Fisheries and Oceans Canada / Pêches et Océans Canada
Science / Sciences

C S A S / **S C C S**

Canadian Science Advisory Secretariat / **Secrétariat canadien de consultation scientifique**

Research Document 2012/037 / **Document de recherche 2012/037**

Central & Arctic Region / **Région du Centre et de l'Arctique**

Results of narwhal (*Monodon monoceros*) aerial surveys in northern Hudson Bay, August 2011

Résultats des relevés aériens du narval (*Monodon monoceros*) dans le nord de la baie d'Hudson, août 2011

Natalie C. Asselin[1]*, Steven H. Ferguson[2], Pierre R. Richard[2] and David G. Barber[1]

[1]Center for Earth Observation Science
Wallace Building, 125 Dysart Road,
University of Manitoba,
Winnipeg, Manitoba,
R3T 2N2

[2]Fisheries and Oceans Canada/Pêches et des Océans Canada
501 University Crescent/501 Université Crescent
Winnipeg, Manitoba
R3T 2N6

* Current address : PO Box 1116, Churchill, MB, R0B 0E0

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

TABLE OF CONTENTS

Correct citation for this publication:

Asselin, N.C., Ferguson, S.H., Richard, P.R. and Barber, D.G. 2012. Results of narwhal (*Monodon monoceros*) aerial surveys in northern Hudson Bay, August 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/037. iii + 23 p.

ABSTRACT

Aerial surveys were conducted 4- 17 August 2011 to estimate the abundance of the Northern Hudson Bay (NHB) narwhal population. The survey was designed to use visual observations and aerial photographs to cover the entire summering range of the NHB narwhal population based on published sources and information from Repulse Bay's Arviq Hunters and Trappers Organization. After preliminary surveying, the final survey design was stratified according to observed narwhal densities and ice conditions. The final survey occurred 14-17 August covering Repulse Bay, Frozen Strait, Wager Bay, Roes Welcome Sound, Lyon Inlet, Gore Bay and parts of Foxe Channel and yielded an estimate of 12,485 (CV=0.26) narwhals. The current population abundance estimate was used with the Potential Biological Removal (PBR) method to calculate a new Total Allowable Landed Catch (TALC) for the Northern Hudson Bay narwhal stock of 157 narwhals.

RÉSUMÉ

Des relevés aériens ont été effectués du 4 au 17 août 2011 pour estimer l'abondance de la population de narvals du nord de la baie d'Hudson. Ces relevés ont été conçus de manière à utiliser des observations visuelles et des photographies aériennes pour couvrir l'aire de répartition d'été de la population de narvals du nord de la baie d'Hudson d'après les sources et les données publiées par l'Arviq Hunters and Trappers Organization de Repulse Bay. Après avoir effectué des relevés préliminaires, le relevé final a été stratifié en fonction des données observées sur la densité des narvals et l'état des glaces. Le relevé final s'est déroulé du 14 au 17 août dans la baie Repulse, le détroit Frozen, la baie Wager, le détroit de Roes Welcome, Lyon Inlet, Gore Bay et une partie du détroit de Foxe et a permis de recenser environ 12 485 narvals (CV = 0,26). On a combiné l'estimation de l'abondance de la population actuelle à la méthode du retrait biologique potentiel pour calculer un nouveau total autorisé des captures débarquées (TACD) pour le stock de narvals du nord de la baie d'Hudson, soit 157 narvals.

INTRODUCTION

The Northern Hudson Bay (NHB) narwhal population is an isolated narwhal population which has a distinct geographic distribution compared to other Canadian and Greenland populations (Richard, 1991; Westdal, 2008) and can be distinguished from them by genetic and contaminant methods (de March and Stern, 2003; de March et al., 2003). In summer (August), the population is most aggregated in Repulse Bay, Frozen Strait and Lyon Inlet (Fig. 1) but groups of narwhals are seen on occasion farther south along the Kivalliq coast (Strong, 1988; Richard, 1991; Gonzalez, 2001). The population is hunted by subsistence hunters from Repulse Bay and other communities in the Kivalliq and Qikiqtaaluk regions of Nunavut. Most animals are taken by residents of the hamlet of Repulse Bay, which neighbours the summering aggregation area of the population, but hunters from other hamlets also travel to Repulse Bay to hunt narwhals. Indices of the narwhal population size have been obtained from aerial photographic surveys conducted in the early 1980s (Richard, 1991) and in 2000 (Bourassa, 2003). The latest attempt to estimate the abundance of the NHB population, in August 2008, was unsuccessful due to a combination of equipment failure and unfavorable weather (Richard, 2010).

