0.0982	0.0412	0.0399

areas. They found that smaller mothers tended to have their calves later in the season, and most appeared to have calved after they had passed Point Barrow. Based on those data, they estimated that ~11% of bowhead whale calves were born after their mothers passed Point Barrow. Thus the fully-corrected estimate of percentage of calves is (raw calf index)/0.89 in low-calf years and 1.046 × (raw calf index) /0.89 in medium- and high-calf years.

Standard errors

Standard errors were obtained by bootstrapping with 100 bootstrap replications. The standard deviation (SD) of the 100 bootstrapped values provides the SE for the estimated correction factor or raw calf index value.

The dataset from which the 1.46 factor was computed included the number of photographs for each of 75 mother-calf pairs and 1,656 other whales. For each of 100 replications, a bootstrap sample of the mother-calf pairs and a bootstrap sample of the other whales was drawn and the bootstrapped value computed as

(mean photos per mother-calf pair) / (mean photos per other whale).

The SE for the 1.69 factor was computed similarly from a dataset with paired data on dive time and time at the surface following the dive for 248 dives made by 13 calves and 302 dives made by 77 other bowhead whales during spring migration near Point Barrow. In this case, bootstrapping was done on whales rather than dives since diving and surface times for the same whale are likely to be correlated; all the paired data for each whale in each calf and other bootstrap sample were included in the computations.

The variability of the 1.46 and 1.69 factors was incorporated in the SE of the raw calf index for a given year by computing bootstrapped values $B_{1.46}$ and $B_{1.69}$ for each of the 100 bootstrap replications. Within each bootstrap replication, images for each week were sampled separately and their weights computed using $B_{1.46}$ and $B_{1.69}$. The bootstrapped value of the raw calf index was then computed as described in the previous section.

No data are available for computing the SE of the 0.89 correction factor used in correcting the raw calf index to obtain the corrected percentage of calves. It was therefore treated as a constant in computing the SE of the corrected percentage by dividing the SE of the raw calf index by 0.89 to obtain $SE_{0.89}$. $SE_{0.89}$ is the SE of the corrected percentage for low-calf years.

For medium- and high-calf years, the year-to-year variability of the 1.046 factor, represented by the SD given above, must be incorporated to obtain the SE of the corrected percentage of calves. The usual approximate formula for estimating the variance of the product $1.046 \times R$, where R is the raw calf index for the year divided by 0.89, is (Goodman, 1960):

$$V(1.046 \times R) = 1.046^2 \times V(R) + R^2 \times V(1.046) + 2 \times 1.046 \times R \times \text{Covariance}(1.046, R)$$

where V denotes estimated variance. To assess the significance of the above covariance term, the correlation between (augmented calf index)/(raw calf index) and (raw calf index) for medium- and high-calf years was computed. This correlation was -0.6, and it was not significantly different from zero (P=0.173). Thus the covariance term in the above formula can be treated as zero. The negative sign of the correlation makes it unlikely that this will lead to $V(1.046 \times R)$ being negatively biased. $SE_{0.89}^2$ was used for $V(R)$ in the formula and 0.054^2 for $V(1.046)$. The square root of $V(1.046 \times R)$ estimates the SE of the percentage of calves in the population for a medium- or high-calf year.

Power analyses

Power analyses were conducted to evaluate the power to detect changes in calf production using the corrected calf index. Examination of the distribution of the corrected calf index suggested some pattern of high (>9%), medium (4%-7%) and low (<1%) years with gaps in between, not inconsistent with the observation by Rugh *et al.* (1992) that calving appears to increase every 3-4 years. While it is possible that sampling in future years will clarify such patterns, only nine years of data were available even when the incomplete 1987 and 1994 surveys were combined and treated as equivalent to an additional year. Therefore no attempt was made to incorporate patterns in the power analyses.

The distribution of available calf index values looks much more like a uniform distribution than a normal distribution, so parametric tests like the *t*-test are not appropriate. It seems reasonable for purposes of power calculations to model calf index values as a sample of size n=9 from a uniform distribution with lower limit 0 and upper limit θ, where θ is estimated by $(n+1)/n$ times the maximum corrected calf index value (Patel *et al.*, 1976, p.170). This estimate of θ is 11.6, and the mean of the corresponding uniform distribution is $\theta/2$=5.8 and the SD=3.35. This SD is quite close to that of the existing corrected calf index values, SD=3.75. It also seems reasonable to assume that if the average calf index value were reduced in the future, there would still be low-calf years with indices near zero, but values of the index in high-calf years would not be as high as at present. This can be modelled by assuming these values are drawn from a uniform distribution with a smaller upper limit.

