

Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002–04

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ABSTRACT. Aerial surveys of narwhals (*Monodon monoceros*) were conducted in the Canadian High Arctic during the month of August from 2002 to 2004. The surveys covered the waters of Barrow Strait, Prince Regent Inlet, the Gulf of Boothia, Admiralty Inlet, Eclipse Sound, and the eastern coast of Baffin Island, using systematic sampling methods. Fjords were flown along a single transect down the middle. Near-surface population estimates increased by 1.9%–8.7% when corrected for perception bias. The estimates were further increased by a factor of approximately 3, to account for individuals not seen because they were diving when the survey plane flew over (availability bias). These corrections resulted in estimates of 27 656 (SE = 14 939) for the Prince Regent and Gulf of Boothia area, 20 225 (SE = 7285) for the Eclipse Sound area, and 10 073 (SE = 3123) for the East Baffin Island fiord area. The estimate for the Admiralty Inlet area was 5362 (SE = 2681) but is thought to be biased. Surveys could not be done in other known areas of occupation, such as the waters of the Cumberland Peninsula of East Baffin, and channels farther west of the areas surveyed (Peel Sound, Viscount Melville Sound, Smith Sound and Jones Sound, and other channels of the Canadian Arctic archipelago). Despite these probable biases and the incomplete coverage, results of these surveys show that the summering range of narwhals in the Canadian High Arctic is vast. If narwhals are philopatric to their summering areas, as they appear to be, the total population of that range could number more than 60 000 animals. The largest numbers are in the western portion of their summer range, around Somerset Island, and also in the Eclipse Sound area. However, these survey estimates have large variances due to narwhal aggregation in some parts of the surveyed areas.

Key words: Monodontidae, line transect, mark-recapture distance sampling, population size, High Arctic, fiord

RÉSUMÉ. Des levés aériens ont été effectués dans l'Extrême arctique canadien dans le but de répertorier les populations de narvals (*Monodon monoceros*) et ce, du mois d'août 2002 à août 2004. Les levés, réalisés à l'aide de méthodes d'échantillonnage systématiques, visaient les eaux du détroit de Barrow, de l'inlet Prince-Régent, du golfe de Boothia, de l'inlet de l'Amirauté, du détroit d'Éclipse et de la côte est de l'île de Baffin. Les fjords ont été survolés le long d'un simple transect situé dans le milieu. Les estimations de population près de la surface augmentaient de 1,9 % à 8,7 % une fois redressées pour tenir compte du biais de perception. Par ailleurs, les estimations ont été de nouveau révisées à la hausse moyennant un facteur d'environ 3 afin de tenir compte des individus qui n'ont pas été vus parce qu'ils se mettaient à plonger en présence de l'avion effectuant les levés (biais de disponibilité). Ces redressements ont donné lieu à des estimations de 27 656 (SE = 14 939) pour la région de l'inlet Prince-Régent et du golfe de Boothia, de 20 225 (SE = 7 285) pour la région du détroit d'Éclipse et de 10 073 (SE = 3 123) pour la région du fiord de l'est de l'île de Baffin. Quand à l'inlet de l'Amirauté, l'estimation s'est chiffrée à 5 362 (SE = 2 681), mais l'on croit que cette estimation pourrait être biaisée. Des levés n'ont pas pu être effectués dans d'autres zones d'occupation connues, comme dans les eaux de la péninsule Cumberland dans l'est de Baffin de même que dans les chenaux plus à l'ouest des régions examinées (détroit de Peel, détroit du Vicomte de Melville, détroit de Smith, détroit de Jones et d'autres chenaux de l'archipel Arctique canadien). Malgré la possibilité que les données soient biaisées et que certaines zones n'aient pas été examinées, les résultats de ces levés montrent que la répartition d'été des narvals dans l'Extrême arctique canadien est vaste. Si les narvals sont philopatriques à leurs aires d'été, comme il semblerait être le cas, la population totale de ce parcours pourrait dépasser les 60 000 individus. Les plus grands nombres se trouvent dans la partie ouest de cette répartition, soit près de l'île Somerset et dans la région du détroit d'Éclipse. Cependant, les estimations découlant de ces levés ont de grandes variances en raison du regroupement des narvals dans certaines parties des régions visées par les levés.

Mots clés : monodontidés, transect linéaire, échantillonnage par distance et marquage-recapture, taille de la population, Extrême arctique, fiord

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INTRODUCTION

The narwhal (*Monodon monoceros*) is one of two medium-sized toothed cetaceans that occupy the northernmost waters of the planet (Reeves and Tracey, 1980). It is a species well adapted to life in the seasonally ice-covered waters where it resides year-round (Richard, 2007). Narwhals summer in the Canadian High Arctic archipelago and in northern Hudson Bay (Richard, 1991; Richard et al., 1994). They are the subject of an active hunt in spring, summer, and fall by various Inuit communities of Nunavut, particularly in the Qikiqtani region, which includes Baffin Island and the Canadian High Arctic communities (Priest and Usher, 2004). Hunting quotas were established in the early 1980s in response to concerns that the sale of ivory tusks might lead to overexploitation of the narwhal population (Land, 1976; Kemper, 1980). These quotas, based on historic hunt levels and limited population information, were negotiated with the communities (Strong, 1988). At the time, the Canadian High Arctic narwhal population had been roughly estimated to number between 20 000 and 30 000 animals (Davis et al., 1978; Smith et al., 1985). However, because population data were imprecise, a detailed assessment of sustainability could not be conducted.

Concerns have been raised about the lack of adequate scientific knowledge pertaining to the sustainability of the narwhal hunt (Reeves, 1992) and the absence of a management system that has legitimacy with the hunters (Richard and Pike, 1993). In 1994, implementation of the Nunavut Land Claim Settlement Act led to the creation of the Nunavut Wildlife Management Board, a body responsible for the co-management of wildlife in Nunavut. New population surveys were also conducted in the High Arctic (Richard et al., 1994; Innes et al., 2002a), but resulting estimates suffered either from a lack of correction for diving animals missed during surveys (Richard et al., 1994), or from limited coverage (Innes et al., 2002a).

In 2004, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recommended that the narwhal be listed under Canada's Species at Risk Act as a species of "special concern" because of "uncertainty about its numbers, trends, life history parameters, and levels of sustainable hunting" (Species at Risk Public Registry, 2005). At its 2005 meeting, the Canada-Greenland Joint Commission on the Conservation and Management of Narwhal and Beluga (JCNB, 2006) reviewed a report on the status of narwhals in Canada and West Greenland by its Joint Scientific Working Group (JWG) with the North Atlantic Marine Mammal Commission and noted, amongst other things, that there is a risk that present catch levels are not sustainable in one of the Canadian sub-stocks considered. The JWG adopted a precautionary approach to delineation of narwhal stocks that is based on their summering areas and evidence that radio-tracked animals are relatively sedentary in summer. Tracked animals remained in the areas where they were tagged and did not visit other narwhal summering areas (Dietz et al., 2001, 2008; Heide-

Jørgensen et al., 2002, 2003). The evidence for multi-year site fidelity is weaker, based so far on only three animals (Heide-Jørgensen et al., 2003; Dietz et al., 2008), but it was considered compelling enough for the JWG to suggest that summering aggregations be managed separately for precautionary reasons (JCNB, 2006). More recently, the International Union for Conservation of Nature (IUCN) listed the narwhal as "near threatened" on the basis of "substantial uncertainty about numbers and trends in large parts of the range" and concerns about "intense hunting (including associated loss due to wounding and sinking) in Greenland and Canada" (IUCN, 2008). Energy and mining interests and the opening of the Northwest Passage in summer as a result of climate warming have led to growing vessel traffic, seismic exploration, and plans for future port development in the Canadian High Arctic.

These concerns highlight the need for a comprehensive assessment of narwhal populations in the Canadian Arctic. The present study, which reports on vast surveys conducted in 2002–04 in the Canadian Eastern Arctic, contributes to such an assessment by providing an update on population numbers. The survey coverage of Canadian High Arctic narwhal summering areas is the most complete to date for that region, including previously unsurveyed areas of the Gulf of Boothia and the east coast of Baffin Island. Furthermore, the estimation methods used here incorporate two new approaches to correct for biases in the estimation of narwhal numbers: a mark-recapture distance-sampling method, which corrects for incomplete visual detection at the track line, and an availability-bias correction method, which adjusts for animals missed during surveys because they were diving at depths where observers could not see them. The distribution of survey sightings reported here will also inform future assessments of the impact of industrial activities on Canadian High Arctic narwhals.