The purpose of this project was to conduct a new survey of northern Hudson Bay in August 2011 to estimate the abundance of the NHB narwhal population. A further objective was to re-calculate the total allowable landed catch based on this updated abundance estimate.

MATERIALS AND METHODS

STUDY AREA

The study area is in northwestern Hudson Bay, Nunavut and includes Wager Bay, Roes Welcome Sound, Repulse Bay, Frozen Strait, Lyon Inlet, Gore Bay and portions of Foxe Channel and Foxe Basin (Fig. 1). The staging area was the community of Repulse Bay, situated on the north shore of the bay by the same name. In August 2011, Repulse Bay and Frozen Strait had little ice at the start of our survey (4 August) but windy conditions increased the ice concentrations throughout our study period (Fig. 1). By 14 August, sea ice at relatively high concentrations was present in Frozen Strait and in the portions of Foxe Channel and Foxe Basin in the study area (Fig. 1). Wager Bay and Roes Welcome Sound were ice free throughout the study period (Fig. 1).

SURVEY DESIGN

Multiple sources of information were used to design the survey. The survey area was initially established in ArcGIS 10 by overlaying the following three types of spatial data on NHB narwhal distributions:

1- areas reported in Traditional Ecological Knowledge (TEK) studies to be used by narwhals in summer (Gonzalez, 2001; Westdal, 2008),
2- locations of all sightings from previous DFO narwhal surveys conducted in 1981, 1982, 1983, 1984, 2000 and 2008 (Richard, 1991; Bourassa, 2003; Richard, 2010) and
3- regions used in summer by narwhals equipped with satellite-linked transmitters (Westdal et al., 2010)