An appropriate test for such a change in distribution of the calf index is the Mann-Whitney test (Breiman, 1973, p.292). If the existing calf index values are denoted by $x_1,\ldots,x_n$ and m is the number of calf index values $y_1,\ldots,y_m$ observed during the period with lower average value, then the Mann-Whitney test statistic U is the sum over the x_i of the number of y_j that exceed x_i. If the distributions of x_i and y_j are in fact the same, for $n \geq 9$ and $m \geq 9$, U is approximately normal with expected value $nm/2$ and variance $nm(n+m+1)/12$. Thus U can be standardised and compared to quantiles of a normal distribution with mean zero and variance one.

For this study, a one-sided test was appropriate as only if the y_j had a lower average value (i.e. U was small) would it be of concern. The null hypothesis (the x and y distributions are the same at the 10% level) was rejected if the standardised value of U was less than -1.28. Tests were done at the 10% rather than the 5% level to gain more power to detect a reduction in the calf index. Power was determined by simulating 1,000 samples in which the y distribution had a smaller θ than the x distribution (reductions of 40%, 50% and 60%) and either $m=n=9$, $m=12$ or $m=18$.

RESULTS

The proportion of the population that was estimated to have passed Point Barrow during each weekly period during each of the survey years is shown in Table 1. 1985 was excluded because of the unusual migration timing in that year (see the 1985 proportions in Table 3 and Koski *et al.* (2006)). The mean proportions over all four years in Table 1 were considered to be representative of the proportions during seasons with medium calf production. The mean proportions over high and lower calf years were assumed to be representative of the proportions passing in such years.

Table 2 shows numbers of photographs of calves and other whales (non calves) near Point Barrow during each of the weekly periods during 1985-86, 1989-92 and 2003-04. In each of these years, flights were made on 10 or more days from 14 May through 7 June, with several days representing each week. The incomplete 1987 and 1994 surveys had flights after 13 May on only 4 and 3 days, respectively, and one of the weeks was missed completely in each year. Table 2 includes all photographs, whether or not length data were available, because calves can be identified based on their colouration and morphology. The inclusion of unmeasured whales of all sizes resulted in larger samples for the calf index calculations.

Table 3 shows the percentages of calves during each weekly period after all corrections for differential detection of mother-calf pairs and increased numbers of photographs of mothers and yearlings or calves versus other whales. The survey proportions used in computing the calf index are also shown in Table 3. The raw calf index for each year, was calculated as

$$\Sigma \text{ Proportion}^1 \times \% \text{ Calves}$$

for each weekly period and is shown in the right hand column. Table 4 also shows the raw calf index, with corrections that can be made to convert index values to % calves in the population, shown with its SE for each year.

The power to detect 40%, 50% and 60% reductions in the maximum of the corrected calf index distribution is shown in Table 5. Clearly there is little power to detect reductions of 40% or less in this maximum at any of the sample sizes compared; even with 18 years of samples after a 40% decline, power is only 68%. To have adequate power to detect a 50% reduction, 12 to 18 years of samples are needed. Additional baseline samples (i.e. before any reduction occurs) would increase n and therefore increase power.

DISCUSSION

The calf index developed in this paper provides a robust method of monitoring trends in calf production at a much lower cost than through ice-based or aerial surveys covering the entire spring migration. Furthermore, the calf index can become a direct estimate of the percentage of calves in the population by incorporating bias corrections for the few whales born before the surveys started and by accounting for calves that are born after their mothers pass Point Barrow. These estimates of calving rates could be used during periodic reviews of the status of B-C-B bowheads whales as they provide data to evaluate whether annual calving rates are within the range tested for the purposes of reviewing the B-C-B bowhead whale *SLA*. They also provide data for evaluating the effect of environmental variability on calving rates. When environmental variability is ignored, estimates of Maximum Sustainable Yield Rate (MSYR) could be substantially positively biased, which may mean that allowable harvest rates could be overestimated (IWC, 2009).

If photogrammetry studies are used to compute the calf index, adjustments should be made for the increased number of photographs of mother-calf pairs in comparison to other

---

[1] See Table 3 for a detailed description of 'Proportion'.

