Surveys of belugas and narwhals in the Canadian High Arctic in 1996

Stuart Innes[1 *], M. P. Heide-Jørgensen[2 **], Jeff L. Laake[3], Kristin L. Laidre[4], Holly J. Cleator[1], Pierre Richard[1] and Robert E.A. Stewart[1]

[1]*Department of Fisheries and Oceans, 501 University Crescent, Winnipeg, Canada R3T 2N6*
[2]*Greenland Institute of Natural Resources, c/o National Marine Mammal Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, USA*
[3]*National Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way NE, Seattle, WA 98115, USA*
[4]*Washington Cooperative Fish and Wildlife Research Unit, School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA*
**This paper was completed after the death of the senior author. The authors have tried to remain true to Stuart's directions but can not anticipate how he might have brought it to conclusion himself. In this and many other aspects of our lives, Stuart is missed.*
***Author to whom correspondence should be addressed.*

ABSTRACT

The summer range of belugas (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) in Prince Regent Inlet, Barrow Strait and Peel Sound in the Canadian High Arctic was surveyed from 31 July to 3 August 1996 with a visual aerial survey of offshore areas and photographic aerial surveys of concentration areas. The visual survey estimate based on the number of belugas visible to the observers using systematic line transect methods was 10,347 (cv = 0.28). This included corrections for whales that were missed by the observers, observations without distance measurements and an estimate of 1,949 (cv=0.22) belugas from a photographic survey in southern Peel Sound. Using data from belugas tagged with satellite-linked time-depth recorders, the estimate was adjusted for individuals that were diving during the survey which resulted in an estimate of 18,930 belugas (cv = 0.28). Finally, counts of belugas in estuaries, corrected for estuarine surface time, were added to provide a complete estimate of 21,213 belugas (95% CI 10,985 to 32,619). The estimated number of narwhals corrected for sightings that were missed by observers was 16,364 (cv = 0.24). Adjusting this for sightings without distance information and correcting for whales that were submerged produced an estimate of 45,358 narwhals (95% CI 23,397 to 87,932).

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INTRODUCTION

Belugas (*Delphinapterus leucas*) that summer near Somerset Island in the Canadian High Arctic migrate during the early fall to wintering areas in the North Water and off the west coast of Greenland (Fig. 1). It is not known if the belugas that winter in the North Water or off West Greenland represent separate populations; however, there is evidence that there are at least two stocks (de March *et al*. 2002, Innes *et al*. 2002).

The size of the beluga stocks in the Canadian High Arctic was estimated during the fall mi-

Fig. 1. Adult beluga are easily visible in clear water from the air. (Photo: Vidar Bakken)

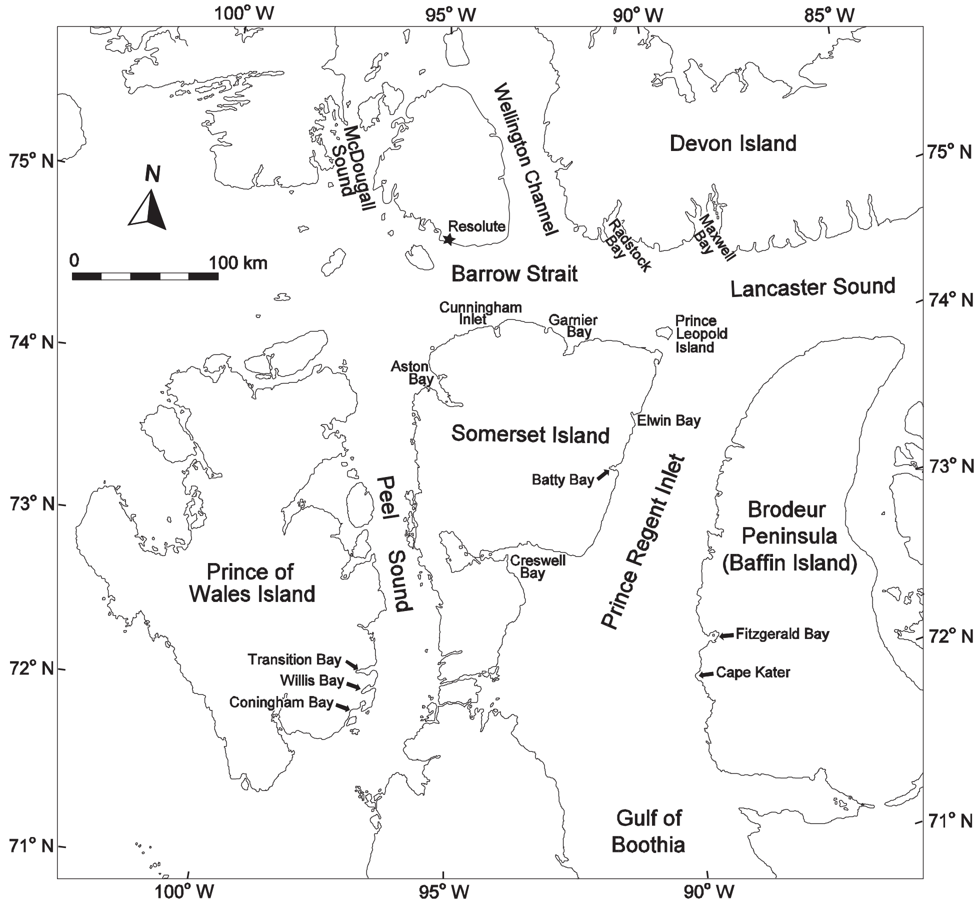


Fig. 2. Study area showing place names mentioned in the text.

gration of 1979 (Koski *et al*. 2002) and during the summer in July and August 1981 (Smith *et al*. 1985). Koski *et al*. (2002) estimated 10,250 to 12,000 belugas migrated at the surface along the south coast of Devon Island (see Fig. 2) from aerial counts in September 1979. This estimate is likely an underestimate because the entire potential range was not surveyed; however, it represents the actual number of belugas moving past Devon Island. Smith *et al*. (1985) estimated there were 9,586 belugas (95% confidence interval (CI) = 2,699 – 16,471) in Lancaster Sound, Barrow Strait, and Prince Regent Inlet in July and August 1981. This estimate was based on strip transect surveys, off-transect sightings, and surveys of concentration areas. The results of the July and August 1981 surveys were incomplete because Peel Sound, an important concentration area for belugas in August (Koski *et al*. 2002, Smith and Martin 1994, Richard *et al*. 2001), was not included. Furthermore, no correction factors were available for the number of belugas at the surface but missed by observers, as well as those that were below the surface when the survey airplane flew over-head.

Spring surveys conducted over pack-ice off the west coast of Greenland have revealed that the number of belugas in the West Greenland wintering area has declined by 60% since 1981 (Heide-Jørgensen *et al*. 1993, Heide-Jørgensen and Reeves 1996, Heide-Jørgensen and Acquarone 2002). During the 1980s and 1990s, the annual catch in Greenland ranged between 600 and 1000 belugas (Heide-Jørgensen and Rosing-Asvid 2002). The other winter concentration area, the North Water, has at least 500 belugas, based on two reconnaissance surveys in 1978 and 1994 (Finley and Renaud 1980, Richard *et al*. 1998).

Narwhals (*Monodon monoceros*) summer in large numbers in the Canadian High Arctic and spend the winter in Baffin Bay. Population estimates of narwhals in Baffin Bay and the Canadian High Arctic were obtained in three independent studies. Koski and Davis (1994) estimated 34,363 (se = 8,282) narwhals were present in offshore areas of Baffin Bay based on aerial surveys conducted during May-July 1979. This estimate excluded whales that were summering in northern Hudson Bay. Richard *et al*. (1994) obtained a population estimate of 17,991 narwhals (90% CI 14,724 to 21,258) based on aerial photographic surveys conducted in the high Arctic. Smith *et al*. (1985) estimated approximately 13,200 to 18,000 narwhals were present at the surface in August in Lancaster Sound and adjoining waterways based on counts from strip transect aerial surveys and reconnaissance surveys conducted between 1974 and 1982. All of these estimates are negatively biased because no corrections were made for movements of whales or availability bias.