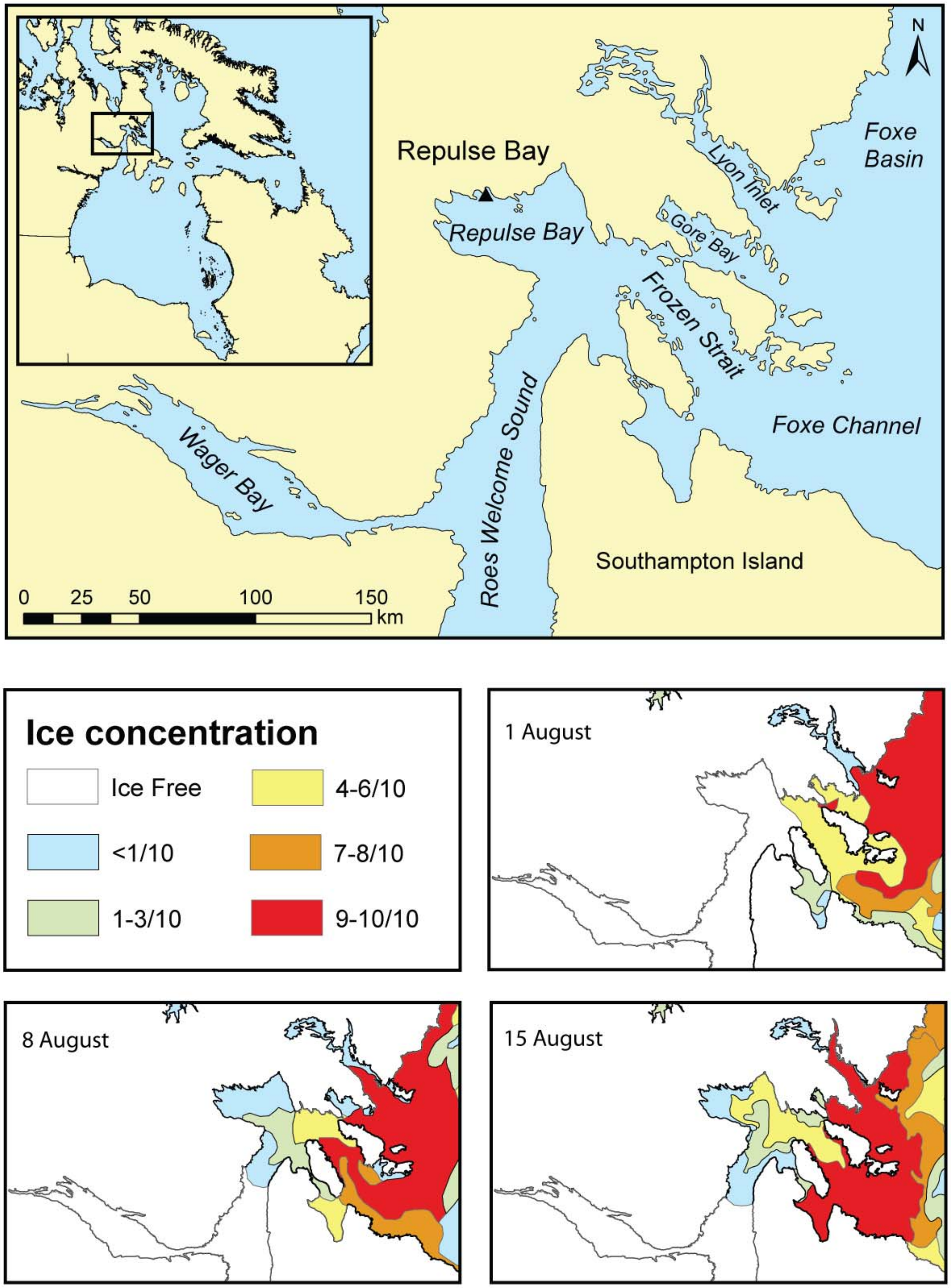

Figure 1. Study area (above) and ice concentrations from 1 August, 8 August and 15 August 2011 (below). Ice concentrations are from the Canadian Ice Service weekly regional ice charts (available at http://ice-glaces.ec.gc.ca).

In addition to these published sources of information, we consulted Repulse Bay's Arviq Hunters and Trappers Organization and the Kivalliq Wildlife Board to identify any known narwhal movements beyond our study area. Letters were sent to both organizations in July 2011 asking for their advice with respect to the study area and for reports of any unusual narwhal movements before or during the surveys. One of us (NA), met with Repulse Bay's Arviq Hunters and Trappers Organization on 4 August 2011 to discuss the survey design and request input.

Based on the work of Richard (1991), Bourassa (2003) and Westdal et al. (2010), we planned to use multiple strata to reflect the higher use by narwhals of Repulse Bay, Frozen Strait and Foxe Channel and thus minimize the variance of the final abundance estimate. Initially, we divided the area into two strata: Main Area and Roes Welcome Sound (Fig. 2.a). Following a meeting with Repulse Bay's Arviq Hunters and Trappers Association on 4 August 2011, we added a Wager Bay stratum (Fig. 2.b) and planned a reconnaissance flight in the inlets north of Lyon Inlet which we flew on 15 August 2011. As we identified narwhals during our reconnaissance flight in these northern inlets we expanded our study area northward. Furthermore, during surveys on 8 August and 15 August we identified relatively high densities of narwhals in Gore Bay and northern Lyon Inlet. We thus adapted our survey design to include a Northern Bays stratum over these areas and the inlets farther north (Fig. 2.c). Lastly, as NHB narwhal movements are impacted by ice conditions (Gonzalez, 2001; Westdal, 2008), we separated the Main Area stratum into two separate strata, Repulse Bay and Foxe Channel, to reflect the ice conditions encountered during the 14 August to 17 August surveys (Fig. 2.d). The Repulse Bay stratum encompasses most of the main areas shown by Westdal et al. (2010) to have been used by narwhals equipped with satellite-linked transmitters in August 2007, when ice concentrations were similar to those in August 2011. Stratified systematic visual line-transect aerial surveys with random start lines were designed in Distance 6.0 (Thomas et al., 2010). In the Repulse Bay, Foxe Channel and Northern Bays strata, a parallel line design was used, with transects 13 km, 13 km and 5.6 km apart respectively, to provide uniform coverage probability (Buckland et al., 2001). The sample lines were angled perpendicularly to the general movement of narwhals in these strata. In the Roes Welcome Sound and Wager Bay strata, we used a zigzag design to maximize coverage and reduce travel time between transects (Buckland et al., 2001).