Table 2

Numbers of images of calves and other whales photographed near Point Barrow, Alaska, during spring photography studies. All photographs are included whether or not length data are available. All images are classified as a calf or non-calf based on morphology.

	14-20 May			21-27 May			>27 May		
Year	Others	Calves	% Calves*	Others	Calves	% Calves	Others	Calves	% Calves
1985	564	0	0.0%	152	0	0.0%	311	22	6.6%
1986	80	16	16.7%	132	42	24.1%	57	37	39.4%
1989	88	5	5.4%	68	65	48.9%	37	36	49.3%
1990	104	12	10.3%	27	26	49.1%	32	22	40.7%
1991	93	37	28.5%	109	34	23.8%	16	9	36.0%
1992	114	0	0.0%	51	0	0.0%	37	18	32.7%
2003	39	0	0.0%	69	48	41.0%	149	94	38.7%
2004	176	97	35.5%	47	38	44.7%	281	63	18.3%
All years	**1,258**	**167**	**11.7%**	**655**	**253**	**27.9%**	**609**	**301**	**33.1%**

*Before corrections.

Table 3

Calculation of the raw calf index as described in the methods using photography data from Table 2. The numbers from Table 2 (both calves and others) have been corrected for the higher probability of encountering a mother-calf pair (/1.69) and the tendency to take more photographs of mothers and calves than other whales (/1.46) when calculating the % calves during each weekly period.

		Weekly period							
		14-20 May		21-27 May		>27 May		Raw calf index	
Year	Calf production	Proportion*	% Calves	Proportion	% Calves	Proportion	% Calves	% Calves	SE
1985	Low	0.3850	0.00	0.1194	0.00	0.2464	2.96	0.73	0.20
1986	High	0.2386	8.42	0.1025	13.98	0.0734	30.35	5.67	0.79
1989	High	0.1944	2.37	0.0923	43.58	0.0798	48.34	8.34	0.82
1990	High	0.1944	4.78	0.0923	46.49	0.0798	32.73	7.83	0.91
1991	Medium	0.1463	17.43	0.0667	12.76	0.0598	25.49	4.93	0.89
1992	Low	0.0982	0.00	0.0412	0.00	0.0399	22.10	0.88	0.18
2003	Medium	0.1463	0.00	0.0667	34.15	0.0598	29.43	4.04	0.38
2004	High	0.1944	25.02	0.0923	35.49	0.0798	9.26	8.88	0.93
Mean of all years								**5.16**	

*The proportion of the migration is from aerial and ice-based visual and acoustic surveys. For years without an ice-based survey, the mean proportions of the highest two ice-based survey years in terms of percent calves seen (1986 and 2001) were used for the high calf production years, the mean of 1988 and 1993 for the low production years and the mean of all four of these years for the medium production years (Table 1). The 1985 ice-based survey proportions were used only for 1985 because the migration that year was unusually late (Koski *et al.*, 2006). The characterisation of years without an ice-based survey as high, low or medium was based on first computing the raw calf index using the "medium" proportions and defining low as ≤2%, medium as 2%-5% and high as >5%.

Table 4

Raw calf indices for the years 1985-86, 1989-92 and 2003-04 and correction factors that can be applied to those indices to estimate the percentage of calves in the population. The <14 May correction is 1.046× for medium and high calf years; no correction was applied for low calf years. The correction for calves born east of Barrow is to divide by 0.89. The estimated percentage of calves and its SE are shown for each year.

			Adjustment for calves			
	Raw calf index				Corrected calf index	
Year	% Calves	SE	<14 May 1.046× or 1.000×	Born east of Barrow (/0.89)	% Calves	SE
1985	0.73	0.20	0.73	0.82	0.82	0.22
1986	5.67	0.79	5.93	6.37	6.66	0.99
1989	8.34	0.82	8.72	9.37	9.80	1.09
1990	7.83	0.91	8.19	8.80	9.20	1.17
1991	4.93	0.89	5.16	5.54	5.79	1.09
1992	0.88	0.18	0.88	0.99	0.99	0.20
2003	4.04	0.38	4.23	4.54	4.75	0.51
2004	8.88	0.93	9.29	9.98	10.44	1.22
Mean of all years	**5.16**		**5.39**	**5.80**	**6.06**	

Table 5

Power to detect various percent reductions in the maximum of the corrected calf index distribution with n=9 baseline samples and various sample sizes m for the index after the reduction in the maximum.