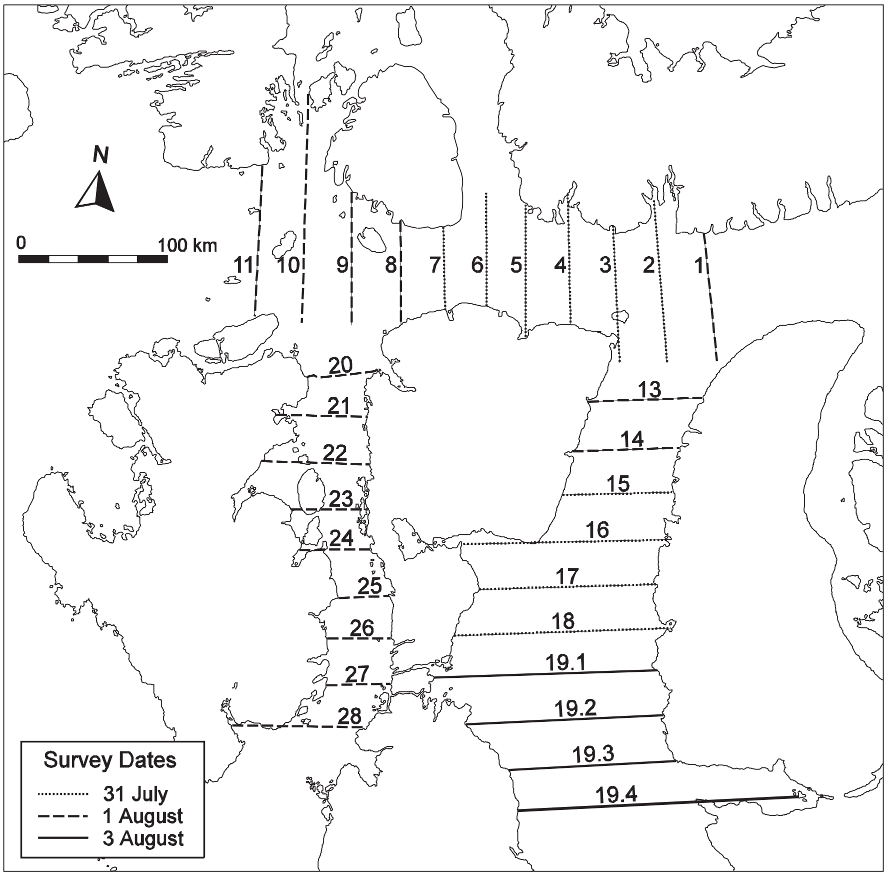
Because of the lack of recent abundance estimates for the beluga populations in the Canadian High Arctic, a survey was designed to estimate the total number of belugas including animals that were submerged and not available to be seen by observers. A similar estimate of abundance of narwhals was derived, although not all areas in the Canadian High Arctic with narwhal concentrations were surveyed (*e.g*. Gulf of Boothia, Admiralty Inlet and Eclipse Sound).

METHODS

Visual surveys of offshore areas

Previous surveys and tagging studies show that the distribution of belugas during late July and early August is centred around Somerset Island in the waters of western Lancaster Sound, Barrow Strait, Peel Sound, Prince Regent Inlet, Wellington Channel and McDougall Sound (Fig. 2; Sergeant and Brodie 1975, Smith *et al*. 1985, Martin *et al*. 1993, Smith and Martin 1994, Koski *et al*. 2002). In the survey reported here, three regions (Barrow Strait, Prince Regent Inlet and Peel Sound) were surveyed between 31 July and 2 August 1996 at a rate of 1 km per 30 km^2 distributed proportionately over the survey area. Transects were flown on each degree of longitude in the areas with north-south transects and every 16 minutes of latitude for east-west transects (Fig. 3). The most northerly east - west transects started on 73º 30' N for Prince Regent Inlet and 73º 46' N for Peel Sound. All transects were oriented approximately perpendicular to the long axis of the water body in an attempt to produce low variability between transects.

Fig. 3. Systematic visual transects surveyed on 31 July, 1 August and 3 August.



Visual surveys of belugas and narwhals were made from DeHavilland Twin Otters (DH-6) equipped with standard flat windows with the inner covers removed. The flat windows limited the viewing angles to 70º from the horizontal or less. The airplanes with visual observers generally flew between 152 m (500 ft) and 305 m (1000 ft) above sea level (a.s.l.) (Table 1). On one occasion they flew as high as 366 m (1200 ft) to reach calm air. Ground speed was approximately 200 km hr^{-1} (108 knots).

The crew consisted of a crew chief and four to six observers. The crew chief recorded the location, speed and altitude every 5 minutes or when conditions changed, monitored the flight path, informed the observers when to start and end transects, and solved problems with equipment. Observers were paired (front and rear observers) on each side of the airplane and maintained their seat positions on flights. Each observer received 3 to 6 hours of pre-flight training on the types of observations that were required. Observers were instructed to concentrate their search effort in the area between about 70º and 20º from the horizontal.

Observers recorded data on time-coded audio disc recorders (MZ-B3 MiniDisc Recorders, Sony Corp.) that were synchronized to a single watch prior to each survey. Each observer also wore a synchronized digital watch. The time was given at the start of each minidisc recording and occasionally thereafter. When a whale group was first seen, the species, the time and the number in the group were recorded. When the group was abeam, the declination angle was recorded using an inclinometer. Experienced observers also made observations on the amount of ice present (in tenths), sea state (in Beaufort scale), fog, snow, and glare in the viewing area.

Estimation and adjustment for perception bias ($\hat{N}$)

Comparisons of visual observer counts on the same side of the aircraft demonstrated that observers missed whales that were at the surface

Table 1. Transect lines split by regions with data on changes in altitude and sea states and the use of the transects in the analyses.

Transect numbers	Region	Date 1996	Altitude m	Sea State	Comments	Inclusion in analyses
1	Barrow Strait	1 August	305	0-1	Only complete transect at flown at 305 feet in Barrow Strait	Included in Barrow Strait region
2-7	Barrow Strait	31 July	152	1-2	Sea State 3 on parts of transect 5	Included in Barrow Strait region
8-10	Barrow Strait	1 August	152	1		Included in Barrow Strait region
11	Barrow Strait	1 August	152-305	?	Data recorder worked only for part of the survey	Not included
13-18	Northern Prince Regent Inlet	31 July and 1 Aug.	305	0-2		Included in Northern Prince Regent Inlet region
19.1-19.2	Southern Prince Regent Inlet	3 August	152	0-3	Sea state 3 on parts of transect 19.2	Included in Southern Prince Regent Inlet region
19.3-19.4	Southern Prince Regent Inlet both	3 August	305	3	Sea state 3 on transects	Not included due to high sea state
20	Northern Peel Sound	1 August	135-305	0	Fog and variable altitude	Not included
21-26	Central Peel Sound	1 August	305	0-2		Included in Central Peel Sound region
27-28	Southern Peel Sound	1 August	366	0-2		Included in Southern Peel Sound region for narwhals but not for belugas
Photo	Southern Peel Sound	2 August	701-914			Included in Southern Peel Sound region for belugas but not for narwhals

during the survey ('perception bias' cf. Marsh and Sinclair 1989). The sightings of the rear and the front seat observers on each side were compared to identify sightings made only by one or the other observer and those made by both observer positions (generically termed 'platforms'). Determination of simultaneous sightings by both platforms was primarily based on coincidence in timing of the sighting but information on declination angle and number of whales in the pods was used as well.

With an observer positioned at the front and rear window of the survey aircraft, there were 3 types of observation events that could occur: 1) the observer at the front window was the only one who detected the whale(s), 2) the observer at the rear window was the only one who detected the whale(s), or 3) both observers detected the whale(s). We use the indices c=1 and c=2 to refer to the first two events and the index c=3 to indicate an observation detected from both platforms. Assuming that whales only occur individually, the total number of whales detected by the observers within a surveyed strip would be $n=n_1+n_2+n_3$ and the number missed would be $n_0=N-n$. To adjust for perception bias and estimate N, we needed to estimate the probability (p) that the whale was detected by at least one of the platforms ($p=n/N$) or conversely to estimate the fraction of the whales that were missed by both platforms (*i.e.* the unobservable events; $1-p=n_0/N$). The abundance estimate would then be constructed as $\hat{N}=n/p$.

One approach to estimate p would be the familiar Petersen estimator for mark-recapture data which using our notation is:
$\hat{N}=(n_1+n_3)(n_2+n_3)/n_3=n/p$,
where $p=p_1+p_2-p_1p_2$, $p_1=n_3/(n_2+n_3)$,
and $p_2=n_3/(n_1+n_3)$.
However, that approach assumes that each

whale has the same probability of being detected and variation (heterogeneity) in detection probability will result in under-estimation of abundance. Alternatively, p can be estimated using distance sampling (Buckland *et al.* 2001) which assumes that the probability each whale (or whale group) is detected, $g(x)$, depends on the whale's perpendicular distance x from the track line. The detection function is averaged (by integration) across all distances within the strip of width W:

$$p = \int_o^W g(x) \frac{1}{W} dx$$

Distance sampling assumes that all whales on the trackline (x=0) are detected ($g(0)=1$) and does not compare detections by various platforms, therefore if $g(0) < 1$ the abundance will be under-estimated. The weaknesses of both of these methods are overcome in the double-platform line transect survey method described by Borchers *et al.* (1998 a,b) with modifications described by Laake (1999) who called the method 'distance-sight-resight'. We describe the method here in some detail for completeness and to document where we have deviated from their descriptions in our use of this method.

The probability that a visible whale (*i.e.* near the surface) or whale group was detected varied with perpendicular distance (x) from the survey trackline, as well as a multitude of other covariates such as the size of the group of whales. It was necessary to broaden the definition of the detection function $g(x)$ used in distance sampling to model the effects of these covariates on detection probability. We modelled detection probability with the following functional form: $p(x,\mathbf{z},\mathbf{w})=g^*(\mathbf{z})g(x,\mathbf{w})$, to implement the method as described by Laake (1999) and also by Evans-Mack *et al.* (2002) with slightly different notation.