Survey Equipment, Crew, Observation Procedure

Surveys were flown in a DeHavilland Twin Otter (DH-6) equipped with bubble windows and an optical glass covered camera hatch at the rear. A Global Positioning System (GPS) unit logged the position, altitude, speed and heading of the aircraft every second. Surveys were conducted at an altitude of 305 m (1000 ft) and a ground speed of 185 km/hr (100 kn) with four observers, two on each side. Using black curtains, observers were visually isolated from each other to ensure that each observation was independent (i.e. that observers were not cueing each other in to sightings). Aircraft noise combined with disconnected aviation headsets provided auditory isolation.

Observer training was provided prior to the start of the surveys in the form of on-the-ground instructions followed by a practice flight and recap discussions. Observers were instructed to focus their attention on the area closest to the track line and to use their peripheral vision for sightings farther afield. Speaking into a handheld Sony PCM-D50 digital recorder, observers counted all whale sightings. When a group of animals was first spotted, observers were instructed to call 'whale'. Using a Suunto clinometer, the perpendicular declination angle to the center of each group was measured once it was abeam of the observer. A 'group' was defined as animals within one body length of each other. Observers also noted the species and number

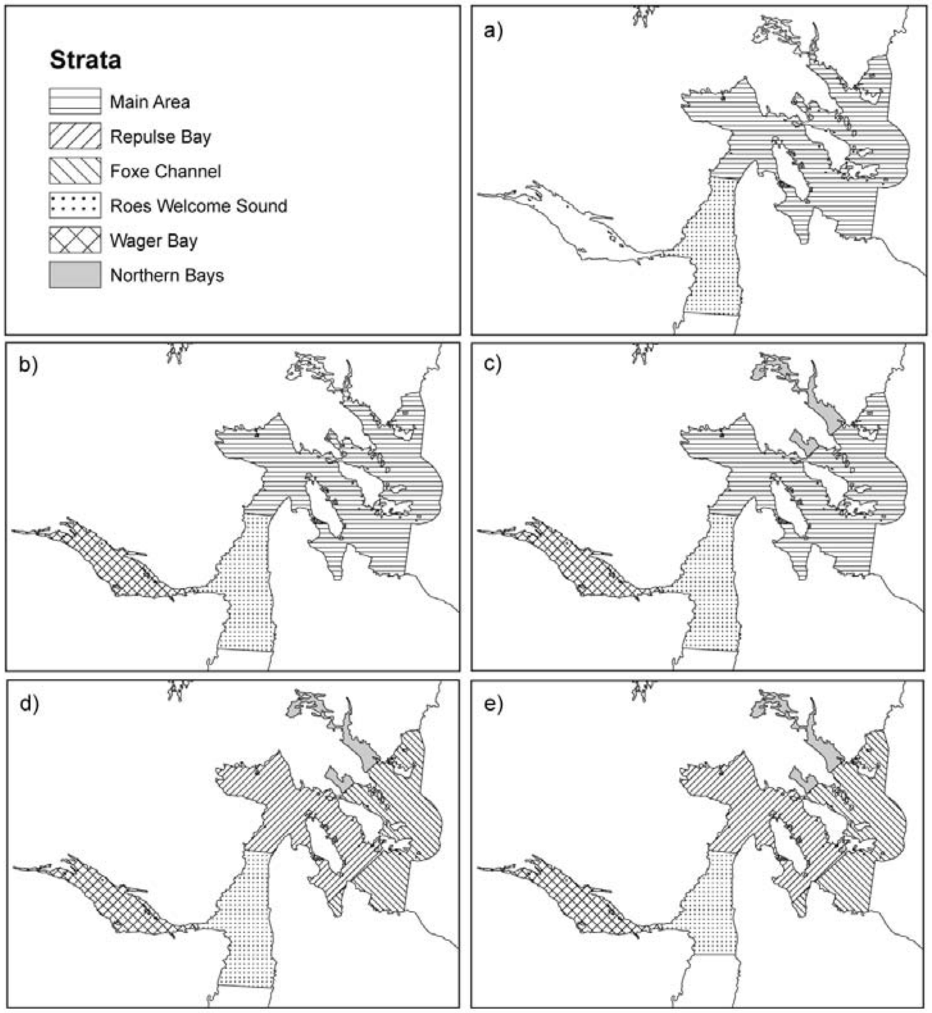

Figure 2. Stages of the study area design showing (a) the initial strata based on literature, (b) the addition of a Wager Bay stratum following a meeting with Repulse Bay's Arviq Hunters and Trappers Organization, (c) the addition of a Northern Bays stratum following a reconnaissance flight and initial surveys, (d) the separation of the Main Area stratum into two strata based on ice condition during the 14 August to 17 August surveys and (e) the reduced areal extent of the Roes Welcome Sound stratum as the two most southern transects were not flown during the 14 August to 17 August surveys.