METHODS

Survey Design

Past tracking studies have shown that narwhals remain in several well-defined summering areas throughout the summer, and there is also reason to believe that narwhals exhibit interannual summering site fidelity (philopatry). Consequently it was reasonable to conduct surveys of different areas over several years in order to cover the vast known range of Canadian High Arctic narwhals, which covers waters from the east coast of Baffin Island to at least the central Arctic archipelago (Richard, 2007). The survey plan included some areas not previously surveyed in summer, such as the Gulf of Boothia and the east coast of Baffin Island, where Department of Fisheries and Oceans' hunt records have shown narwhals to be present in summer. Surveys were conducted in August, when narwhals are aggregated in summering areas and ice cover is minimal. The goal was to cover previously surveyed areas known for their

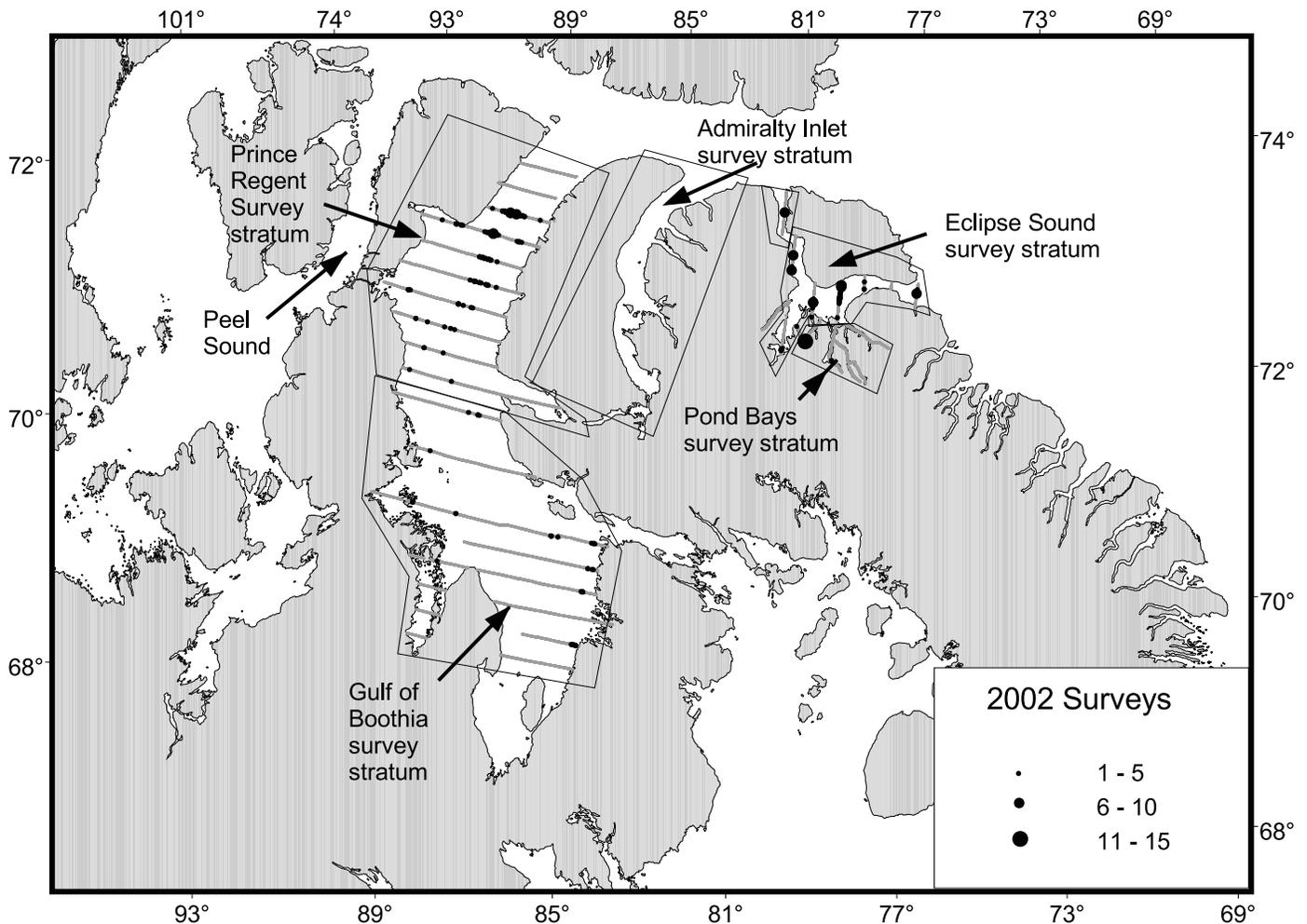


FIG. 1. Narwhal aerial surveys conducted in August 2002, with sightings and group sizes.

summer aggregations of narwhals (Eclipse Sound, Admiralty Inlet, Prince Regent Inlet, and Peel Sound; Fig. 1), but also other areas (the Gulf of Boothia, Baffin Island's eastern coast to Cumberland Sound, Lancaster Sound, and island passages farther north or west of those areas; Figs. 2 and 3). Because of vagaries in weather, that plan had to be modified annually, as explained below, in order to cover certain survey strata that could not be flown in a particular year, or to resample them because marginal visibility conditions or inadequate sampling design produced issues of bias or precision in the results.

Surveys in aggregation areas and large open waterways were systematic random line transects, with the first transect chosen at random and others spaced systematically through the survey stratum. Because fiords are linear and narrow and often surrounded by high vertical walls that make navigation difficult, we flew straight down the middle of them.

Equipment, Crew and Observation Procedure

Surveys were flown in a DeHavilland Twin Otter (DH-6) equipped with standard flat windows with the inner covers removed. The flat windows limited viewing angles from

about 20° from vertical and outward. The survey crew consisted of a recorder and four observers, two on each side. In 2002 and 2003, location, speed, and altitude were measured by a global positioning system (GPS) and a radar altimeter recording every second on a data-logging system operated by the recorder. In 2004, the altitude was recorded using a GPS linked to a satellite differential GPS to improve 3D precision. In all three years, the recorder also operated a Roland multi-channel digital recording system, with a single channel for each observer. Observers received pre-flight training on the types of observations that they were required to make. They were instructed to concentrate their observational effort at close range and to use peripheral vision for sightings farther afield. Observers were paired (front and rear observers) on each side of the airplane and maintained their seat positions in flight. Front and back observers were separated by a curtain so that rear observers could not be cued by reactions of the front observers when sighting an animal, or vice versa. The heavy headsets worn by observers were disconnected from the communication system during sighting effort, and when combined with the loud aircraft noise, completely blocked sounds from other observers. When a whale group was first seen,

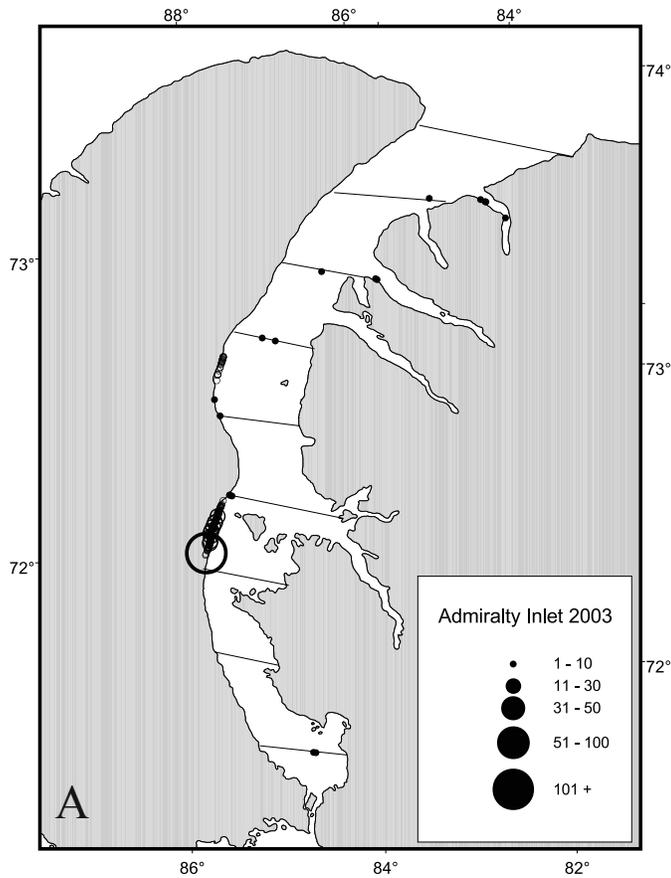
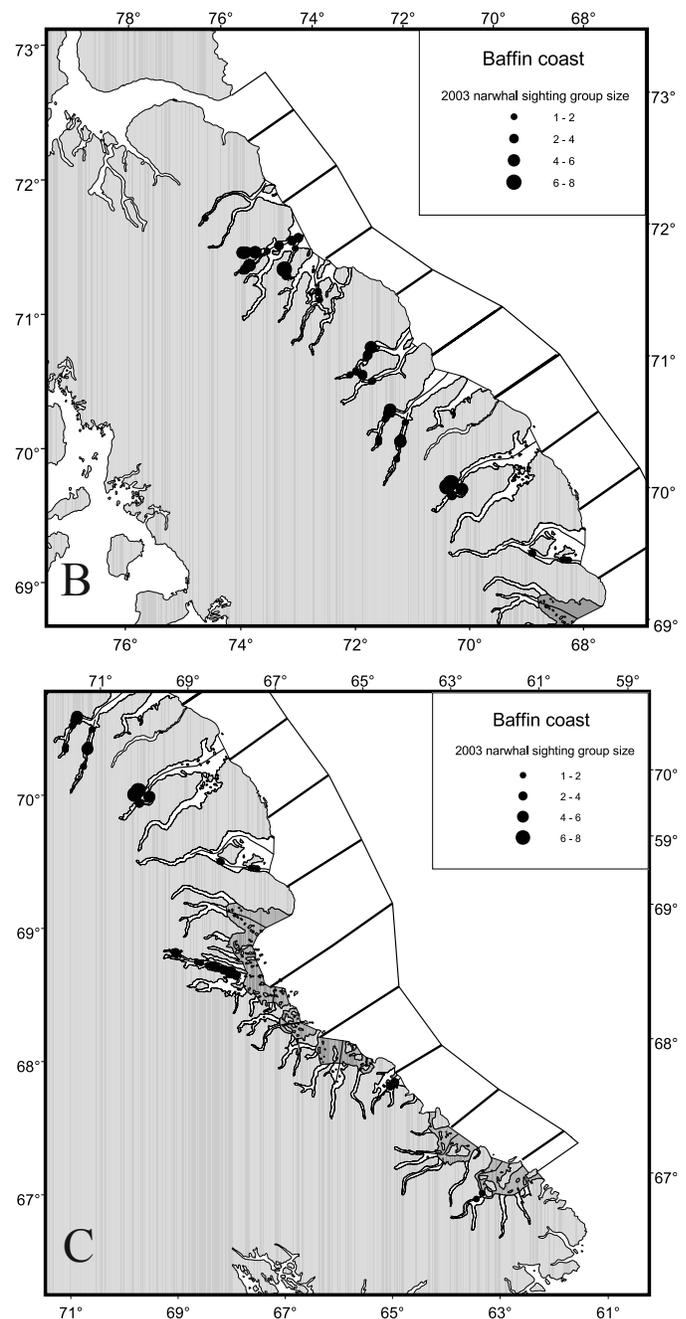