The function $g(x,\mathbf{w})$ is an extension of the detection function described by Buckland *et al.* (2001) to incorporate scale covariates that are generically represented as the vector $\boldsymbol{w}$. The scale covariates ($\boldsymbol{w}$) affect the distance (*i.e.* scale) at which detections can be made. For example, if all whale groups could be seen at x=0 but larger whale groups were easier to see at longer distances, then group size would be a candidate for $\boldsymbol{w}$. Various functional forms could be used for $g(x,\mathbf{w})$ but they are restricted such that $g(0,\mathbf{w})=1$. We used a half-normal detection function with scale covariates ($\boldsymbol{w}$):

(1)
$$g(x,\mathbf{w}) = e^{-\left(\frac{x}{e^{\theta_0+\Sigma\theta_i w_i}}\right)^2} ,$$

where $\boldsymbol{\theta}$ is a vector of parameters that describe the relationship between the covariates ($\boldsymbol{w}$) and the scale which for (1) is proportional to the standard deviation of a normal distribution. Following with the above example, if group size was the only scale covariate then (1) would be:

(2)
$$g(x,s) = e^{-\left(\frac{x}{e^{\theta_0+\theta_1 s}}\right)^2} ,$$

and the natural logarithm of the standard deviation (scale) would be represented by the linear relationship with group size (s) and θ_0 and θ_1 would be the intercept and slope respectively.

Detection probability at x=0 described by $g^*(z)$ was modelled as a logistic function of the covariates $\boldsymbol{z}$:

(3)
$$g^*(z) = \frac{e^{\beta_0+\sum\beta_i z_i}}{1+e^{\beta_0+\sum\beta_i z_i}} ,$$

where $\boldsymbol{\beta}$ is a vector of parameters. The effect of $\boldsymbol{z}$ on detection probability is independent of distance x (*i.e.* adjust detection probability equally for all distances). For example, if detection probability on the line $g^*(0)$ depended only on the platform (*i.e.* rear or front) then (3) would be:

(4)
$$g^*(z) = \frac{e^{\beta_0+\beta_1 z}}{1+e^{\beta_0+\beta_1 z}} ,$$

where the platform covariate could be defined as z=0 for the front platform and z=1 for the rear platform. While detection probability could vary by platform by using it in $\boldsymbol{z}$ or $\boldsymbol{w}$ or both, detection probability for each platform has been explicitly denoted using a subscript (in the following description.

Following Borchers *et al.* (1998a), the probability that a whale at distance x with covariates $\boldsymbol{z}$ and $\boldsymbol{w}$ was detected by at least one platform is the sum of the probabilities of the 3 observable events:

(5) $P.(x,\mathbf{z},\mathbf{w})=P_1(x,\mathbf{z},\mathbf{w})+P_2(x,\mathbf{z},\mathbf{w})+P_3(x,\mathbf{z},\mathbf{w})$

where $P_1(x,\mathbf{z},\mathbf{w})=p_1(x,\mathbf{z},\mathbf{w})(1-p_2(x,\mathbf{z},\mathbf{w}))$ and $P_2(x,\mathbf{z},\mathbf{w})=p_2(x,\mathbf{z},\mathbf{w})(1-p_1(x,\mathbf{z},\mathbf{w}))$

However, these probability relationships are only correct if all variation in the detection probability is encompassed by x and the observed covariates z and w. Laake (1999) made a simple modification that allows for unspecified variation in detection probability at $x > 0$ by defining a separate detection probability for the matched detections:

(6) $P_3(x,\mathbf{z},\mathbf{w})=g^*_1(\mathbf{z})g^*_2(\mathbf{z})g^*_3(x,\mathbf{w})$,

and re-defining $P_1(x,\mathbf{z},\mathbf{w})=p_1(x,\mathbf{z},\mathbf{w})-p_2(x,\mathbf{z},\mathbf{w})$, $P_2(x,\mathbf{z},\mathbf{w})=p_2(x,\mathbf{z},\mathbf{w})-p_3(x,\mathbf{z},\mathbf{w})$ and $P_3(x,\mathbf{z},\mathbf{w})=p_3(x,\mathbf{z},\mathbf{w})$. Typically, if there is unspecified variation in detection probability $P_3(x,\mathbf{z},\mathbf{w}) > p_1(x,\mathbf{z},\mathbf{w})p_2(x,\mathbf{z},\mathbf{w})$ the estimate of $P.(x,\mathbf{z},\mathbf{w})$ would be too high resulting in an under-estimation of abundance. The functional form for $p_3(x,\mathbf{z},\mathbf{w})$ was specifically constructed such that $p_3(0,\mathbf{z},\mathbf{w})= p_1(0,\mathbf{z},\mathbf{w})p_2(0,\mathbf{z},\mathbf{w})$ (*i.e.* conditionally independent for x=0) otherwise some parameters are not identifiable. To achieve an unbiased estimate, all covariates z that affect detection probability at x=0 must be included in the model.

To estimate the vectors of parameters $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$, we wrote custom software using NLMINB in the S+ language to maximize the likelihood described by Laake (1999) which is equivalent to the formulation of Borchers *et al*. (1998a) for "unbinned" data. We considered a set of models that included one or more of the following covariates for z and w: altitude, group size, region (Barrow Strait, Prince Regent Inlet, Peel Sound), and platform (front or rear). For scale covariates other than platform, we included w in a separate model for $g_3(x,\mathbf{w})$ if it was included in $g_1(x,\mathbf{w})$ and $g_2(x,\mathbf{w})$. Models with both region and altitude covariates were not considered because most regions were flown at the same altitude. However, beyond that restriction we did not have any *a priori* reasoning to limit the set of models. Instead, a forward selection type approach was used for model selection by fitting models with each combination with a single covariate in each of z and w. A second order Akaike Information Criterion (AICc, Burnham and Anderson 1998) was used to select the best model from the initial set and then considered additional models by adding each of the non-included covariates one at a time. The model with minimum AICc was used for estimating abundance.

Potentially each detected whale group could have its own estimated detection probability resulting from the unique set of covariates z and w and its perpendicular distance x. Borchers *et al*. (1998b) suggested using the average detection probability by integrating over x but conditioning on the other covariates. This implicitly assumes that the covariate values are independent of perpendicular distance. Thus, for the i^{th} whale group, the estimated probability that it was detected by at least one observer was computed as:

7) $$p_{..}(\mathbf{z}_i,\mathbf{w}_i\,|\,\hat{\beta},\hat{\theta}) = \int_0^W [p_1(x,\mathbf{z}_i,\mathbf{w}_i\,|\,\hat{\beta},\hat{\theta}) + p_2(x,\mathbf{z}_i,\mathbf{w}_i\,|\,\hat{\beta},\hat{\theta}) - p_3(x,\mathbf{z}_i,\mathbf{w}_i\,|\,\hat{\beta},\hat{\theta})]\frac{1}{W}\,dx\,,$$

using the estimated parameters and the observation specific covariate values. The estimated number of whale groups within the survey strips was computed as the sum of the reciprocal of the n estimated probabilities:

(8) $$\sum_{i=1}^{n}\frac{1}{p_{..}(\mathbf{z}_i,\mathbf{w}_i\,|\,\hat{\beta},\hat{\theta})}\,,$$

which is equivalent to n/p if all of the probabilities are constant. The estimated abundance within a region was computed by scaling the abundance from the surveyed strips to the survey region. For the total abundance of the three regions, the estimator of abundance can be expressed as (equations (1) and (3) from Borchers *et al*. (1998b)):

(9) $$\hat{N}_g = \sum_{j=1}^{3}\frac{A_j}{2L_jW}\sum_{i=1}^{n_j}\frac{1}{p_{..}(\mathbf{z}_{ij},\mathbf{w}_{ij}\,|\,\hat{\beta},\hat{\theta})}\,,$$

where A_j is the size of the j^{th} region, L_j is the length of line surveyed in the j^{th} region, W is the transect width, and n_j is the number of whale groups detected in the j^{th} region. Likewise, we estimated the abundance of whales using equations (1) and (15) from Borchers *et al*. (1998b):

(10) $$\hat{N} = \sum_{j=1}^{3} \frac{A_j}{2L_jW} \sum_{i=1}^{n_j} \frac{s_{ij}}{p_{..}(\mathbf{z}_{ij}, \mathbf{w}_{ij} \mid \hat{\beta}, \hat{\theta})} ,$$

where s_{ij} is the size of the whale group which may also be represented in $\mathbf{z}_{ij}$ or w_{ij} if group size affects detection probability.

The variance estimator from Borchers *et al*. (1998b) (their equation 13) provides the variance of the abundance within the surveyed transects but doesn't include the variance associated with extrapolation from the surveyed transects to the entire region. They recommended using a bootstrap re-sampling of survey lines to estimate the variance and confidence interval coverage of the regional abundance. However, this was not an option for this analysis because we had an insufficient number of survey lines per region to construct a reliable bootstrap variance. Therefore, we developed the following variance estimator that extends the variance estimator of Borchers *et al*. (1998b) to include the transect sampling variance:

(11) $$\hat{\text{var}}(\hat{N}) = D(\hat{\beta}, \hat{\theta})' I^{-1}(\hat{\beta}, \hat{\theta}) D(\hat{\beta}, \hat{\theta}) + \sum_{j=1}^{3} \left[\left(\frac{A_j}{2L_jW} \right)^2 L_j \sum_{i=1}^{k_j} \frac{l_{ij} \left(\frac{\hat{N}_{ij}}{l_{ij}} - \frac{\hat{N}_j}{L_j} \right)^2}{k_j - 1} \right] ,$$

where k_j is the number of lines in the j^{th} region, l_{ij} is the length of transect i in region j, is the estimated abundance within transect i of region j, is the estimated abundance within all of the transects in the j^{th} region, $D(\hat{\beta}, \hat{\theta})$ is the first derivative of $\hat{N}$ with respect to the estimated parameters, and $I^{-1}(\hat{\beta}, \hat{\theta})$ is the inverse of the information matrix of the estimated parameters. The first term in the variance is equivalent to the same term in the Borchers *et al*. (1998b) variance. It measures the variation associated with estimation of the detection probability parameters. Instead of the second term of the Borchers *et al*. (1998b) variance the variance estimator of Buckland *et al*. (2001; equation 3.78) was used applied to the estimated abundance rather than the observed number of sightings. Thus, it includes variation in both encounter rate and group size.