of individuals in the group. When time permitted, observers were instructed to give additional details on the sightings, such as the presence of calves, tusked narwhals, behaviour and direction of travel. The two observers with the most scientific research experience were designated as 'Primary' and the other two as 'Secondary'. Primary observers, in addition to counting animals, were charged with describing the following environmental conditions throughout the surveys: ice concentrations (in tenths), sea state (Beaufort scale), fog [% of field of view and intensity (Light, Medium or Heavy)], glare [% of forward field of view and intensity (Light, Medium or Heavy)], cloud-cover (clear, scattered clouds, partly cloudy, broken or overcast) and presence of rain (yes or no). These environmental conditions were stated at the start of each transect and re-stated at any time a change was detected throughout the survey.

Collection of aerial photographs

In addition to the visual survey, we photographed the area directly below the aircraft throughout the flights. To do so, we installed two identical camera systems in the aircraft, each consisting of a Canon EOS 5D Mark II camera, a 35.00 mm lens, a WFT-E4A Wireless File Transmitters (WFT), a Garmin GPSmap76CSx GPS unit and a laptop computer. We connected a GPS unit to the WFT of each camera, which was then connected to a laptop. The laptop was used to control the camera and to store the geo-referenced images in real time. The two cameras were installed on a custom-made mount above the optical glass in the aircraft's rear camera hatch . The cameras were oriented widthwise (long side perpendicular to the track line) and angled obliquely: one to the Port side and the other to the Starboard side. A continuous stream of photographs was taken throughout the survey.

To allow each camera to capture an oblique image from the track line outward, the viewing inclination angle of each camera (α) was simply equal to half its field of view (shown as β in Fig. 3), calculated using Covington's (1985:59) formula (eq. 1):

(1) $$\alpha = \beta = \arctan\left(\frac{SensorWidth}{FocalLength \times 2}\right)$$

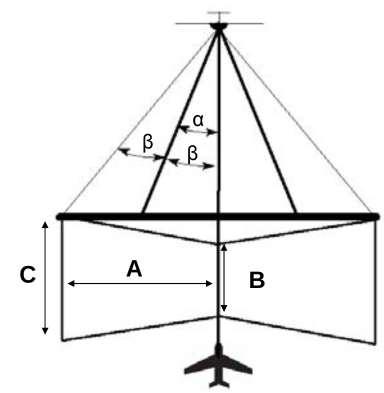

Figure 3. Geometry of oblique aerial photos (modified from Grenzdörffer et al., 2008).

The Canon EOS 5D Mark II sensor width and height are 36.00 mm and 24.00 mm respectively. As the focal length of the lens used is 35 mm, the viewing angle of the cameras (α) was set at 27°.

Based on the sensor height of 24.00 mm and a survey altitude of 305 m (1000 ft), we calculated the dimensions of the oblique images (eq. 2, Grenzdörffer et al., 2008) (Fig. 3), the swath width for our two camera system (2**A*) and the necessary photographic interval to allow for 20% endlap of the photos while flying at a speed of 100 kn (Table 2):

(2)

$$A = Altitude \times \tan\left[radians(\alpha + \beta)\right]$$

$$B = \left\{ \frac{Altitude \times \cos\left[radians(\beta)\right]}{FocalLength \times \cos\left[radians(\alpha - \beta)\right]} \right\} \times sensorheight$$

$$C = \left\{ \frac{Altitude \times \cos\left[radians(\beta)\right]}{FocalLength \times \cos\left[radians(\alpha + \beta)\right]} \right\} \times sensorheight$$

Where: $\alpha =$ angle of camera
$\beta =$ half the field of view of the lens

Table 1. Dimensions of images at 305 m of altitude and image interval needed for 20% endlap (refer to Fig. 3)

Altitude (m)	305
A (m)	420
B (m)	186
C (m)	317
Interval (sec)	3

Field Work Summary

The survey team was based in Repulse Bay. Between 4 August and 8 August, wind or fog limited survey flights to half days (Fig. 4). On 8 August, we flew three transects, 13 km apart, in Gore Bay and sighted many narwhals. As a result, we adapted the survey plan and flew two additional transects between the original lines, decreasing the transect spacing to 6.5 km and therefore increasing our coverage of this small area. Poor weather lasting from 9 August to 13 August prevented further surveying. After the weather cleared, wind conditions were calm or light allowing all but two transects of the survey to be flown from 14 August to 16 August (Fig. 4). The two most southerly transects of the Roes Welcome Sound stratum were not flown due to fuel limitations. On 17 August we flew an additional survey of the Repulse Bay stratum (Fig. 4).