	Percent reduction		
m	40%	50%	60%
9	57%	70%	85%
12	62%	76%	87%
18	68%	82%	90%

whales as documented by Koski *et al.* (2006). In future analyses, the correction factor to account for increased effort to photograph mothers and calves in comparison to other whales should be calculated for each specific survey with adequate data. The value of 1.46 is based on a dataset that does not include 2003 or 2004 data.

If the calf index is calculated using aerial survey data, the index will be negatively biased; earlier studies have shown that some calves are missed during aerial surveys unless mothers with calves are circled for extended periods of time (Davis *et al.*, 1983; Koski *et al.*, 1993). With some circling of whales this bias can be minimised.

Although ice conditions near Point Barrow have been highly variable from year to year, the timing of the migration has been similar in all years of photogrammetry studies except 1985. Available evidence indicates a delayed migration in 1985 (Koski *et al.*, 2006). Since the migration is size-structured (Angliss *et al.*, 1995; Koski *et al.*, 2006; Withrow and Angliss, 1992; 1994), length data from photographs collected during calf index surveys can be used to assess whether the migration timing was typical or unusual. If the timing were unusual, the length data could be used to adjust the index for the unusual timing in that season as was done by Koski *et al.* (2006) for the 1985 data.

Koski *et al.* (2006) noted that the proportion of the migration that passes Point Barrow late in the season (see Table 1) may have been underestimated during their and past studies, particularly in years with high calving success. The inclusion of different proportions of the migration for weekly periods, depending on whether the season was a low-, medium- or high-calf year, is a significant improvement over the average proportion used by Koski *et al.* (2006). During years with relatively low calf production, ~17.9% of the migration passed Point Barrow after 13 May but during high-calf years ~36.6% passed during that same period (Table 1). The procedure used by Koski *et al.* (2006) underestimated the percent calves in the population during medium- and high-calf years and overestimated the percent during low-calf years, but during low-calf years, the percentage of calves was so low that the mean value was underestimated. Further analyses of the 2003 and 2004 photogrammetry data may be useful in assessing the proportion of the migration that passed Point Barrow late in these seasons.

Monitoring of the percentage of calves in the B-C-B bowhead whale population using the calf index suggested above will permit detection of changes in reproductive success that may be used to warn of a possible change in the rate of increase or decrease in population size before it becomes detectable by a change in the population estimates. This information may be useful during periodic reviews of the status of B-C-B bowhead whales. Previous studies have found that the percentage of calves has varied widely from year to year (Angliss *et al.*, 1995; Koski *et al.*, 1993), so several years of surveys would be needed to cover the range of variation in calving that can be seen in Table 4.

Power analyses (Table 5) indicate that the power to detect a reduction in the maximum of the calf index distribution is low unless the reduction is large. Eighteen years of calf indices after a decline has occurred are required to have a 68% chance of detecting a 40% decline in the maximum of the calf index distribution. Nine years are adequate to detect a decline of 60% or more. In fact, if five years of calf index values after a decline of 60% were tested there would be a 78% chance of detecting that a decline had occurred. The low power to detect smaller declines is due more to the large year-to-year variability in the percentage of calves in the population than to the relatively small SE of the corrected percentages shown in Table 4. Power increases if additional years of data are collected before a decline in calf production occurs. Additional years of data would also aid in assessing whether the variability in % Calves is adequately modelled by the variability of a sample from the uniform distribution assumed in the power calculations. Although not all sources of variability have been captured in these calculations, we believe that the uncaptured variability would not have a significant impact on the calf index values that were calculated (Table 6).

At the population level, reproductive success in cetaceans appears to be influenced by many factors. The age structure of a population determines the number of mature females that are available to have calves. A growing population with many immature animals, such as the B-C-B bowhead whale population, would have a smaller proportion of mature females than a stable population. The age structure can also be influenced by whaling, predation or other sources of mortality. Changes in the age at first calving and the frequency of calving after whales become sexually mature can have marked effects on the percentage of calves in the population. Both are probably influenced by the body condition of individual whales. That is, whales with good body condition may become sexually mature at an earlier age (Gabriele *et al.*, 2007), and once sexually mature, they probably have calves at more frequent intervals than nutritionally stressed whales. There is strong evidence that in at least some cetaceans the adult females become nutritionally stressed following calving. For example, Pettis *et al.* (2004) found that female North Atlantic right whales (*Eubalaena glacialis*) were significantly thinner during calving years and the year after giving birth than the year before giving birth.