Adjustment for missing distances ($\hat{N}^*$)

A perpendicular distance was not always recorded for each observation. We assumed that the observations with missing perpendicular distance were a random sample of all observations and adjusted the estimated abundance in the following manner:

(12) $$\hat{N}^* = \hat{N}\left(1 + \frac{n_m}{n}\right),$$

where n_m is the number of observations with a missing perpendicular distance and n is the total number of observations with a recorded distance including those beyond truncation limits. We estimated the variance as:

(13) $$\hat{\text{var}}(\hat{N}^*) = \hat{\text{var}}(\hat{N})\left(1 + \frac{n_m}{n}\right)^2 .$$

Photographic surveys of estuaries

Photographs of areas of beluga concentrations were made using a 9" x 9" Wild RC10 photogrammetric camera and Kodak (2445) Aerocolour negative film at altitudes between 549 m (1,800 ft) and 1,525 m (5,000 ft) a.s.l. with an optimum altitude of 915 m (3,000 ft) and overlap between successive frames. Initially it was planned to photograph all of the traditional estuary concentration areas around northern and eastern Somerset Island. However, few or no belugas were seen in most of these estuaries (T. Smith pers. comm), so with the exception of Creswell Bay, they were surveyed by visual counts made while on transect or while ferrying between transects or fuelling locations. The waters adjacent to the north shore of Creswell Bay were photographed in concert with the visual surveys on 31 July (Fig. 4). An area about 30 km by 30 km in the southern waters of Peel Sound near the coast of Prince of Wales Island was identified as a second concentration area during previous work (Smith and Martin 1994) and during the visual survey. Approximately one-sixth of this area was sampled using aerial photography the day after the visual survey (*i.e*. 2 August). The altitude during this survey varied between 701 m (2,300 ft) and 914 m (3,000 ft) a.s.l. according to the available cloud ceiling.

Whales on all photographs were counted by at least one of three experienced photo interpreters using a binocular dissecting microscope (Nikon SM2-1) on a light table (Richards GFL 940MC). Each observer initially counted the belugas on five photographs as a short training and standardising exercise. Belugas detected were classified as surfaced or submerged. Since most of this imagery was taken at less than 914 m (3,000 ft; *i.e.*, >1:6,000 scale), little interpretation was needed and most belugas were easily detected. It was possible to see foreflippers, flukes and shadows on most surfaced and many submerged belugas.

Although it was expected that all belugas in the estuaries would be visible on the photographs (Heyland 1974), it was apparent that some shapes on the photographs could not be clearly identified as belugas, suggesting that it may not have been possible to see belugas all the way to the bottom. This may have been due to high turbidity resulting from recent rain in the area. Therefore, some images on the photographs were classified as questionable belugas or narwhals, usually due to their depth or the presence of glare on the area of the photograph. Questionable whales were not included in estimates.

Estimation and adjustment for availability bias ($\hat{N}^{**}$)

The number of belugas that were submerged during the presence of the survey aircraft ('availability bias' cf. Marsh and Sinclair 1989) was estimated based on time-depth data recorded and summarized by satellite-linked radio transmitters of belugas instrumented from Cunningham Inlet, Elwin Bay, and Creswell Bay before July 25 (see Heide-Jørgensen *et al.* 2001). Likewise submergence time for narwhals was obtained from retrievable time-depth-recorders deployed on narwhals in Prince Regent Inlet and in Tremblay Sound (72.3° N, 81.1° W) (Laidre *et al.* 2002). Information from narwhals instrumented with satellite-linked time-depth-recorders in West Greenland was used for comparison (Heide-Jørgensen and Dietz 1995). The proportion of whales that

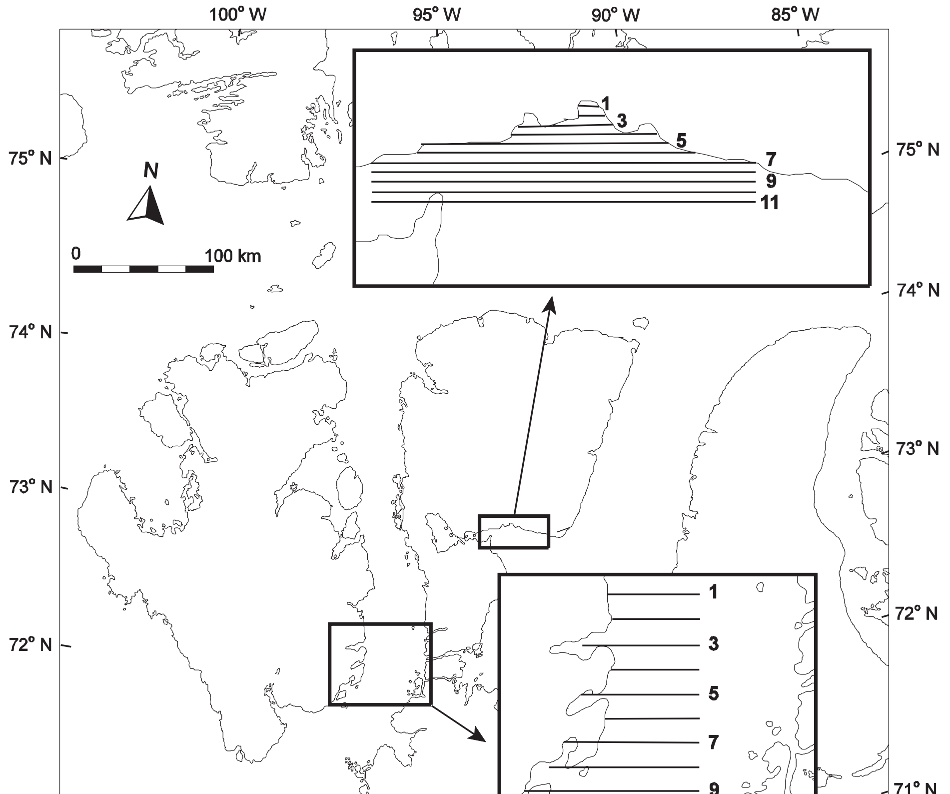


Fig. 4.
Locations of photographic transects flown in Creswell Bay (top inset) and in southern Peel Sound (bottom inset).

were available to be seen or photographed (p_a) was estimated as the mean of values for individual whales over selected periods and depth ranges. The var(p_a) was the squared standard error of the mean p_a of the tagged whales.

The abundance estimate was corrected for availability bias by dividing the estimated abundance ($\hat{N}^*$) by the proportion of time the whales were available to be seen:

$$(14) \qquad \hat{N}^{**} = \frac{\hat{N}^*}{p_a} \quad .$$

The variance of the corrected abundance estimate was computed as:

$$(15) \quad \hat{\text{var}}(\hat{N}^{**}) = \left(\hat{N}^{**}\right)^2 [cv^2(\hat{N}^*) + cv^2(p_a)]$$

where $cv^2(x)=var(x)/x^2$.

Counts of whales in estuaries

Off-transect concentrations of belugas were counted in the following estuaries (Fig. 2): Elwin Bay, Batty Bay, Garnier Bay, Cunningham Inlet, Radstock Bay, Maxwell Bay, Coningham Bay, Willis Bay, Transition Bay and estuaries on the west side of Brodeur Peninsula. Coningham Bay was also included in the photographic survey but counts from all other estuaries were corrected for whales that were submerged during the count and the numbers were added to the abundance estimate.

Abundance estimation

The abundance estimate for belugas included both visual survey estimates and photographic estimates with each corrected for availability bias. The estimate and variance were constructed with the following steps:

1) A perception bias model was developed with all of the data including Southern Peel Sound to develop estimated detection probabilities (equation 7),
2) The regional and total abundance estimates and variances were constructed using equations 10 and 11 excluding Southern Peel Sound,
3) To correct for missing distances (equation 12 to 13), we adjusted each estimate using a pooled adjustment from all of the regions to avoid further complications in estimating the total variance,
4) We added the Southern Peel Sound photographic count to the visual survey estimate and adjusted the total estimate for availability bias (equation 14), and
5) Finally, we added the counts from the estuaries not covered by systematic surveys, after correcting for the availability bias in the shallow estuarine waters.

The narwhal abundance estimate was based solely on the visual survey estimate (steps 1-3 above) with the Southern Peel Sound transects included in the Peel Sound estimate.