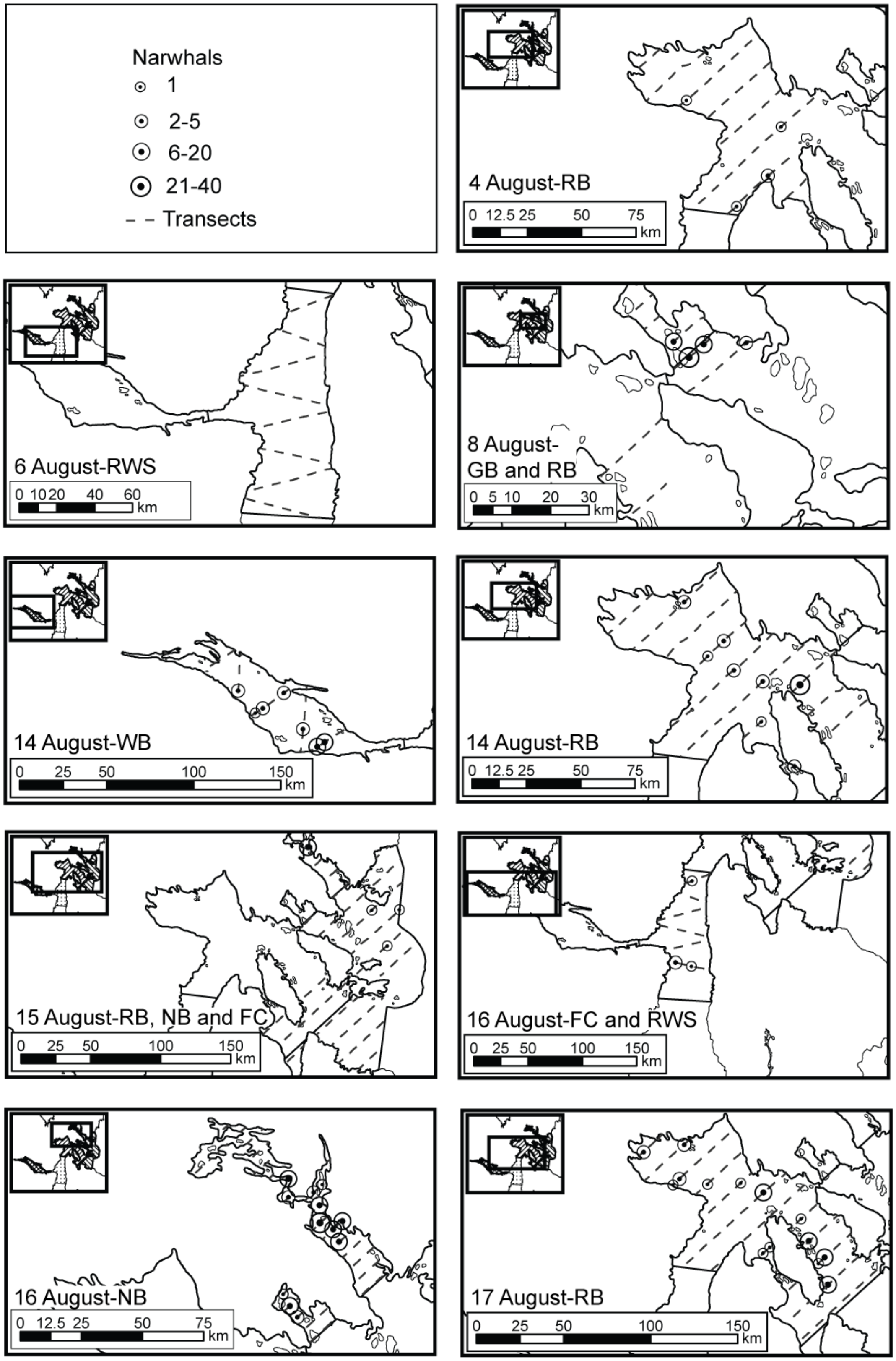

Figure 4. Maps of transects flown and narwhal sightings. Labels indicate date transects were flown and strata: Foxe Channel (FC), Gore Bay (GB), Wager Bay (WB), Northern Bays (NB), Repulse Bay (RB) and Roes Welcome Sound (RWS). Note: narwhal sightings were grouped at 5 km intervals for map clarity.