FIG. 2. Narwhal aerial surveys conducted in August 2003, with sighting group sizes: Panel A) Admiralty Inlet; Panel B) East Baffin surveys north half, Panel C) East Baffin Survey south half. Note: The open circles in Admiralty Inlet, which represent the ~500 sightings between transects, illustrate the extreme off-transect clumping during that survey.

observers called “whale” and then stated the species and number of individuals in the group. When the group was abeam, the perpendicular declination angle to the sighting was recorded using a Suunto clinometer. Front observers, who were the most experienced, also made observations on the ice cover (tenths), sea state (Beaufort scale), fog (%), or glare (%) in the front half of their viewing area.

Estimation and Adjustment for Perception Bias (\hat{N})

Observers often miss narwhals at the surface within their field of view (Innes et al., 2002a). This *perception bias* (term coined by Marsh and Sinclair, 1989) can be accounted for by combining line-transect sampling with double-observer counts on each side of the aircraft to estimate the proportion of narwhals that are missed by both observers (Borchers et al., 1998a, b, 2006; Laake, 1999; Innes et al., 2002a; Laake and Borchers, 2004). The combined method estimates the probability of detection ($p(x)$) using line-transect analysis to estimate relative detection probability (assuming $p(0) = 1$) as a function of perpendicular distance (x) from the line and the double-observer data in a mark-recapture (sight-resight) context to estimate detection probability on the line



($p(0)$). To analyze the double-observer data, it is necessary to identify which sightings were seen by both rear and front observer (duplicates). Because the data were collected independently by each observer, we identified duplicate sightings as part of the analysis using the following criterion:

- the timing of both observations was similar within 5 sec
- the group size was similar (± 3 individuals)
- the perpendicular angle was similar (± 10 degrees)

In a few cases ($n = 3$), observers stated some doubts on the accuracy of a reported group size or a perpendicular angle measurement. In those cases, we used comments on the animals' behaviours to determine if these sightings were duplicates.

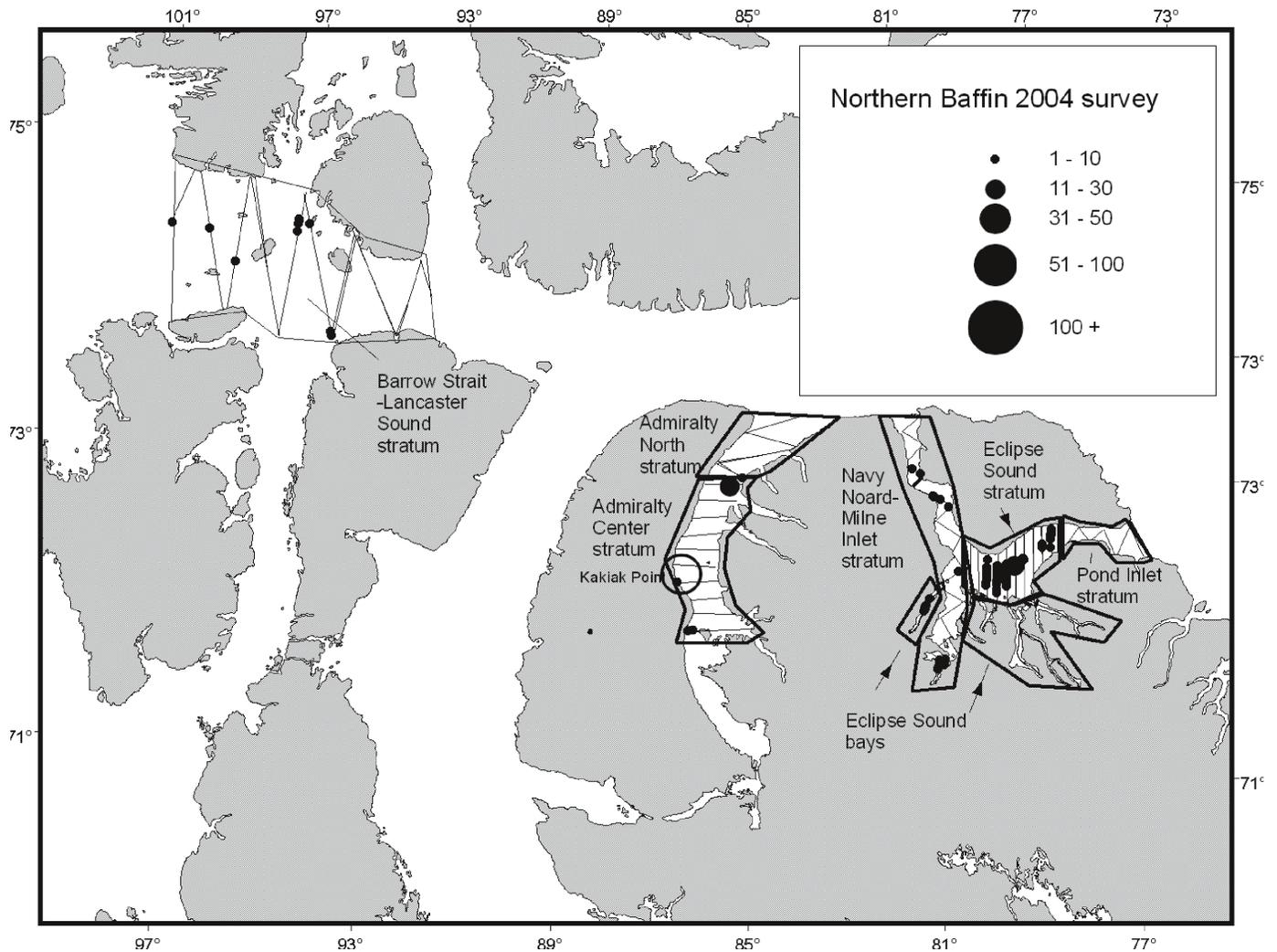


FIG. 3. Narwhal aerial surveys conducted in August 2004 with sighting group sizes. Note: Open circle is a sighting between transects (~300) in Admiralty Inlet, shown to illustrate the extreme clumping off transect during that survey.

The analysis approach, as described by Laake and Borchers (2004) and Borchers et al. (2006), can be viewed as a two-step process. First we obtain a conventional line-transect estimate of the detection function $g(x)$ from the unique observations (duplicates used only once) combining rear and front observations. That function assumes that all narwhals on the line are seen ($g(0) = 1$). The line ($x = 0$) was defined to be offset 300 m in 2002 and 2003 and 200 m in 2004 to compensate for lack of visibility below the aircraft. We refer to $g(x)$ as the unconditional detection function which can incorporate covariates that affect the scale (i.e., how far away narwhals can be detected).

The next step is to “compare” the detections of the rear and front observers to estimate conditional detection functions. The conditional detection functions provide an estimate of $p(0)$, such that the full detection function is $p(x) = p(0)g(x)$, to “correct” the initial estimate from the first step. The term “conditional” represents the comparative nature of the probability estimate. For example, we can crudely estimate a conditional probability that the rear observer saw a narwhal given that it was seen by the front observer

($Pr [seen\ by\ rear\ | \ seen\ by\ front]$) by dividing the number of duplicates by the number seen by the front observer. Likewise, we can estimate $Pr [seen\ by\ front\ | \ seen\ by\ rear]$ by dividing the number of duplicates by the number seen by the rear observer. Those crude estimates are equivalent to estimated probabilities in a Petersen mark-recapture estimator, and they assume that the conditional detection probability does not depend on distance or any other covariate except observer. More realistic conditional detection functions with relevant covariates, like distance, can be fitted using iterative logistic regression. We refer to the set of covariates used in the second step as the conditional model.