Ninety-five percent confidence limits were calculated based on the assumption of log-normal distribution following Buckland *et al*. (2001) where the lower and upper confidence limits of an estimate D are D/V and D x V and

$$(16) \qquad V=\exp[1.96 \times \text{sqrt}(\ln[1+var(D)/D^2])] \quad .$$

RESULTS

Distribution of belugas and narwhals

The belugas were concentrated in the central parts of Prince Regent Inlet and in Peel Sound with only few sightings in Barrow Strait (Fig. 5). Reconnaissance surveys revealed no belugas in Elwin Bay, Batty Bay, Garnier Bay, Cunningham Inlet or along Brodeur Peninsula between 72°15'N and 71°30'N. A group of about 400 was counted in and near the estuary in Radstock Bay on 31 July, 1996 (Table 2). On the same day 797 belugas were counted on the photographic survey of Creswell Bay. No belugas were seen in Radstock Bay on 1 August, 1996, but a group of about 250 was counted in Maxwell Bay. Both groups were found in association with sea birds, and in Maxwell Bay with several hundred harp seals (*Phoca groenlandica*), in what appeared to be feeding aggregations. On 1 August, about 350 were counted in the inlet on the north side of Coningham Bay and on 2 August, 346 were counted on photographs of this inlet (100% coverage at 5,000 ft). In addition, on 2 August, 78 and 474 belugas were counted visually in Willis Bay and Transition Bay, respectively. The sightings of narwhals were concentrated in Prince Regent Inlet, and in southern Peel Sound (Fig. 6). In

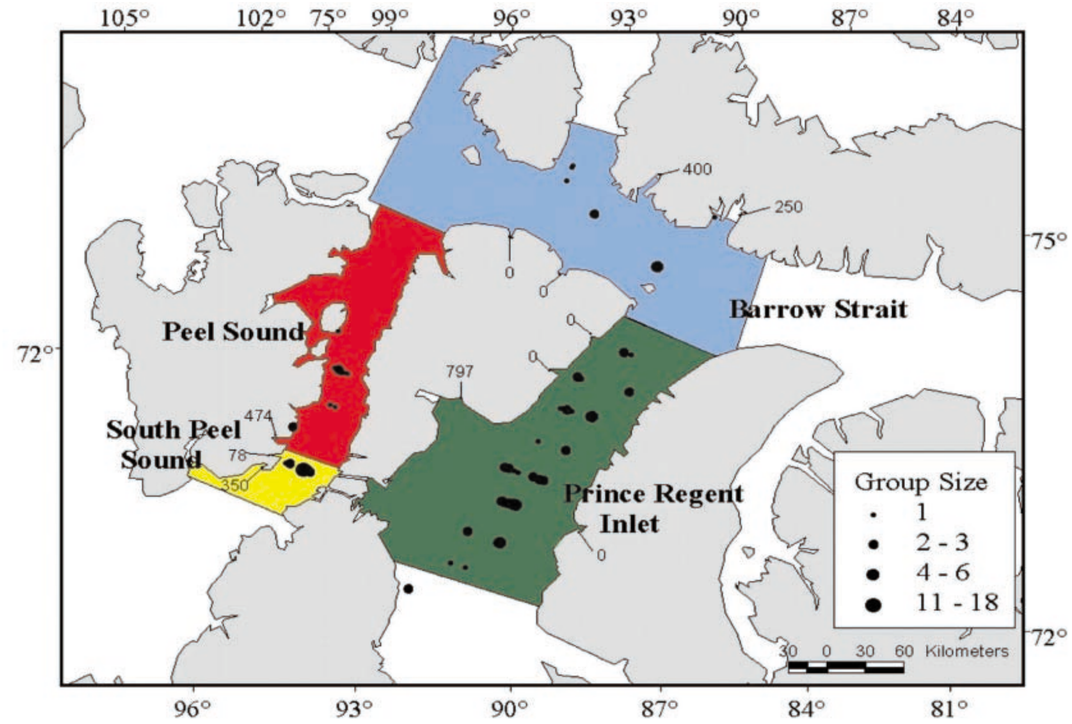


Fig. 5. Sightings of belugas made by the front observers with definitions of regions.

both areas the narwhals were seen primarily offshore in areas with deep water.

Data selection

Low cloud ceiling prevented the survey from being completed at the target altitude of 305 m and some transect lines had to be flown at 152 m or at variable altitudes (see Table 1). Some transect lines encountered Beaufort sea states above 2 and some had to be flown at 366 m to avoid turbulence. In one region (Barrow Strait) the two bordering transects (nos. 1 and 11) were flown at 305 m and the rest at 152 m. Since the data recorder failed on one side of transect 11, we excluded transect 11 from the analyses. Transects 19.3 and 19.4 encountered sea state 3 on the entire transects and were therefore excluded. Transect 20 in the northern area of Peel Sound was not included due to fog and variable flight altitudes.

The observation windows were flat which precluded observing directly below the aircraft. However, even if that region was excluded the histograms of the distance data were non-monotonic (Fig. 7) reaching maximum height somewhere near 200 m from the trackline. While it is possible to fit a non-monotonic detection function, we chose to avoid this complication and left-truncated the data at a distance of 200 m from the trackline. This excluded 14% and 19% of the beluga and narwhal observations, respectively. We did not right-truncate the data and used the maximum observation as the transect width (W=948-200=748m).

Table 2. Counts of belugas in estuaries. The corrected number of whales is corrected for an estimate of availability bias of 87.5 % at 0 to 2 m (cv=0.032). Coefficient of variation is shown in parenthesis.

	Creswell Bay	Radstock Bay	Maxwell Bay	Willis Bay	Transition Bay	Sum
Date	31 July	31 July	1 August	2 August	2 August	
Number of whales observed at surface	797	400	250	78	474	1,999
Number of whales corrected for availability bias ≤2m	910	457	286	89	541	2,283 (0.03)

Fig. 6. Sightings of narwhals made by the front observers with definitions of regions.

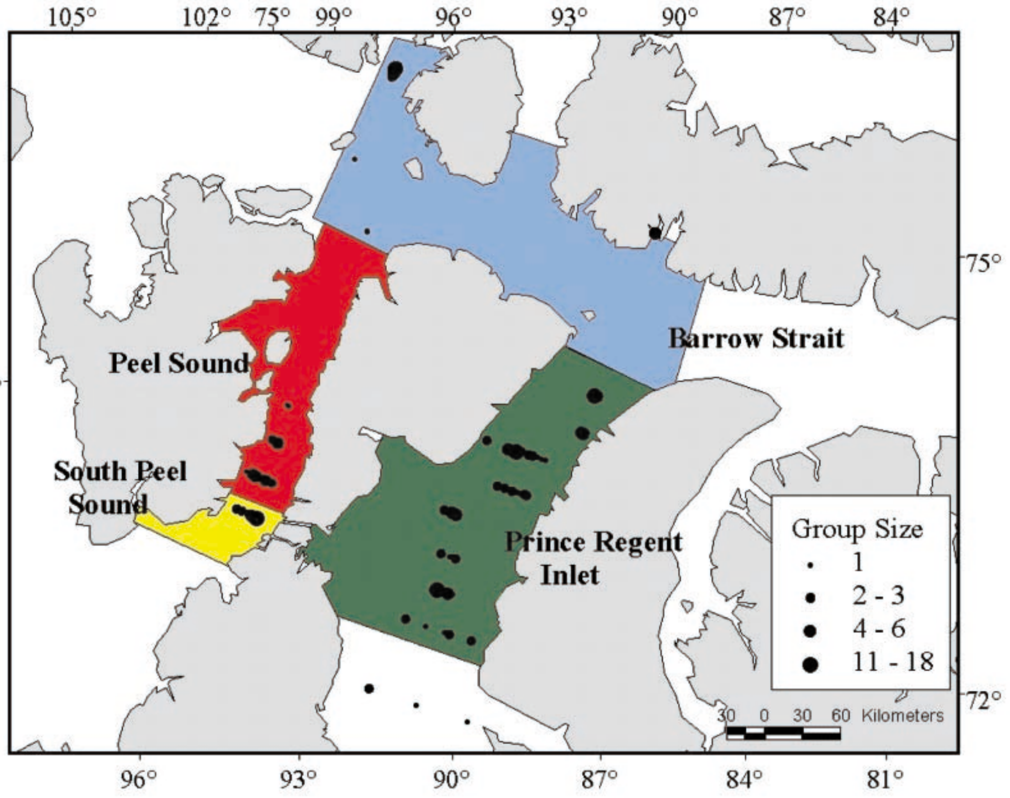


Fig. 6. Sightings of narwhals made by the front observers with definitions of regions.

Estimation of perception bias

The models of perception bias for both beluga and narwhal detections demonstrated the obvious effect that larger groups were easier to detect than smaller groups (Tables 3 and 4, Fig. 8). The only other important effect was due to variation in detection probability of narwhal between regions. The effect of regions in the scale model was primarily due to a steeper decline in detection probability with distance for Prince Regent Inlet (Table 4). The more striking difference due to regions was in g*(z) (Fig. 9). Detection probability of a single narwhal at x=0 (+200m offset) was lowest in Barrow Strait (0.27) and highest in Peel Sound (0.86). There were numerous differences between regions (observers, altitude, visibility conditions) so it is difficult to attribute these differences to any one reason. Interpretation of the differences is further confused by the lack of any regional differences in beluga detection probability.

The average detection probability within the 750 m strip (200-950 m on either side of the line) was higher in general for beluga than narwhal. In Barrow Strait, the average detection probability was 0.43 for beluga and 0.25 for narwhal. In Prince Regent Inlet, the average detection probability was 0.44 for beluga and 0.26 for narwhal. Peel Sound was the only exception with average detection probability for narwhal at 0.66 exceeding the average for beluga at 0.44.