ANALYTICAL METHODS

Survey Estimation Methods

Audio recordings of visual observers were transcribed and each whale sighting was geo-referenced by matching the observed time with the GPS time. Survey conditions, as described by the primary observers, were assigned to each sighting. Narwhal sightings and aircraft flight tracks were mapped using ArcGIS 9.2 (ESRI Inc.) (Fig. 4). Transect lengths and stratum areas were determined in ArcGIS. A Gore Bay sub-stratum was created to estimate the density of narwhals encountered on 8 August in that one bay. The southern boundary for the Roes Welcome Sound stratum survey conducted on 16 August was adjusted to account for the two missed transects (Fig. 2.e). Declination angles measured by the observers were converted to perpendicular distance from track measurements. For observations missing accurate declination angles, aerial photos taken at the same time were searched for the sighting. These included sightings for which observers did not give a declination angle and sightings made by one observer who demonstrated bad technique while measuring angles in the field. For sightings found on the photographs, we estimated their perpendicular distance (eq.3). If a sighting was on more than one photograph, we averaged the distance measurements.

(3) $$D_s = Altitude \times \tan\left[radians\left(\frac{X_T - X_S}{X_T} \times (2 \times \beta) \right) \right]$$

Where:
D_s = Distance of the sighting
X_T = Total number of pixels in image widthwise (5616)
X_S = Widthwise pixel count from the image's outer edge
$\beta =$ half the field of view of the lens

Adjustment for Perception Bias

Aerial survey observers miss some of the narwhals visible at the surface (Innes et al., 2002; Richard et al., 2010) ('perception bias' sensu Marsh and Sinclair, 1989). Observations from two observers on each side of the plane can be used to correct for perception bias by combining line-transect sampling with mark-recapture methods (Borchers and Burnham, 2004; Laake and Borchers, 2004) We thus planned to conduct a Mark-Recapture Distance Sampling (MRDS) analysis with the point independence fitting method in Distance 6.0 (Thomas et al., 2010). MRDS combines Conventional Distance Sampling with mark-recapture analysis to estimate abundance when the probability of detection at distance zero is less than one (Laake and Borchers, 2004). To conduct MRDS analysis in Distance, duplicate sightings (those seen by both the primary and secondary observer) must be identified. The following criteria were used to identify duplicate sightings:

1) Timing of sightings no more than 10 seconds apart
2) Difference between abeam declination angle of sightings not more than 15°.

For sightings with a difference in declination angles of more than 10°, we searched the photographs to confirm the number of sightings (1 or 2). If the photographs did not provide conclusive evidence to the contrary, we analyzed the data as a re-sighting as this leads to a more conservative estimate overall. If observers indicated different species, we searched the photographs to identify the species. If the photographs did not provide conclusive evidence, we used the species given by the primary observer. In addition, as MRDS analysis in Distance requires that duplicate sightings be identical, when this was not the case, we made the following adjustments to the data:

1) Used perpendicular declination angle as measured by the primary observer
2) Used group size as the average of group size from the two observers
3) Used highest level of group differentiation of the two observers and photographs (e.g., if one observer said one group of three narwhals and the other said three singles in succession, sighting was analyzed as three singles)

Distance Analysis

A histogram of distances for each sighting indicated that many observations were missed by the primary and secondary observers within 100 m and 200 m of the track line, respectively (Fig. 5), partly due to the reduced visibility below the plane. Distance Analysis requires a monotonic declining detection function to be able to estimate density. Consequently, we left-truncated the data by 200 m prior to analysis. Using Distance 6.0, we tested the fit of different detection models and combinations of covariates including Beaufort Sea State, observer, side of aircraft, glare intensity, ice cover and cloud cover. Model selection for the best combination of detection function and covariates was based on the fit of the curve and an Akaike's Information Criterion (AIC) within 2 of the lowest (Buckland et al., 2001; Burnham and Anderson, 2002). A global detection function was modeled and then used to calculate surface estimates by stratum.