As in Innes et al. (2002a), the covariates (w) in the first step affect the scale of the distance at which observations were made and the covariates (z), affect $p(0)$. We used a hazard rate for $g(x)$ and a logistic conditional detection function. The complete detection function can be expressed as:

$$p(x) = \frac{1}{1 + e^{\beta_0 + \sum \beta_i z_i}} \left(1 - e^{-\left(\frac{x}{\sigma(w)}\right)^{-p}} \right)$$

TABLE 1. Fitted models for conditional (mark-recapture) and unconditional (distance) models for distance estimation with two observers (Note: the best fits, models with the lowest Akaike information criteria, are shown; in the conditional (mark-recapture) model, “observer” refers to either front or rear observer on the same side.)

	Mark-Recapture Model	Distance Model
2002 Prince Regent Inlet–Gulf of Boothia		
Function	logistic	hazard rate
Covariates	~distance+observer	~sea.state
2002 Eclipse Sound		
Function	logistic	hazard rate
Covariates	~distance+observer	~ice
2003 East Baffin Fiords		
Function	logistic	hazard rate
Covariates	~distance+observer	~ice
2003 Admiralty Inlet		
Function	logistic	hazard rate
Covariates	~distance+observer	~ice
2004 Eclipse Sound		
Function	logistic	hazard rate
Covariates	~ distance	~stratum + ice
2004 Admiralty Inlet and Barrow Strait		
Function	logistic	hazard rate
Covariates	~ distance	~stratum + ice

TABLE 2. Proportion of the time narwhal instrumented with time–depth recorders spend between 0 and 2 m depth.

Time-Depth Recorder	Sex	Proportion of Time at 2 m or Less
STDR 2006-57595 F	F	0.348
STDR 2006-57599 F	F	0.271
STDR 2006-57599 F	F	0.375
ATDR Cres1	F	0.382
ATDR Cres2	F	0.276
ATDR Trem3	M	0.340
ATDR MM-2 ¹	M	0.287
STDR 2006-57596 M	M	0.286
STDR 2006-57597 M	M	0.305
	Mean	0.319
	SD	0.043
	SE	0.0143
	CV	0.045
	n	9

¹ From Laidre et al., 2002.

where p is the estimated power, $\sigma(w) = e^{y_o + \sum y_i w_i}$, and β and γ are vectors of estimated coefficients for sets of covariates z and w , respectively. Model selection and fitting for the conditional and unconditional detection functions are done separately because the likelihood can be separated into two independent components with no shared parameters (Borchers et al., 2006). The models were fitted with program code written in the statistical language R (R Development Core Team, 2006), which is embedded in the mark-recapture distance sampling (MRDS) analysis component of DISTANCE 5 release 2 (Thomas et al., 2007).

A variety of conditional and unconditional models dependent on sighting conditions and observer variables were examined for fit (Table 1), and the Akaike Information Criterion (AIC) was used for model selection (Burnham and Anderson, 2002). With the best model (lowest AIC), we

estimated the total abundance (\hat{N}) that was available to be seen using the following formula in DISTANCE:

$$\hat{N} = \sum_{i=1}^n \frac{s_i}{\hat{p}_i} \frac{A}{2LW}$$

where s_i is the size of the i^{th} narwhal group of n observed groups,

$$\hat{p}_i = \int_0^w p(x|\mathbf{z}_i, \mathbf{w}_i) dx$$

is the estimated average detection probability for the i^{th} narwhal group given the observed covariate values, A is the total size of the area, L is the transect length, and W is the transect half-width. An estimate of abundance was computed for each stratum, and the total abundance was the sum of the stratum abundance estimates.

Adjustment for Unequal Coverage in Fiords

The coverage of fiords along Baffin Island was problematic because fiords there are very deep with vertical walls higher than the survey altitude and because they tend to vary in width, generally tapering from entrance to end. For safety reasons, we flew down the middle of the fiords. The fiords were treated as samples of the total area of all fiords. A correction for unequal coverage due to variation of the width of an individual fiord along its length was derived as follows:

$$n_c = n \frac{w}{W}$$

where n is the sighting group size, n_c is the corrected group size, w is the width of the fiord at the location of the sighting, and W is the average stratum fiord width. The average fiord width was calculated by dividing the sum of fiord areas by the sum of fiord lengths. Although this approach will correctly estimate abundance, it will underestimate the variance if the majority of groups are found in narrower-than-average locations and overestimate the variance if most groups are found in wider-than-average locations. To avoid this potential bias, the variance calculation was made with unweighted group sizes.

Estimation and Adjustment for Availability Bias

Richard et al. (1994) found that narwhal models could be detected and correctly identified to species on analog aerial photographs to a depth of approximately 2 m. The proportion of narwhals that were at the surface during the overflight of the survey aircraft (availability bias) was estimated from the proportion of time that individual narwhals with archival time-depth recorders (ATDR) and satellite-linked time-depth recorders (STDR) spent at or above 2 m of depth (Table 2). Four ATDRs were deployed on narwhals, three in Creswell Bay (Laidre et al., 2002) and a fourth one in Tremblay Sound in 1999. Five STDRs were also deployed in Lyon Inlet (northern Hudson Bay) in 2005 (this study). ATDRs recorded depth every second with a resolution of 1 m (Martin et al., 1994;

TABLE 3. Survey coverage, sightings, and uncorrected estimates by stratum (w = weighted group sizes; CVs are in parentheses).

Label	Area (sq km)	Area of Covered strip ¹ (sq km)	Sightings with Distance	Average Group Size	Average Probable Detection over Distances $g(x)$	Estimated Coverage (km) ²	Average Probable Detection at Track Line $p(0)$	Surface Estimate
August 2002:								
Eclipse Sound	5914	359	48	2.3 (0.10)	0.27 (0.15)	98	0.92 (0.04)	7397 (1.30)
Eclipse Fiords	1810	762	3	8.0 (0.37)	0.27 (0.15)	207	0.92 (0.04)	180 (0.87)
Area sum								7578 (1.26)
Prince Regent Inlet	30628	2092	94	1.8 (0.07)	0.40 (0.10)	831	0.87 (0.05)	7429 (0.71)
Gulf of Boothia	56567	1783	10	3.0 (0.13)	0.40 (0.10)	708	0.87 (0.05)	2407 (0.30)
Area sum								9836 (0.54)
August 2003:								
Admiralty Inlet	8596	629	3	5.0 (0.31)	0.31 (0.29)	194	0.84 (0.03)	1272 (0.68)
Admiralty Fiords (w)	868	136	5	1.8 (0.27)	0.31 (0.29)	42	0.84 (0.03)	584 (0.52)
Area sum								1857 (0.52)
Baffin Coast Fiords (w)	11204	3282	181	1.5 (0.21)	0.31 (0.29)	1013	0.84 (0.03)	3487 (0.27)
August 2004:								
Eclipse Sound	2702	1131	144	2.6 (0.29)	0.20 (0.06)	229	0.88 (0.03)	5383 (0.43)
Navy Board – Milne Inlet	2794	1286	55	2.1 (0.17)	0.20 (0.06)	260	0.88 (0.03)	1107 (0.63)
Eclipse Fiords (w)	1194	1358	13	1.8 (<0.1)	0.20 (0.06)	274	0.88 (0.03)	187 (1.15)
Area sum								6677 (0.36)
Admiralty Center	3998	1218	3	4.6 (0.67)	0.20 (0.06)	240	0.88 (0.03)	448 (0.84)
Admiralty North	2392	395	1	2.0 (0.00)	0.20 (0.06)	78	0.88 (0.03)	94 (1.01)
Area sum								542 (0.72)
Barrow Strait-Lancaster Sound	21599	3669	11	1.4 (0.96)	0.20 (0.06)	723	0.88 (0.03)	963 (0.46)

¹ The covered area given for each stratum is calculated from a strip width equal to the maximum distance at which a sighting was reported and multiplied by the average probability of detection over that strip, $g(x)$.

Wildlife Computers, 2005). The five STDRs recorded the proportion of each six-hour sample that was spent in each of two depth bins: 0–1 m and 1–2 m (Wildlife Computers, 2004).

The combined ATDR and STDR data from these nine narwhals (five females and four males) were used to estimate what proportion of time narwhals spent at or within 2 m of the surface during August, when the surveys were conducted. The average was 31.9% (SE = 1.43%) (Table 2). The proportion of whales that were available to be seen (p_a) was thus estimated by this mean proportion, assuming that sightings were almost instantaneous. The $\text{var}(p_a)$ was the squared standard error of the mean p_a of the tagged whales.