The availability of food has an obvious and direct effect on body condition and reproductive success as demonstrated by Perryman and Lynn (2002) and Perryman *et al.* (2002; 2004). Rice and Wolman (1971) noted seasonal differences in body mass of gray whales, and later Perryman and Lynn (2002) found a significant difference in the length/width ratios of southbound and northbound gray whales, indicating that two months of fasting in wintering areas resulted in measurable differences in body condition. Perryman *et al.* (2002; 2004) found a strong correlation between dates of retreat of sea ice in gray whale summer feeding areas and calf production. A longer feeding season resulted in higher calf production which was presumably related to gray whale mothers either feeding for longer or obtaining higher quality food during years with early ice retreat. The calf index studies that are recommended here for bowhead whales will not identify the cause of changes in reproductive success, but they will identify that they are occurring. Also, if photogrammetry data are collected to calculate the calf index, morphometric measurements from the photographs will provide information on the body condition of whales that can be useful for evaluating changes in calving rates.

If calf index surveys incorporated aerial photography, they would be a relatively economical method of obtaining additional data to refine and update B-C-B bowhead whale population parameters such as estimates of calving intervals (Miller *et al.*, 1992; Rugh *et al.*, 1992) and adult survival (Zeh *et al.*, 2002). Long-term photogrammetry studies of southern right whales (*E. australis*) have shown that by concentrating photographic effort on adult females, key reproductive and life-history parameters could be obtained. Payne *et al.* (1990) obtained estimates of survival, population growth, calving intervals and age of first calving for southern right whales, and with additional years of data Cooke *et al.* (2001) were able to improve the precision of earlier estimates. Best *et al.* (2001) estimated the same parameters using right whale photographs obtained along the south coast of Africa during a 28-year period.

ACKNOWLEDGEMENTS

We thank the captains and crews of the Barrow Whaling Captain's Association for allowing us to fly surveys during the spring whaling period. We also thank the many field personnel and pilots who assisted with the surveys, particularly Dave Rugh who was involved in all NMML surveys. The value of calf index surveys was first recognised while working on a project funded by the Marine Mammal Commission to examine bowhead whale body condition and reproductive success in relation to sea ice cover. This paper evolved from that work and from discussions with Andre Punt and Robert Suydam. We thank them for sharing their ideas. We also thank Andre Punt, Dave Rugh and Rolph Davis for reviewing a draft of this paper.

The data analysed here were collected during photographic surveys conducted primarily by the NMML (1985-2004), LGL (1989, 1991-92, 2003-04) and the North Slope Borough Department of Wildlife Management (NSBDWM) (2003-04). Photographic surveys were conducted under Scientific Research Permits 580 and 782-1438 (NMML) and 670 (LGL) issued by the US National

Table 6

Evaluation of factors that could affect calculation of the calf index and of whether variation that has not been quantified is likely to be consequential to use of the index for comparing year-to-year variation in the percentage of calves in the B-C-B bowhead whale stock.

Factors that could affect the calf index	Impact of the factor on index values	Has uncertainty been quantified?	Is unquantified uncertainty likely to be consequential?
Variability in proportion of population passing each week in low, medium and high calf years	Minor impact expected	No; few years with proportion data are available	No; believed to be much lower than variation between low, medium and high calf years
Variability of percentage of calves passing in each week in low, medium and high calf years	Major impact expected in medium and high calf years but data are collected during each survey	Yes; uncertainty is included in SE in Table 4	
Survey misses one or more days in a week	Little provided surveys conducted on 2-3 other days during the weekly period	Yes; included in SE in Table 4	
Encounter rates of mother-calf pairs vs others	Major impact before corrections but minor after corrections	Yes; 1.69 (SE = 0.14) times as likely to encounter mother-calf pair as other whales; included in SE in Table 4	No; some minor variability remains due to effects of year-to-year variation in ice on encounter rates
Extra photographs of mother-calf pairs	Major before corrections but little after corrections; future surveys will correct for bias using survey-specific data	Yes; 1.46 (SE = 0.17) times as many photos of mother-calf pairs as other whales; included in SE in Table 4	No
Lingering in study area	Minor	Partially accounted for in above correction	No; minimum impact on year-to-year comparisons for use of index, but may result in positive bias in estimates of % calves
Births before 14 May	Minor	Yes; 1.046 (SD = 0.054); included in last SE column in Table 4	No; correction is small compared to year-to-year variation in % calves; better quantification possible with additional surveys
Calves born east of Barrow	Minor	No; summer surveys required in same year	No; little variability expected; late season calving is by primiparous females which are recruited at low rate; correction small compared to year-to-year variation in % calves