For both the beluga and narwhal detection probability, the differences in the estimates for various models were relatively small. The differences in detection probability and estimated abundance between the simplest model (intercept only) and the chosen model was less than 1% and 3%, respectively, for beluga and 6% and 12%, respectively, for narwhal. The latter differences reflect the large differences between regions.

Correction for missing distances

The beluga abundance estimates were increased by 10% (11/109) to adjust for the 11 groups that were missing a distance. Likewise, the narwhal abundance estimates were increased by 7% (9/134) to adjust for the 9 observations that were missing a distance. There was slight variation in the proportion of missing distances between regions. Had we used region-specific corrections for missing distances, the total abundance estimate would have changed by less than 1%. Some regional estimates would have changed more but the uncertainty was already exceptionally large for the region specific estimates.

Estimation of availability bias

Eleven tags transmitted time-at-depth information during the survey (see Heide-Jørgensen *et al*. 2001). During that period the belugas spent considerable time inside estuaries. To separate offshore surfacing time from estuarine surfacing time, the whales that spent >89% of their time ≤ 6m depth were considered to be in the shallows. In the offshore areas, it was assumed that a beluga could be seen to 4 m in depth (see Richard *et al*. 1994), whereas in the less transparent estuaries, it was assumed that belugas could only be detected to 2 m in depth. Thus, 2 surfacing times were calculated for a period of 5 days before and after the survey for 11 belugas. The offshore surfacing time of belugas was 54% of the time above 4 m (cv=0.014) and the inshore surfacing time was 87% of the time above 2 m (cv=0.032).

Richard *et al*. (1994) found that submerged narwhal models could be detected and correctly identified to species to approximately 2 m in depth on analog aerial photographs. Two studies have estimated the time spent at the interval 0 to 2 m depth for narwhals: Martin *et al*. (1994) found that a female narwhal during August spent about 48% of its time between 0 and 2 m in depth and Laidre *et al*. (2002) studied 2 male narwhals in the same area and period and found that they spent 5.7% and 18.7% of their time at 0 to 2 m in depth. Studies of a large number of narwhals in Canada and Greenland showed that the surface time at 0 to 5 m depth is close to 50% during August (Heide-Jørgensen *et al*. 2001). The three whales that were exam-

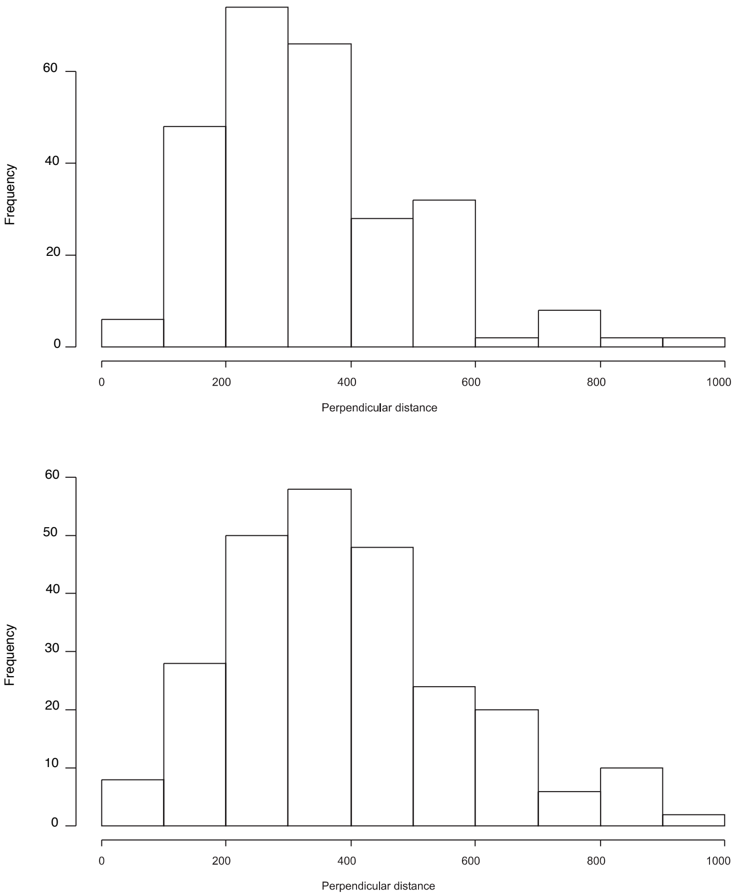


***Fig. 7**. Histogram of perpendicular distance (m) for all on-effort observations of narwhal (A) and beluga (B) during systematic surveys. The remaining plots of distance are relative to the 200 m offset from the line directly below the aircraft.*

Table 3. Parameter estimates and standard errors for detection probability models of narwhal and beluga observation data. The parameters are expressed using treatment contrasts for factor (*e.g.* regions) variables where the intercept represents the value for the first factor (regions) and the other estimates are differences. For example, $g^*(z)=e^{-1.28+2.82+2*0.29}/(1+e^{-1.28+2.82+2*0.29})$ is the detection probability at x=0 for narwhal in Peel Sound for a group of 2 whales and for Barrow Strait (the intercept) the same probability is $g^*(z)=e^{-1.28+2*0.29}/(1+e^{-1.28+2*0.29})$ The scale is parameterized in the same manner using a log-link function.

	Model	Effect	β	SE
Narwhal	g^*	Intercept	-1.28	0.86
		Size	0.29	0.17
		Prince Regent Inlet	1.28	0.73
		Peel Sound	2.82	1.42
		Effect	**θ**	**SE**
	Scale - g_1 & g_2	Intercept	5.82	0.22
		Prince Regent Inlet	-0.66	0.23
		Peel Sound	-0.13	0.26
	Scale – g_3	Intercept	9.30	10.13
		Prince Regent Inlet	-4.21	10.13
		Peel Sound	-4.27	10.13
Beluga		**Effect**	**β**	**SE**
	g^*	Intercept	0.14	0.35
		Size	0.22	0.18
		Effect	**θ**	**SE**
	Scale - g^* & g_2	Intercept	5.71	0.08
	Scale - g_3	Intercept	5.61	0.11

ined for surface times for the 0 to 2 m depth spent 30.3%, 52.9% and 55.7% of their time at 0 to 5 m, which suggests that the whale with a low time at both 0 to 2 m and 0 to 5 m deviates from the other whales. If that whale is excluded, an average surface time for 0 to 2 m of 38% (cv=0.25) is achieved.

Abundance estimation

Four regions provided uncorrected beluga abundance estimates (incl. the photographic survey in southern Peel Sound) of 9,577 (cv=0.28) belugas at the surface with the largest densities in Prince Regent Inlet and southern Peel Sound (Table 5). When the three regions that were

Table 4. AICc values of fitted models of detection probability for beluga and narwhal observation data. The model with the lowest AIC value is indicated by bold script.

		Scale model						
	g(0) model	**Intercept**	**Region**	**Altitude**	**Platform**	**Group size**	**Region+ Platform**	**Region+ Group size**
Beluga	Intercept	1,637.3	1,643.2	1,639.6	1,639.2	1,640.4		
	Region	1,640.9	1,649.1	1,643.9	1,643.0	1,644.2		
	Altitude	1,638.9	1,645.6	1,641.8	1,640.9	1,642.2		
	Platform	1,638.9	1,644.7	1,641.0	1,639.7	1,642.0		
	Group size	**1,636.1**	1,643.0	1,637.7	1,638.0	1,638.7		
	Group size + Region	1,640.5						
	Group size + Altitude	1,638.1						
	Group size + Platform	1,637.6						
Narwhal	Intercept	1,573.6	1,560.4	1,575.0	1,575.7	1,574.0		
	Region	1,577.6	1,563.1	1,577.9	1,579.8	1,580.6		
	Altitude	1,575.5	1,562.7	1,576.2	1,577.6	1,575.5		
	Platform	1,573.6	1,560.8	1,575.1	1,574.2	1,572.8		
	Group size	1,572.6	1,559.8	1,574.3	1,574.7	1,576.1	1,562.1	1,564.2
	Group size + Region		**1,558.9**				1,561.5	1,563.4
	Group size + Altitude		1,560.9				1,563.3	1,565.3
	Group size + Platform		1,560.1				1,562.0	1,564.6