If sightings were instantaneous (i.e., observer could see narwhal only along a line perpendicular to the line of travel), the abundance estimate could be corrected for availability bias as follows:

$$\hat{N}^{**} = \frac{\hat{N}^*}{p_a}$$

where \hat{N}^* is the surface estimate (Table 3). But this correction is biased upward when observers can see the animal in their field of view ahead of the perpendicular (abeam) position because the animal is at or near the surface (less than 2 m depth). McLaren (1961) devised a correction factor C_a to accommodate this kind of situation:

$$C_a = \frac{t_d}{t_o + t_s}$$

where t_o is the time available for an observer to see a group forward along the track line, t_d is the average time for a complete dive cycle, and t_s is the average time at the surface per dive cycle.

To determine a value for t_o , we examined the length of time between the initial recorded detection of a sighting and the recorded abeam-angle measurement (Fig. 4). This value, called “time in view,” is different for each survey year because observers and survey conditions varied from year to year. In 2002, when narwhal sightings were farther apart and observers had time to sight them ahead of the plane and follow them to the abeam position, the average time in view was 5.2 sec (SE = 0.16). In 2004, when high densities of narwhals were present in Eclipse Sound (where most sightings were made that year), observers spotted almost all sightings while looking down at the perpendicular (abeam position). They did not have time to move their gaze forward or outward as more sightings passed abeam; they only had time to record the perpendicular angle and move on to the next sighting. That year, the average time in view was 1.5 sec (SE = 0.07). Times in view in 2003 were intermediate, averaging 3.9 sec (SE = 0.16).

If we used $t_o = 0$, then we would expect C_a derived from the ATDR dive-cycle data to be equal to $1/p_a$ derived from the pooled TDR data. However, because we had a larger data set to estimate $1/p_a$ ($n = 9$; Table 2), we chose to use $1/p_a$ as the baseline instantaneous correction factor and adjust for time in view t_o using the observed frequency of times in the data. The estimator C_{ca} used for availability is a weighted estimator of the C_a value for the various observed values of t_o :

$$C_{ca} = C_a * \frac{\sum_{i=1}^n f_i (1 - b_i)}{\sum_{i=1}^n f_i}$$

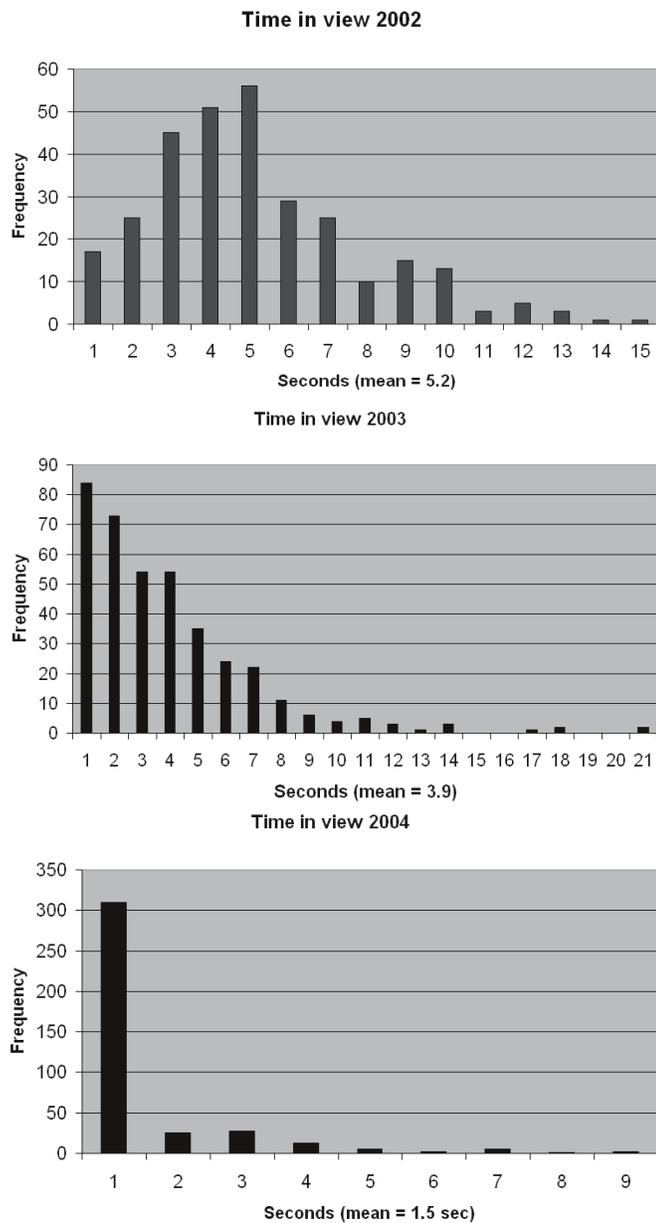


FIG. 4. Times in view for each narwhal group in each survey year.

where f_i is the frequency of times in view of duration i sec, and b_i is the percent bias of an instantaneous correction C_a for a time in view of i sec (Table 4). The abundance estimate was therefore adjusted by the availability correction factor:

$$\hat{N}^{**} = \hat{N}^* C_{ca}$$

RESULTS

Timing of Surveys Accomplished

The August 2002 survey plan covered areas with the largest known aggregations of narwhals, namely Eclipse Sound, Admiralty Inlet, Prince Regent Inlet, and Peel Sound (Richard et al., 1994). We also planned to cover the

Gulf of Boothia. Despite interruptions caused by inclement weather, we were able to fly the Eclipse Sound stratum and most of the Prince Regent Inlet and Gulf of Boothia strata, with the exception of two transects (Fig. 1). Prolonged rain, fog, low ceilings and high winds prevented surveys of Admiralty Inlet and Peel Sound.

The August 2003 survey plan covered the east coast of Baffin Island from Bylot Island to the mouth of Cumberland Sound (Fig. 2). We were able to cover almost all those areas, with the exception of the southern part of the east coast stratum, from east of Merchants Bay to Cumberland Sound. Having failed to survey Admiralty Inlet and Peel Sound the previous year, we tried again in 2003. During the Admiralty Inlet survey, we observed a large herd of narwhals between two transects in the middle of the inlet. Rough counts were made of narwhals in that herd as the plane transited to the next transect, but the counts are probably biased low because the large number of animals overwhelmed the observers. Worsening weather did not permit a second attempt to survey that herd. Again, Peel Sound could not be surveyed because of inclement weather.

The August 2004 survey plan was to cover Eclipse Sound and Admiralty Inlet a second time, using higher sampling coverage in those parts where density was found to be the highest in the earlier surveys (Fig. 3). We also planned to cover areas that had been not been covered in 2002–03: Lancaster Sound, Barrow Strait, Peel Sound, channels east and west of Cornwallis Island, and the western end of Parry Channel as far as Viscount Melville Sound. There again, repeated fog and low ceilings precluded coverage of all but Eclipse Sound and part of Barrow Strait. The northern and central parts of Admiralty Inlet were surveyed in poor visibility conditions due to rain, while the southern part of the inlet and adjacent fiords could not be surveyed because of low ceilings. Once again, despite higher coverage, the survey design missed a large herd of narwhals, which was observed while in transit between two transects in the middle of the inlet. As in 2003, the rough counts made of narwhals in that herd are probably low because the numbers were overwhelming. Worsening weather did not allow us to finish the survey area or to make a second attempt. Table 3 gives the sequence of surveys accomplished in all three years.

Flight and Visibility Conditions

During surveys, with few exceptions, pilots were able to maintain an altitude of 1100 ft (335.3 m). In a few instances, pilots either had to duck under low clouds at the beginning of a transect, or climb at the end of a transect to avoid oncoming cliffs. These departures from target altitude were brief and varied no more than a few hundred feet. In all surveys, pilots maintained an air speed of about 100 knots, but the speed could occasionally vary because of variations in the strength and heading of winds aloft.

Fog was absent or light on most transects, except in parts of some offshore transects of the East Baffin stratum in 2003 and in patches of transects flown in Barrow Strait

TABLE 4. Percent bias (b_i) of an instantaneous correction for different times in view, frequency of times in view in each survey year and the resulting weighted annual availability corrections, C_{ca} .

T_i (sec)	$C_{McLaren}$	C_i	b_i	$f_{i,2002}$	$f_{i,2003}$	$f_{i,2004}$
1	2.969	3.039	2.3%	17	84	310
2	2.903	3.039	4.5%	25	73	25
3	2.839	3.039	6.6%	45	54	27
4	2.779	3.039	8.6%	51	54	13
5	2.720	3.039	10.5%	56	35	5
6	2.664	3.039	12.3%	29	24	2
7	2.611	3.039	14.1%	25	22	5
8	2.559	3.039	15.8%	10	11	1
9	2.510	3.039	17.4%	15	6	2
10	2.462	3.039	19.0%	13	4	0
11	2.416	3.039	20.5%	3	5	0
12	2.372	3.039	22.0%	5	3	0
13	2.329	3.039	23.4%	3	1	0
14	2.288	3.039	24.7%	1	3	0
15	2.249	3.039	26.0%	1	0	0
16	2.210	3.039	27.3%	0	0	0
17	2.173	3.039	28.5%	0	1	0
18	2.137	3.039	29.7%	0	2	0
19	2.103	3.039	30.8%	0	0	0
20	2.069	3.039	31.9%	0	0	0
21	2.037	3.039	33.0%	0	2	0
			Year	2002	2003	2004
			C_{ca}	2.806	2.883	3.030

and central Admiralty Inlet in 2004. Low ceilings halted the survey of the southern Admiralty Inlet in 2004, and that stratum could not be completed later. Glare was light in most transects and moderate in the remainder. Ice cover was absent or light in all but the Prince Regent and Gulf of Boothia strata in 2002 and the Barrow Strait stratum in 2004, when it reached up to 90% in many of the transects.