Marine Fisheries Service under the provisions of the US Marine Mammal Protection Act and US Endangered Species Act. Preparation of the paper was funded by LGL, the NSBDWM and the Marine Mammal Commission through their project 'Relating Bowhead Whale Body Condition and Reproduction to Summer Ice Conditions in the Changing Beaufort Sea'.

REFERENCES

Angliss, R.P., Rugh, D.J., Withrow, D.E. and Hobbs, R.C. 1995. Evaluations of aerial photogrammetric length measurements of the Bering-Chukchi-Beaufort Seas stock of bowhead whales (*Balaena mysticetus*). *Rep. int. Whal. Commn* 45: 313-24.

Best, P.B., Brandão, A. and Butterworth, D.S. 2001. Demographic parameters of southern right whales off South Africa. *J. Cetacean Res. Manage. (special issue)* 2: 161-69.

Breiman, L. 1973. *Statistics: with a view towards applications*. Houghton Mifflin Company, Boston. 399pp.

Cooke, J.G., Rowntree, V.J. and Payne, R.S. 2001. Estimates of demographic parameters for southern right whales (*Eubalaena australis*) observed off Península Valdés, Argentina. *J. Cetacean Res. Manage. (special issue)* 2: 125-32.

Cooper, L.W., Ashjian, C.J., Smith, S.L., Codispoti, L.A., Grebmeier, J.M., Campbell, R.G. and Sherr, E.B. 2006. Rapid seasonal sea-ice retreat in the Arctic could be affecting Pacific walrus (*Odobenus romarus divergens*) recruitment. *Aquat. Mamm.* 32(1): 98-102.

Davis, R.A., Koski, W.R. and Miller, G.W. 1983. Preliminary assessment of the length-frequency distribution and gross annual reproductive rate of the western Arctic bowhead whale as determined with low-level aerial photography, with comments on life history. Paper SC/35/PS5 presented to the IWC Scientific Committee, June 1983, Brighton, UK (unpublished). i-ix+91pp+15 plates. [Paper available from the Office of this Journal].

Gabriele, C.M., Straley, J.M. and Neilson, J.L. 2007. Age at first calving of female humpback whales in southeastern Alaska. *Mar. Mammal Sci.* 23(1): 226-39.

George, J.C., Suydam, R.S., Philo, L.M., Albert, T.F., Zeh, J.E. and Carroll, G.M. 1995. Report of the spring 1993 census of bowhead whales, *Balaena mysticetus*, off Point Barrow, Alaska, with observations on the 1993 subsistence hunt of bowhead whales by Alaska eskimos. *Rep. int. Whal. Commn* 45: 371-84.

George, J.C., Suydam, R.S., Zeh, J. and Koski, W.R. 2004a. Estimated pregnancy rates of bowhead whales from examinations of landed whales. Paper SC/56/BRG10 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy (unpublished). 7pp. [Paper available from the Office of this Journal].

George, J.C., Zeh, J., Suydam, R. and Clark, C. 2004b. Abundance and population trend (1978-2001) of western Arctic bowhead whales surveyed near Barrow, Alaska. *Mar. Mammal Sci.* 20(4): 755-73.

Goodman, L.A. 1960. On the exact variance of products. *J. Am. Stat. Assoc.* 55: 708-13.

International Whaling Commission. 2009. Report of the MSYR Workshop, 16-19 November 2007, National Marine Mammal Laboratory, Alaska Fisheries Science Center, Seattle, WA, USA. *J. Cetacean Res. Manage.* 11(Supplement): In press.

Koski, W.R., Davis, R.A., Miller, G.W. and Withrow, D.E. 1993. Reproduction. pp.239-74. *In*: Burns, J.J., Montague, J.J. and Cowles, C.J. (eds). *The Bowhead Whale. Special Publication No.2*. The Society for Marine Mammalogy, Lawrence, Kansas. 787pp.