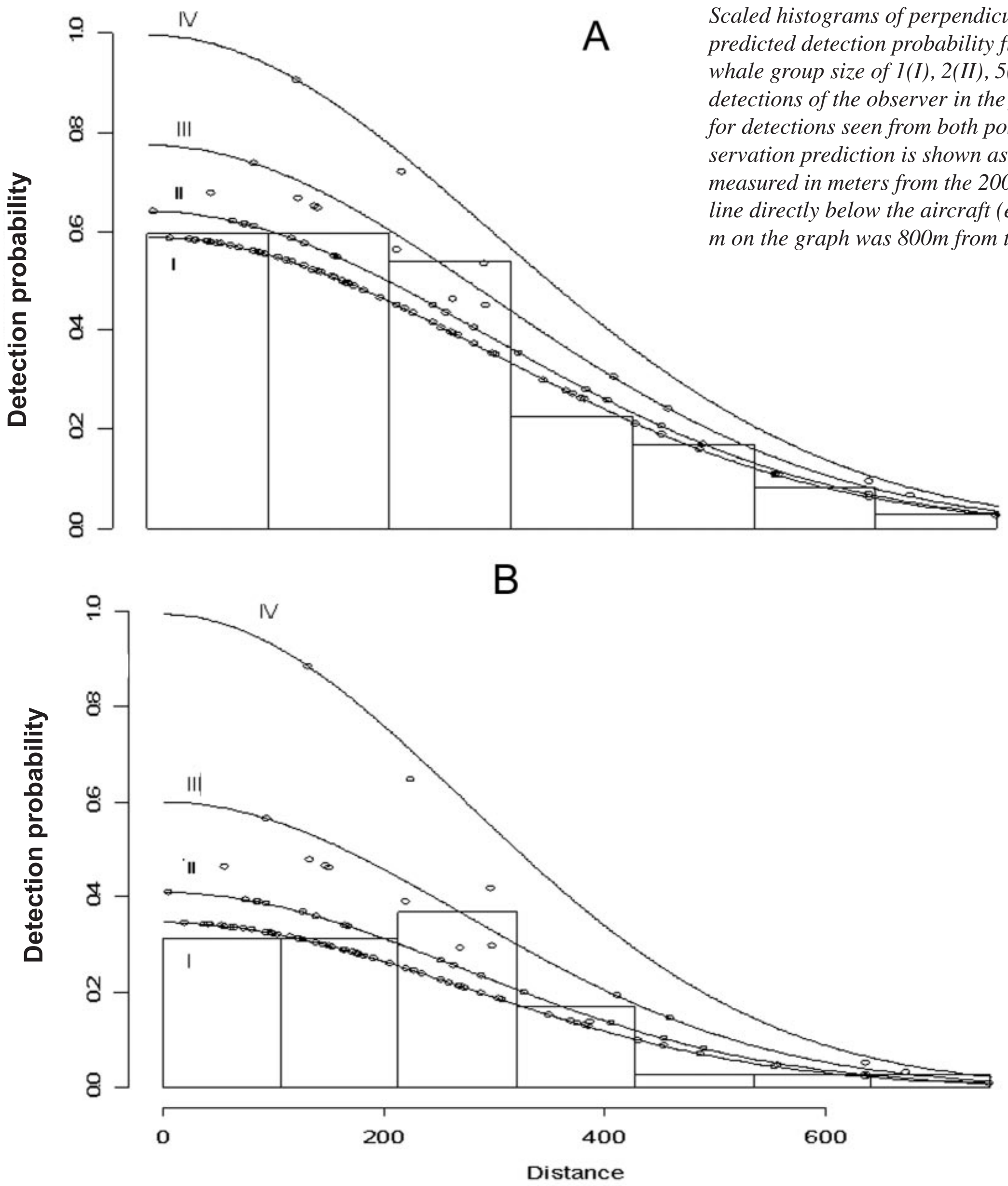
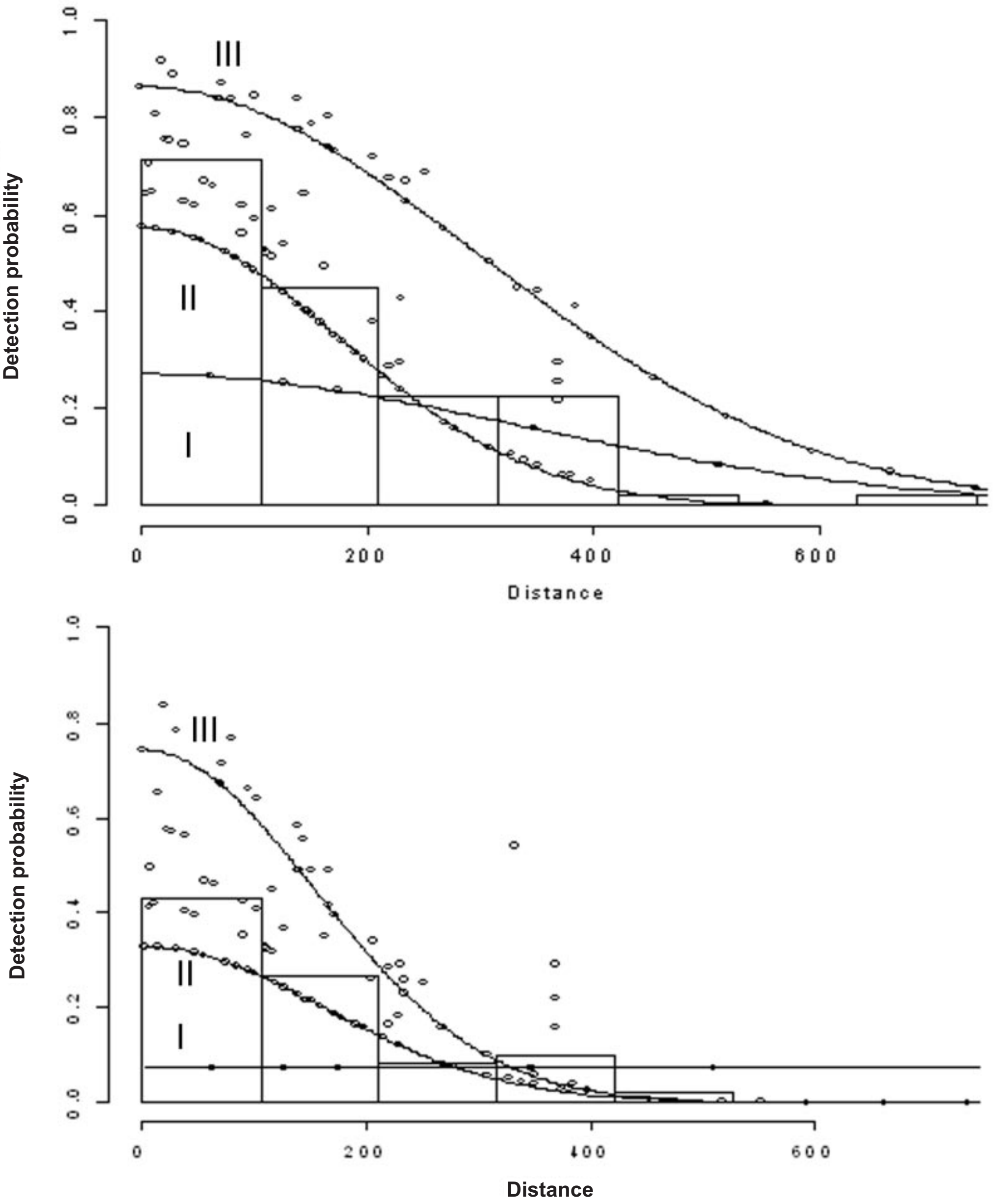


Fig. 8.
Scaled histograms of perpendicular distances and predicted detection probability functions for beluga whale group size of 1(I), 2(II), 5(III) and 25(IV) for detections of the observer in the front seat (A) and for detections seen from both positions (B). Each observation prediction is shown as a circle. Distance is measured in meters from the 200 m offset from the line directly below the aircraft (e.g. a distance of 600 m on the graph was 800m from the line).

covered by visual surveys were corrected for missing data on distance to sightings, the total estimate for all four regions was 10,347 (cv=0.28). When the correction factor for submerged whales was applied to the offshore and photographic survey in southern Peel Sound, the corrected abundance estimate was 18,930 belugas (cv=0.28). Belugas were seen off transect in only a few of their traditional estuaries (see Table 2) and when these counts were added to the estimate, corrected for the inshore availability factor (0.87, cv=0.032), the abundance estimate was 21,213 belugas (95% CI: 10,985 to 32,619).

For the three regions, the total narwhal abundance was 16,364 (cv=0.24) narwhals present at the surface with the largest densities in Prince Regent Inlet (Table 6). The abundance estimate was adjusted upward by 7% for the sightings with missing distances which gave an estimated total for the three regions of 17,463 (cv=0.24) narwhals at the surface. Applying a surface correction factor of 0.38 (cv=0.25) to the estimated

Fig. 9.
Scaled histograms of perpendicular distances and predicted detection probability functions for a single narwhal whale in Barrow Strait (I), Prince Regent Inlet (II), and Peel Sound (III) for detections of the observer in the front seat (A) and for detections seen from both positions (B). Each observation prediction is shown as a circle. Distance is measured in meters from the 200 m offset from the line directly below the aircraft (e.g. a distance of 600 m on the graph was 800m from the line).



number of whales at the surface produces an estimate of the total number of narwhals of 45,358 (95 % CI: 23,397 to 87,932).

DISCUSSION

In this survey, 120 beluga sightings were expanded to a survey estimate of 21,213 belugas (95% CI = 10,985– 32,619) based on line transect estimation methods and adjustments made to account for belugas not at the surface and belugas counted in estuaries. Similarly, for narwhals, less than 100 sightings were used to derive an estimate of 45,358 narwhals (95% CI = 23,397 to 87,932) using line transect methods and adjusting for submerged whales.