Sea states were generally favourable for observations (Beaufort scale < 3) throughout the surveys, except in August 2003 for a few offshore transects in the East Baffin stratum and a few fiords with large glaciers at their head, where winds seemed to blow continuously, no matter what the weather conditions were elsewhere. In Barrow Strait in 2004, near-shore winds caused sea states higher than 3 at the beginning or end of a few transects.

Survey Effort and Sighting Results

An area of 150 266 km² was surveyed during the three years at a coverage varying between 1.3% and 9.3% in large bodies of water and 4.8% to 23% in fiords (Table 3). The estimated coverage is calculated from a strip width equal to the maximum distance at which any sighting was reported in each year, minus the left truncation distance (i.e., part of the strip near the track line where detection was hampered by the flat windows). The strip is then multiplied by the linear survey effort (km) and the average probability of detection over that stratum, $g(x)$, to give the approximate survey coverage.

In total, 590 sightings of narwhals were made during those surveys. Nineteen of the sightings were reported without a distance measurement and were discarded from

the analysis. Average sighting group sizes varied between 1.5 and 5.0 in most strata, but larger groups (average = 8.0 narwhals, $n = 3$) were also seen in Eclipse fiords in August 2002 (Table 3).

Detection probability of front observer (labeled as Observer 1 in Figs. 5–7) and rear observer (Observer 2) varied from year to year, with front observers having a higher probability of sighting narwhals. Observers 1 and 2 detected between 50% and 70% of the narwhals at the closest distances afforded by the flat windows (shown as 0 m on the x-axis), keeping in mind that the perpendicular distances were truncated 300 m for the 2002–03 data and 200 m for the 2004 data. Duplicate sightings were detected about 40% of the time in all three years (Figs. 5–7). Pooled detections in all three years (Figs. 5–7 bottom right panels) show that detection probability dropped by more than half in the first 400 m of the truncated distance and that narwhals were seldom detected beyond 600 m of that distance. More detailed comparisons of individual observers are not possible since observers varied in different years and did not survey the same areas.

Estimates of $g(x)$, the average probability of detection with distance, were quite low and variable between years (0.20–0.40) (Table 3), indicating that detection dropped off rapidly away from the truncated distance. This means that only 20% to 40% of the sightings that would be expected from a strip transect with constant detection were made.

The average probability of detection at the track line (actually the truncated distance) obtained from the mark-recapture model, $p(0)$, varied between years from 0.84 to 0.92, meaning that between 8% and 16% of narwhal sightings were missed by observers when narwhals were available to be seen. Consequently, the estimate was corrected for perception bias by $1/p(0)$, or between 1.087 and 1.190, depending on the survey (Table 3).

Surface Estimates

Estimation of population size was done using DISTANCE software's MRDS module. The software calculates the joint likelihood of the detection probability with perpendicular distance (distance model) and the probability of detection at the track line (mark-recapture model), conditional on survey condition covariates. MRDS can fit either of two detection functions for the distance model, a half-normal or a hazard rate. In all cases, the hazard rate had a higher likelihood, i.e., fit better than the half-normal, given the data (Table 1). The logistic function is the default function fitted for the mark-recapture model. The model also fit the effect of factors that were hypothesized to have an effect on detectability in each survey year. The covariates considered were ice, glare, sea state, and stratum for the distance model and observer, side, and platform (position of observer, front or back) for the mark-recapture model. Several sets of models using combinations of these covariates were run. The function-covariate set that resulted in the highest likelihood, or lowest AIC, was retained (Table 1).

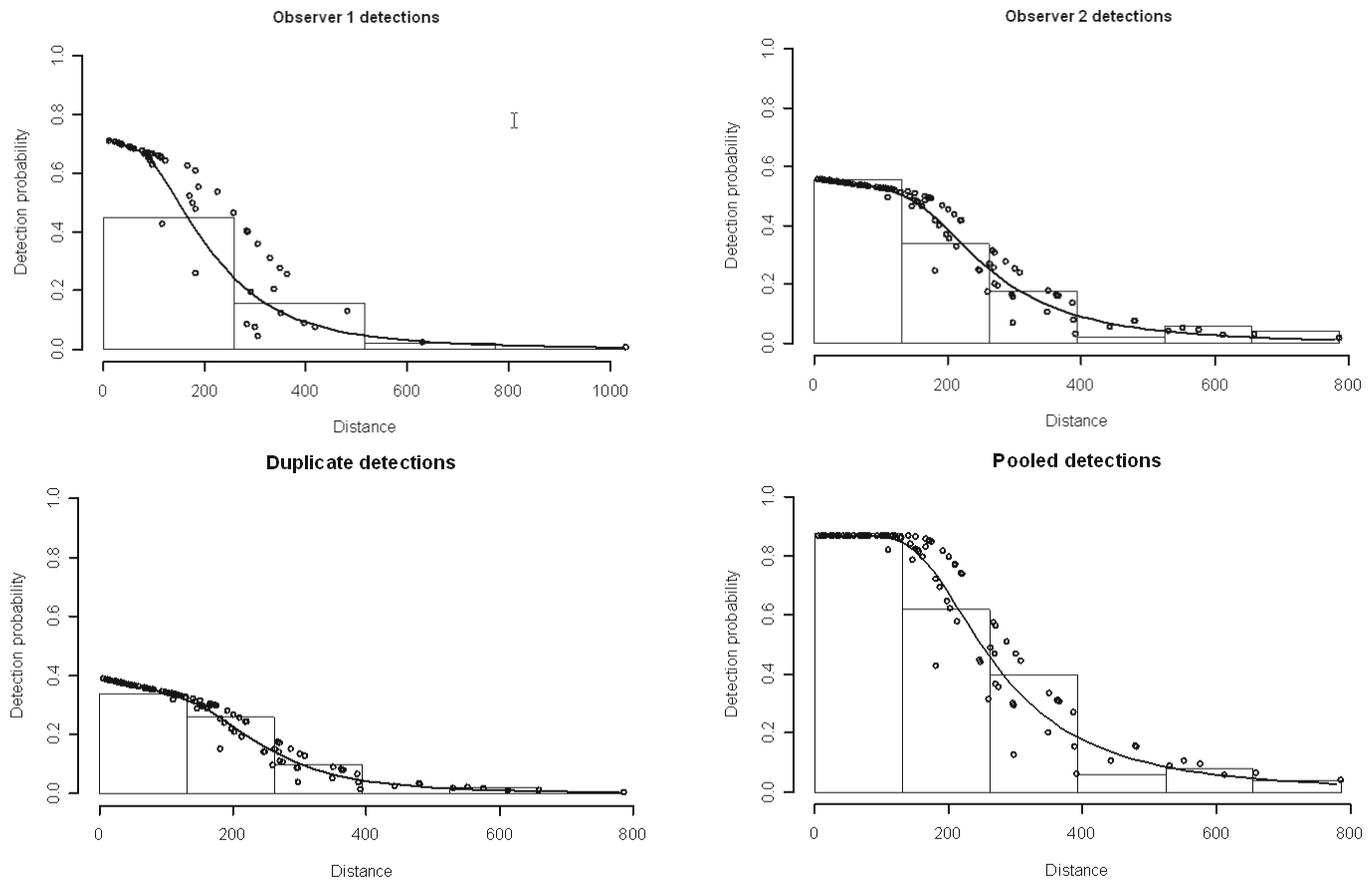


FIG. 5. Probability of detection by single observers and by both observers and pooled detections at various distances in August 2002 surveys. Note: distance data were truncated by 300 m. These are plots of the fitted detection functions, superimposed on histograms showing the frequency of sightings. The estimated probability of detection of each observation, given its covariate values and distance, is also shown.

Observer had an effect on the mark-recapture model in 2002 and 2003, but not in 2004. The choice of covariates sea state and ice cover for the distance model resulted in the best fit for the 2002 and 2003 data, while in 2004, the best fit was obtained with the covariates ice cover and stratum. Distance is the default covariate for the mark-recapture model, as recaptures are expected to decline with distance.

While the estimation process used in software is more complex, roughly speaking the surface estimate is obtained by dividing the number of sightings by the estimated cover area times the average probability of detection at the truncation distance, and multiplying the result by the average estimated group size times the stratum area (Table 3). This conceptual description is approximately right if n is large. But the estimates also incorporate the effect of covariates, so that simple calculation, depending on sample size and the effect of covariates, can yield quite different results.

In most strata, the ratio of stratum areas to sampled areas (approx. $2\times$ to $30\times$), did the most to expand the surface estimates of narwhals (Table 3), but these estimates were also affected, in declining order, by the $g(x)$ detection probability ($2.5\times$ to $5\times$), the covariate model effects ($< 2.6\times$), and the $p(0)$ probability ($1.09\times$ to $1.14\times$).