Koski, W.R., Miller, G.W., Richardson, W.J. and Würsig, B. 2004. Bowhead whale (*Balaena mysticetus*) mothers and calves during spring migration in the Alaskan Beaufort Sea: Movements, behaviour and life history data. Paper SC/56/BRG27 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy (unpublished). 31pp. [Paper available from the Office of this Journal].

Koski, W.R., Rugh, D.J., Punt, A.E. and Zeh, J. 2006. An approach to minimise bias in estimation of the length-frequency distribution of bowhead whales (*Balaena mysticetus*) from aerial photogrammetric data. *J. Cetacean Res. Manage.* 8(1): 45-54.

Miller, G.W., Davis, R.A., Koski, W.R., Crone, M.J., Rugh, D.J., Withrow, D.E. and Fraker, M.A. 1992. Calving intervals of bowhead whales – an analysis of photographic data. *Rep. int. Whal. Commn* 42: 501-06.

Patel, J.K., Kapadia, C.H. and Owen, D.B. 1976. *Handbook of Statistical Distributions*. Marcell Dekker, Inc., New York. 302pp.

Payne, R., Rowntree, V., Perkins, J.S., Cooke, J.G. and Lankester, K. 1990. Population size, trends and reproductive parameters of right whales (*Eubalaena australis*) off Peninsula Valdes, Argentina. *Rep. int. Whal. Commn (special issue)* 12: 271-78.

Perryman, W.L., Donahue, M.A., Perkins, P.C. and Reilly, S.B. 2002. Gray whale calf production 1994-2000: Are observed fluctuations related to changes in seasonal ice cover? *Mar. Mammal Sci.* 18(1): 121-44.

Perryman, W.L. and Lynn, M.S. 2002. Evaluation of nutritive condition and reproductive status of migrating gray whales (*Eschrichtius robustus*) based on analysis of photogrammetric data. *J. Cetacean Res. Manage.* 4(2): 155-64.

Perryman, W.L., Watters, G.M., Schwartz, L.K. and Rowlett, R.A. 2004. Preliminary results from shore-based surveys of northbound gray whale calves in 2003 and 2004, with a comparison to predicted numbers based on the distribution of seasonal ice. Paper SC/56/BRG43 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy (unpublished). 7pp. [Paper available from the Office of this Journal].

Pettis, H.M., Rolland, R.M., Hamilton, P.K., Brault, S., Knowlton, A.R. and Kraus, S.D. 2004. Visual health assessment of North Atlantic right whales (*Eubalaena glacialis*) using photographs. *Can. J. Zool.* 82: 8-19.

Rice, D.W. and Wolman, A.A. 1971. *The Life History and Ecology of the Gray Whale (Eschrichtius robustus)*. American Society of Mammalogists, Special Publication No. 3, Stillwater, Oklahoma. viii+142pp.

Rugh, D.J., Miller, G.W., Withrow, D.E. and Koski, W.R. 1992. Calving intervals of bowhead whales established through photographic identifications. *J. Mammal.* 73(3): 487-90.

Stirling, I., Lunn, N.J. and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic changes. *Arctic* 52(3): 294-306.

Stirling, I. and Parkinson, C.L. 2006. Possible effects of climate warming on selected populations of polar bears (*Ursus maritimus*) in the Canadian Arctic. *Arctic* 59(3): 261-75.

Withrow, D. and Angliss, R. 1992. Length frequency of bowhead whales from spring aerial photogrammetric surveys in 1985, 1986, 1989 and 1990. *Rep. int. Whal. Commn* 42: 463-67.

Withrow, D. and Angliss, R. 1994. Length frequency of the bowhead whale population from 1991 and 1992 spring aerial photogrammetric surveys. *Rep. int. Whal. Commn* 44: 343-46.

Zeh, J., Poole, D., Miller, G., Koski, W., Baraff, L. and Rugh, D. 2002. Survival of bowhead whales, *Balaena mysticetus*, estimated from 1981-98 photo-identification data. *Biometrics* 58: 832-40.

Zeh, J.E. and Punt, A.E. 2005. Updated 1978-2001 abundance estimates and their correlations for the Bering-Chuckchi-Beaufort Seas stock of bowhead whales. *J. Cetacean Res. Manage.* 7(2): 169-75.

Date received: July 2008
Date accepted: August 2008