While the transect coverage for this survey represents only a small proportion of the study area, it is comparable to the amount of coverage used in other marine mammal surveys (*e.g.* Norton and Harwood 1985, Smith *et al.* 1985, Stenson *et al.* 1993, Harwood *et al.* 1996) and this level of effort is sufficient to survey areas where there is little aggregation (*i.e.* belugas or narwhals are dispersed in small groups over the survey area). Thus, the survey most likely represents the number of belugas in Prince Regent

Table 5. Survey estimates of beluga abundances in different regions (see Fig. 5) in the Canadian High Arctic in July-August 1996. The density in the unsurveyed northern part of Peel Sound is assumed to be similar to the density in central Peel Sound. The sightings are given as the total number of sightings (n) and the number with missing distances (n_m). The corrected number of whales is corrected for an estimate of availability bias of 0.55 (cv= 0.04). Coefficient of variation is shown in parenthesis.

	Barrow Strait	Central Peel Sound	Prince Regent Inlet	Southern Peel Sound photographic survey	Sum
Area, km² (A)	27,405	11,612	29,296	1,523	68,313
Altitude, m	152	305	152-305	701-914	
Effort in km (L)	951	332	825	337	2,108
Number of transect lines (k)	10	6	8	9	24
Sightings, n/n_m	14/1	80/7	26/3	409	120/11
Pod size	1.13	1.46	1.77	-	1.64
Density of whales (whales per km²)	0.015	0.144	0.190	1.28	0.112
	(0.52)	(0.40)	(0.43)	(0.22)	(0.34)
Extrapolated number of whales corrected for perception bias ($\hat{N}$)	400	1,670	5,559	1,949	9,577
	(0.52)	(0.40)	(0.43)	(0.22)	(0.28)
Adjustment for missing distances ($\hat{N}$*)	440	1,838	6,120	1,949	10,347
	(0.52)	(0.40)	(0.43)	(0.22)	(0.28)
Number of whales corrected for availability bias ($\hat{N}$**)	805	3,363	11,196	3,566	18,930
	(0.53)	(0.40)	(0.43)	(0.22)	(0.28)
Addition of belugas seen in estuaries					21,213
					(0.25)

Inlet, Barrow Strait and Peel Sound reasonably well, although a few sightings in high sea state on the southern transects in Prince Regent Inlet indicate that belugas can be found south of the surveyed area in Prince Regent Inlet. This level of sampling effort may not accurately reflect the density of belugas in estuaries or in a few large and widely-dispersed groups off transect. Smith *et al*. (1985) reported 27 beluga groups in August 1981, of which 3 contained between 16 and 40 whales. During our survey, the front observers saw 101 groups (on and off effort) of which only one contained between 16 and 40 belugas (Fig. 5). However, the group size differences between Smith *et al*. (1985) and the present study were not statistically significant.

The occasional large groups or large densities of whales are difficult to pick up in low intensity sampling surveys. In the present survey, a high density area in southern Peel Sound was covered through intense photographic sampling, adding considerably to the precision of the total abundance estimate for belugas.

Within the survey area there are 13 estuaries traditionally used by belugas: Creswell Bay, Batty Bay, Elwin Bay, Garnier Bay, Cunningham Inlet, Aston Bay, Transition Bay, Willis Bay, Coningham Bay, Radstock Bay, Maxwell Bay, Fitzgerald Bay and Cape Kater (Sergeant and Brodie 1975, Smith *et al*. 1985, Martin *et al*. 1993, Smith and Martin 1994, Richard *et al*. 2001). Many transects in our visual survey ended near estuaries but none actually included an estuary. Thus, belugas in estuaries were likely under-represented. While these traditional estuaries were not included in the survey transects, they were visited during ferrying flights and observer or photographic counts were made. These counts represented about 2,000 belugas which, when adjusted for the proportion of time spent at the surface, increased to 2,283. This estuary count has been

Table 6. Survey estimates of narwhal abundances in three regions (see Fig. 6) in the Canadian High Arctic in July-August 1996. The density in the inadequately surveyed northern part of Peel Sound is assumed to be similar to the density in central Peel Sound. The sightings are given as the total number of sightings (n) and the number with missing distances (n_m). The corrected number of narwhals is corrected for an estimate of availability bias of 0.38 (cv=0.25). Coefficient of variation is shown in parenthesis.

	Barrow Strait	Central Peel Sound	Prince Regent Inlet	Sum
Area, km^2 (A)	27,405	14,735	29,296	71,436
Altitude, m	152	305-366	152-305	
Effort, km (L)	951	470	825	2,246
Number of transect lines (k)	10	8	8	26
Sightings, n/n_m	17/4	86/1	40/4	143/9
Pod size	2.77	1.92	2.05	2.08
Density of whales (whales per km^2)	0.08	0.13	0.42	0.23
	(0.71)	(0.55)	(0.25)	(0.24)
Extrapolated number of whales corrected for perception bias ($\hat{N}$)	2,150	1,891	12,324	16,364
	(0.71)	(0.55)	(0.25)	(0.24)
Adjustment for missing distances ($\hat{N}$*)	2,293	2,017	13,151	17,463
	(0.71)	(0.55)	(0.25)	(0.24)
Number of whales corrected for availability bias >2m ($\hat{N}$**)	5,898	5,240	34,159	45,358
	(0.75)	(0.60)	(0.35)	(0.35)

added to the survey estimate and its confidence intervals to produce a total abundance of belugas.

Fewer belugas were seen or photographed within estuaries compared to numbers counted in previous surveys. During the August 1981 survey, Smith *et al*. (1985) reported about 5,100 belugas in estuaries, not including counts from three major estuary aggregations along the eastern coast of Prince of Wales Island. Although they give little detail of their surveys, Sergeant and Brodie (1975) reported up to 10,000 belugas in estuaries and bays of the same area. The reasons why fewer belugas were present in estuaries in this study are unclear but could be related to the pattern of ice break-up in July that favoured early estuary use in 1996. The Barrow Strait floe edge was west of Somerset Island during the winter of 1995/96. This is unusually far west compared to typical years, when it forms from Prince Leopold Island north to Devon Island or from Brodeur Peninsula north to Devon Island (Finley *et al*. 1990, Hammill *et al*. 1991). Belugas may have been able to use these estuaries earlier in 1996 than in most years in the last several decades. Consistent with this 'early' year hypothesis, the peak of the 1996 migration into the estuaries appeared to be about 10 days earlier than average (T. Smith, pers. comm.). Therefore, belugas may already have moved out of the estuaries they traditionally used in early to mid-summer, when the previous aerial surveys were usually flown.

Direct comparison of this survey with previous surveys is difficult because earlier surveys did not have the same timing nor did they cover the same area. Both belugas and narwhals show large shifts in distribution during July and August and surveys conducted at different dates during the 2 months likely yield different results. The 1981 survey (Smith *et al*. 1985) did not include Peel Sound and the 1984 survey (Richard *et al*. 1994) did not include Barrow Strait. There were an estimated 3,702 belugas (cv=0.20) in Prince Regent Inlet and Barrow Strait in early August (10 and 14) 1981 (Smith *et al*. 1985). In this survey, there were about 5,959 (cv=0.40) belugas in the same area. The latter estimate is corrected for perception bias, but timing of surveys alone could explain the different estimates. We encountered most belugas in Prince Regent Inlet, whereas more belugas were seen in Barrow Strait and western Lancaster Sound in the 1981 survey. A larger proportion of the belugas might have been in Peel Sound when Smith *et al*. (1985) did their survey because belugas are known to move to Peel Sound in early August (Richard *et al*. 2001).

The uncorrected density of narwhals was generally about twice the density of belugas and the precision of the estimate was better for narwhals. The corrected narwhal abundance estimate was, however, much less precise than the beluga survey. This is due to the high variability of the estimate for the availability bias. The precision of the survey could be considerably improved with an increased sample size of TDR deployments, sampling the diving and surfacing behaviour of narwhals. These data are valuable for developing more precise correction factors for availability bias for cetaceans.

Smith *et al*. (1985) also reported a higher abundance of narwhals than belugas from their survey. They estimated 11,142 (cv=0.09) narwhals in Barrow and Prince Regent Inlet in August 1981 compared to the present estimate of 14,474 (cv=0.24) narwhals at the surface in the same area. The latter survey is corrected for perception bias, which could account for most of the difference. A survey in late August 1984 estimated 9,754 (cv=0.18) and 1,701 (cv=0.17) narwhals at surface in Prince Regent Inlet and Peel Sound, respectively (Richard *et al*. 1994), which is similar to the present estimate of 12,324 (cv=0.25) and 1,891 (cv=0.55) narwhals corrected for perception bias.

The highly variable number of sightings of belugas per kilometre survey line made the largest contribution to the variance of the beluga abundance estimate (91%). The variance estimate for narwhals was most influenced by the low precision on the availability bias (52%). The sighting rate was the second largest contributor to the variance (40%). The detection probability contributed equally to the variance for both species (8%). Obvious ways to improve estimates of both species would be increased survey effort, better allocation of effort (less effort in Barrow Strait), and more high-intensity photographic sampling of concentration areas. However, between year differences in the timing and pattern of the breakup of fast ice will alter whale distributions in ways that can not be anticipated before the survey season.

In this study, we assumed that the observers could not detect belugas deeper than 4 m below the surface and narwhals deeper than 2 m. Although this is consistent with prior experimental evidence (Richard *et al*. 1994), selecting a shallower depth would increase the adjustment factor considerably. Further refinement of abundance estimates for narwhals would require more testing of the visibility of whales at different depths and the collection of more data on the proportion of time spent at these depths.

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