Estimates of Population

The weighted availability corrections (C_{ca}) were 2.805, 2.883, and 3.029 respectively for 2002, 2003, and 2004, with a coefficient of variation (CV) of 0.045. These corrections were used to expand the area surface estimates (Table 3) to obtain total population numbers (Table 5). Area estimates indicate that narwhals were most numerous in Prince Regent Inlet (2002) and Eclipse Sound (2002 and 2004) (Table 5). The estimates for Admiralty Inlet (2003 and 2004) were low but not surprising, since large numbers of animals were off transect in both survey years, suggesting that there is a bias in the estimate. The numbers in the Gulf of Boothia (2002) and along East Baffin Island (2003) were surprisingly high. These areas were not thought to contain high densities of narwhals, yet the surface estimates yielded several thousand animals in each area. The variance of estimates of narwhals in all areas was large. The most precise estimates for the East Baffin fiord area in 2003 and the Eclipse Sound area in 2004 had CVs greater than 0.30, which is still a large imprecision in the numbers. As mentioned above, the Admiralty Inlet estimate was affected by clumping of whales in large aggregations that were not fully captured by the systematic random transect design.

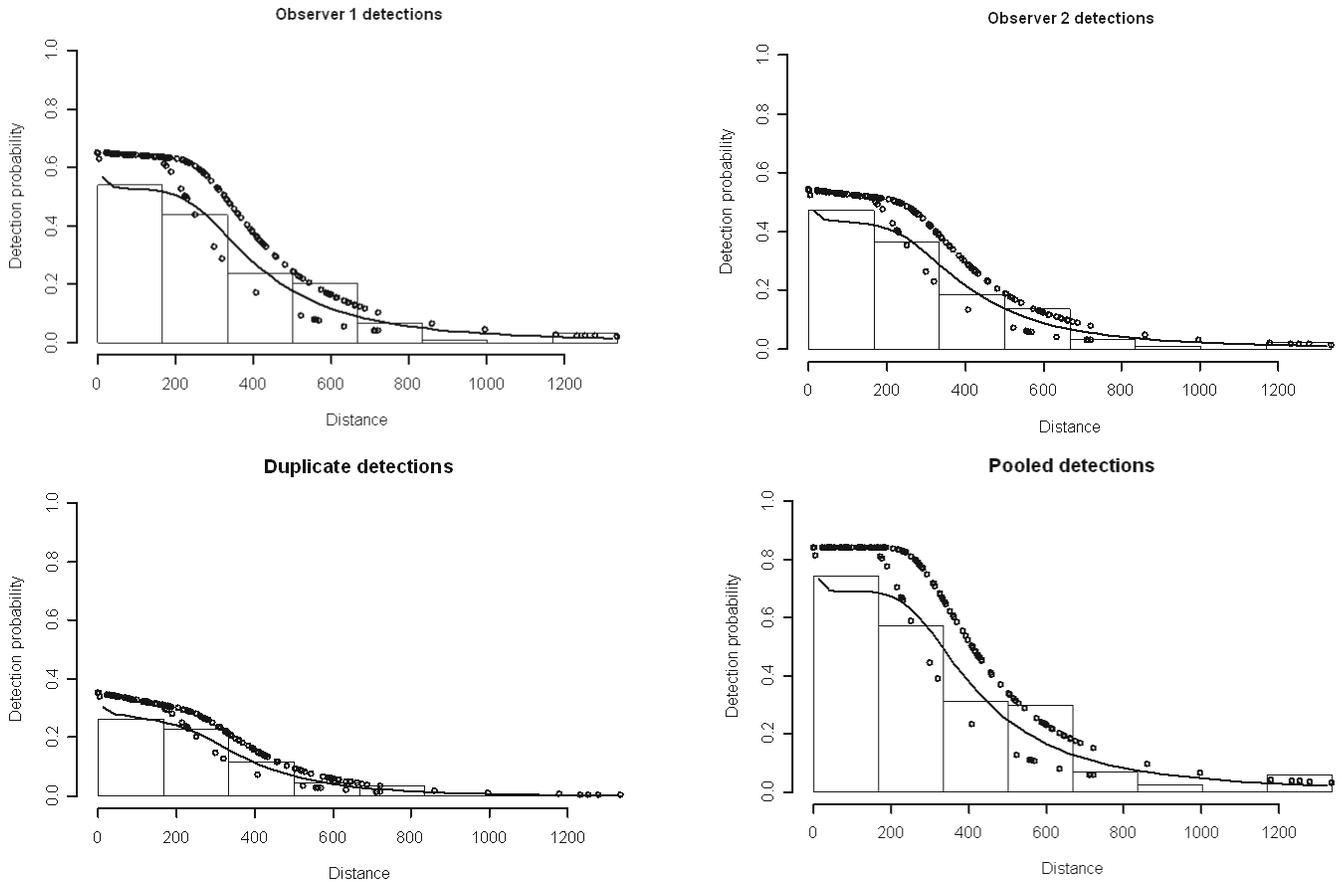


FIG. 6. Probability of detection by single observers and by both observers and pooled detections at various distances in August 2003 East Baffin surveys, also used to fit the Admiralty Inlet data. (Details as in Fig. 5.)

DISCUSSION

As mentioned above, this study tried to address two problems in the estimation of the current size of the Canadian High Arctic population. The first is adequate coverage of their entire range. It is well documented that narwhals aggregate in four summering areas of the Canadian High Arctic: Peel Sound, Prince Regent Inlet, Admiralty Inlet, and Eclipse Sound and adjacent fiords (Koski, 1980; Fallis et al., 1983; Smith et al., 1985; Strong, 1988; Richard et al., 1994). The summer occurrence of narwhals in the Gulf of Boothia, along the east coast of Baffin Island, and in passages of the Arctic archipelago was also known (Mansfield et al., 1975; Brody, 1976; Kemp, 1976; Roe and Stephen, 1977; Smith, 1977; Reeves and Tracey, 1980; Strong, 1988), but it was assumed that the density of narwhals was lower in those parts of their range (Richard et al., 1994). Yet, the size of the summer catches of narwhals in those areas (DFO, unpubl. data) suggested that they should be included in comprehensive surveys.

The surveys were first expanded into the Gulf of Boothia, where—contrary to what was expected—about 6700 animals were estimated to be present (Table 5). These animals could have moved south from Prince Regent Inlet because ice conditions allowed them to do so. If so, some or all of

these narwhals could be part of the larger number estimated by Innes et al. (2002a) in Prince Regent Inlet in 1996. We could not cover Peel Sound, also an important aggregation area for narwhals in August (Richard et al., 1994; Innes et al., 2002a), because of unfavourable weather conditions in all three years. Those three areas contain the largest stock identified by the JWG (JCNB, 2006), the Somerset Island stock.

The second major survey expansion was along the east side of Baffin Island. That survey resulted in an estimate of approximately 10 000 narwhals. Unfortunately, again because of weather, that survey could not be completed all the way to Cumberland Sound as had been planned. The weather also prevented further expansion of surveys into Lancaster Sound and Viscount Melville Sound. Time, funding, and the need to redo surveys of Eclipse Sound and Admiralty Inlet prevented survey expansion into Jones Sound and other channels in the High Arctic archipelago.

The second problem this project addressed was correcting biases (other than distance effects on sightability) that affect the estimation of population numbers. An important one was availability bias: animals missed because they were not available to observers. This bias was addressed by estimating correction factors from time-depth recordings of the proportion of time animals were below 2 m and from data

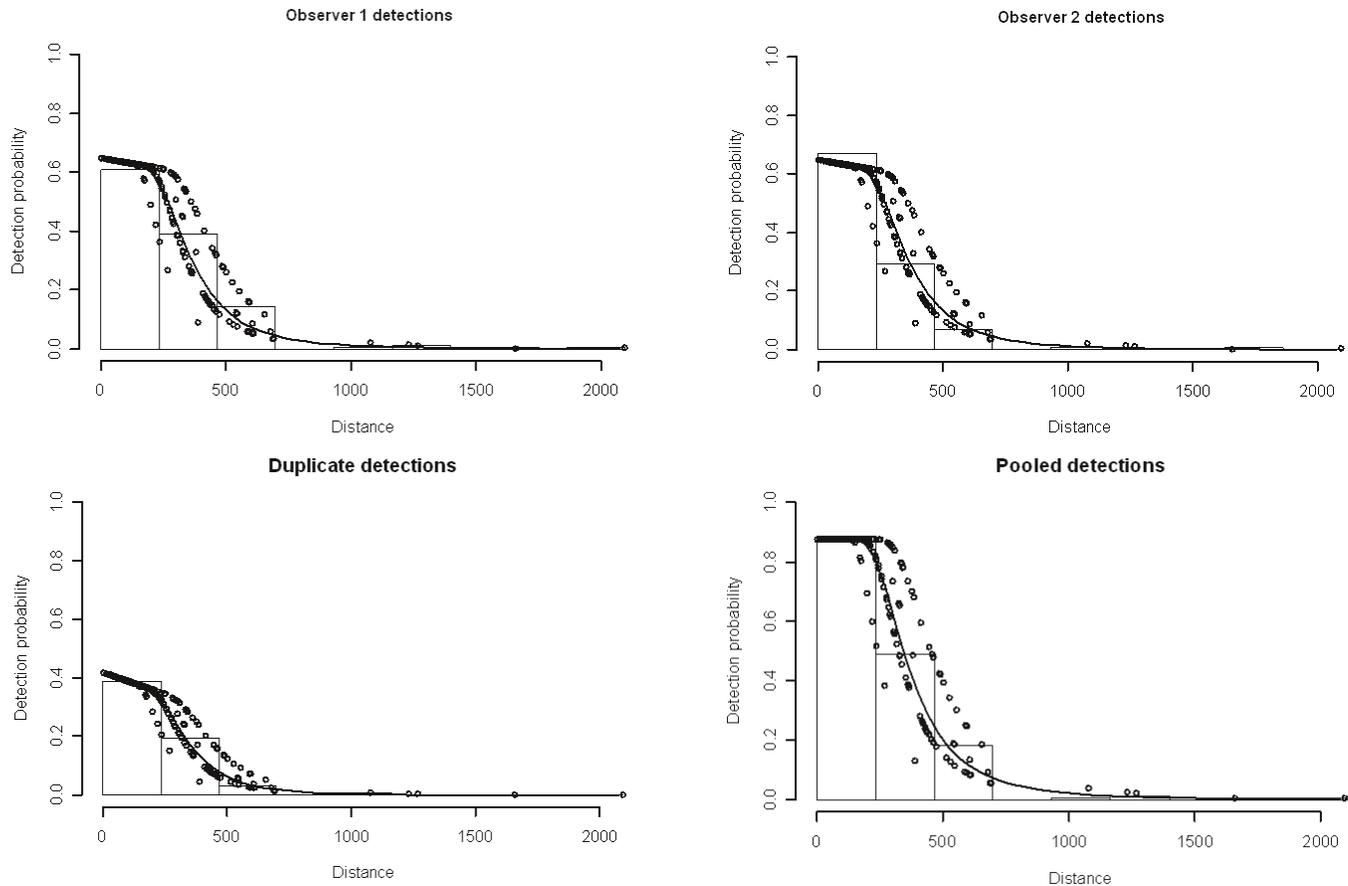


FIG. 7. Probability of detection by single observers and by both observers and pooled detections at various distances in August 2004 Eclipse area surveys, and also used to fit the Admiralty and Barrow data. (Details as in Figs. 5 and 6, except that distance data were truncated by 200 m.)

on the distribution of times in view. The method used is a new approach, adapted from the McLaren method for availability bias. In this survey, unlike earlier surveys (Richard et al., 1994) that used photographic methods to count narwhals, sightings were not instantaneous: observers had a few seconds to see them. The time in view varies depending on how busy the observer is, and that depends on whether the encounter rate (number of sightings per kilometre) is high or low. The method attempts to correct for the time observers are actually available to view narwhal sightings when animals are in their field of view, considering that an observer's ability to search for new sightings depends on whether that observer is busy recording data on previous sightings. In that way, it differs from the McLaren method, which was designed for slow-moving boat surveys that give observers ample time to spot an animal when it is available (i.e., t_0 is close to t_s). In aerial surveys flown at about $185 \text{ km}\cdot\text{hr}^{-1}$, as these were, observers have little time to spend on a sighting (i.e., t_0 is relatively small in comparison to t_s ; Fig. 4). Admittedly, this method is ad hoc and could likely be improved. It was used in absence of a method that could model the sighting process experienced by observers more precisely. Such methods have yet to be developed.

The second bias that needed to be corrected is perception bias. The grey or dark colour of most narwhals does not

contrast very well against the dark waters of the Arctic; consequently, it was reasonable to suspect that there is perception bias in visual surveys—that narwhals would not all be seen even when they were “available” to both observers near the track line ($p(0) < 1$). Indeed, it was estimated from the mark-recapture data that, depending on the survey, observers saw only 84% to 92% of the available narwhals near the aircraft (Table 3); hence, 8% to 16% of them were missed.

Of the two corrections, the availability bias correction had the largest effect on the total estimates, expanding numbers by a factor of 3. The perception bias correction was smaller (1.087 to 1.190), but not negligible. The contribution of these corrections to total variance is small compared to the contributions of differences in group size (Table 3) and differences in the encounter rate between transects (Figs. 1–3).

On the question of how many narwhals there are in total in the Canadian Eastern Arctic, one could sum the estimates in Table 5 to obtain a minimum number for the areas that were surveyed. But it could be argued that, because different strata were surveyed in different years, this method would lead to a biased total if individual narwhals move around a lot and do not necessarily return to the same summering areas. In fact, there is reasonably good evidence from satellite-linked radio tracking that narwhals are sedentary in

TABLE 5. Estimates of narwhal population numbers in the individual stock areas.

Area	C.L. 2.5%	Mean	C.L. 97.5%	CV
Prince Regent Inlet 2002	4805	20871	59157	0.71
Gulf of Boothia 2002	3638	6770	11862	0.30
<i>Sum Regent – Boothia 2002</i>	<i>9080</i>	<i>27656</i>	<i>66061</i>	<i>0.54</i>
Admiralty Inlet Area 2003	1920	5362	12199	0.50
East Baffin Fiords 2003	5333	10073	17474	0.31
Eclipse Sound Area 2004	9471	20225	37096	0.36
Barrow Strait 2004	1140	2925	6270	0.46

their summering areas during the month of August and do not move between strata (Dietz et al., 2001, 2008; Heide-Jørgensen et al., 2002, 2003). There is also some evidence for multiyear site fidelity, based so far on only three animals that returned in late spring or early summer to the summering area where they had been tagged a year earlier (Heide-Jørgensen et al., 2003; Dietz et al., 2008). These results suggest that narwhals, like their close relative the beluga whale (*Delphinapterus leucas*), are philopatric to specific areas (O’Corry-Crowe et al., 1997, 2002; de March et al., 2002; Innes et al., 2002b). This hypothesis is reinforced by the fact that narwhals tagged in the same summering areas in different years use the same migration routes to move to the same wintering areas (Heide-Jørgensen et al., 2003; Dietz et al., 2008). It is therefore quite plausible that they choose to go to familiar summering areas every year. If Eastern Canadian narwhals are indeed philopatric in summer, then the estimate of the mean total population would be around 66 000 narwhals for the areas that were surveyed in 2002–04. Also, this number is a minimum estimate because it does not include narwhals in Jones Sound, Smith Sound, Lancaster Sound, Peel Sound, the Parry Islands and the western Parry Channel.

While biases have been reduced by correction, these survey estimates are quite low in precision (i.e., high in variance), in large part because of large variations in the encounter rate from one transect to the next (Figs. 1–3). Through stratification and increased coverage, the CV of the Eclipse Sound 2004 surface estimate was reduced to about one-third that of the 2002 estimate, but it was still high (CV 0.43).

In Admiralty Inlet, narwhal aggregation was even more severe, and a large herd was missed (off transect) again in 2004 despite stratification and increased coverage. The consequence of missing that herd is a small estimate associated with a smaller variance than there would have been if the herd had been caught by a transect. Adaptive sampling combined with spatial analysis might improve population estimation in similar instances (Hedley et al., 2004; Pollard and Buckland, 2004).

Finally, what can be said about the trend in numbers of the Canadian High Arctic narwhal population? Past surveys in that region used different methods of counting and estimation. Richard et al. (1994) conducted photographic strip-transect counts of Eclipse Sound, Admiralty Inlet, Prince Regent Inlet, and Peel Sound areas in 1984, while Innes

et al. (2002a) used methods quite similar to the ones used here but surveyed only Prince Regent Inlet, Barrow Strait, and Peel Sound. They also did not correct availability bias exactly the same way: they used an instantaneous correction based on dive data available from only two time-depth recorders at the time. The differences in methods and coverage complicate comparisons, and the high variance of all these estimates would not provide sufficient power for trend analysis, unless those differences were quite high. This problem speaks to the importance of finding ways to reduce the variance of estimates, as mentioned above.

In conclusion, the narwhal population in the Canadian High Arctic is distributed broadly in summer, and numbers are larger than was previously thought. While the largest numbers of these narwhals were again found in the western part of their summer range, particularly in Prince Regent Inlet and Eclipse Sound, this study has shown that substantial numbers of narwhals also occupy the fiords of East Baffin Island and the Gulf of Boothia. The results, although imprecise, do show that there is a large population out there, one that can probably sustain a large hunt. However, because of the imprecision of the estimates and questions of stock structure, management should be exercised with caution.

Future narwhal visual surveys should increase coverage and sampling effort and use stratified or adaptive sampling methods to improve the precision of estimates. To ensure that surface estimates from different surveys are comparable for trend analysis and population dynamic modeling, perception bias should be estimated and corrected. Finally, availability correction is essential to obtain total population estimates that can be used for management purposes. As shown here, both perception and availability biases are affected by the behaviour of observers, sighting conditions, and the encounter rate of narwhals.

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