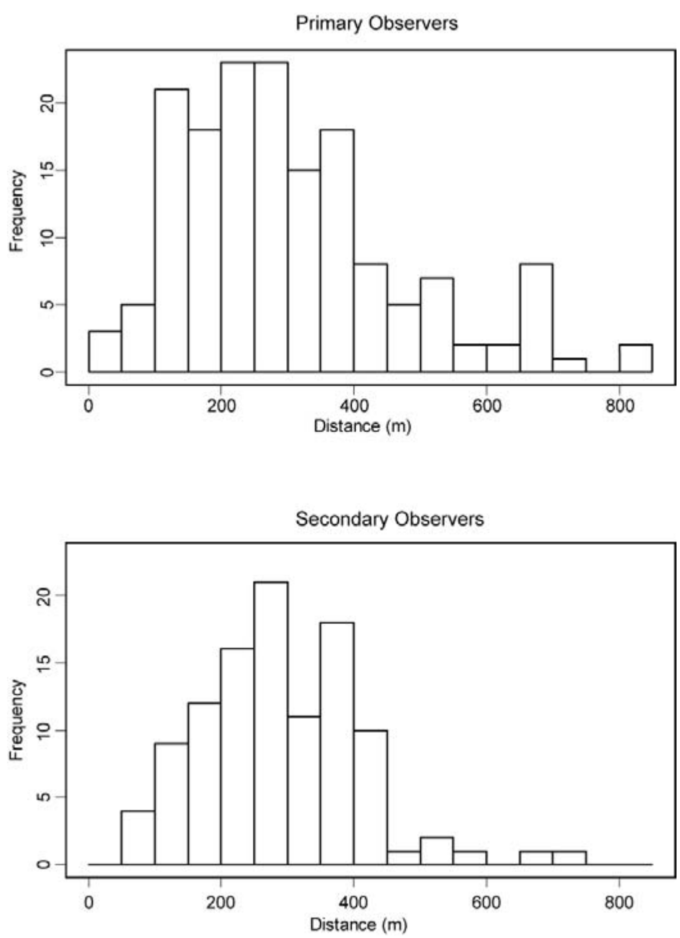

Figure 5. Distribution of narwhal sighting distances for primary observers (top) and secondary observers (bottom)

As narwhals had time to re-locate within the study area between 8 August and 14 August, only the surveys flown from 14 August to 17 August were used in the abundance estimate. The final abundance estimate for the Repulse Bay stratum ($\hat{N}_R$) was calculated by averaging the estimates from the two surveys conducted on 14/15 August and 17 August. Averaging was done using a mean weighted by effort (eq. 4):

(4) $$\hat{N}_R = \frac{E_{R1}\hat{N}_{R1} + E_{R2}\hat{N}_{R2}}{E_{R1} + E_{R2}}$$

Where E_i is the effort calculated as the area covered by the survey *i*.

The variance of the mean estimate was calculated as follows (eq. 5):

(5) $$\text{var}(\hat{N}_R) = \frac{E_{R1}^2 \text{var}(\hat{N}_{R1}) + E_{R2}^2 \text{var}(\hat{N}_{R2})}{\left(E_{R1} + E_{R2}\right)^2}$$

The total surface estimate was calculated by summing the individual estimates from all strata flown from 14 August to 17 August. The variance of that surface estimate is the sum of the variances of the individual stratum estimates.

<u>Adjustment for Availability Bias in the Visual Surveys</u>

In order to estimate species abundance, visual and photographic aerial surveys of aquatic marine mammals must be corrected for availability bias (Marsh and Sinclair, 1989), animals that are in the study area but not visible to observers (i.e., underwater). Experiments with narwhal-shaped models showed that narwhals could be seen and identified by observers (i.e., are available) at depths of about 2 m but not deeper (Richard et al., 1994) and this depth threshold for visibility has been used to correct for availability bias in narwhal surveys (Richard et al., 2010; Asselin and Richard, 2011). Using data from nine narwhals equipped with satellite-linked time-depth recorders (STDR) (5 captured in Lyon Inlet in 2006 and 4 captured in Repulse Bay in 2007), Westdal (2008) estimated the proportion of time narwhals spend within 2 m of the surface estimated as 0.316 (CV=0.053). This is the proportion of whales available to be seen when sightings are instantaneous (p_{aI}) (e.g., on an aerial photo). The correction factor for availability bias when sightings are instantaneous (C_I) is given by (eq. 6):

(6) $$C_I = \frac{1}{p_{aI}}$$

Where: p_{aI} = proportion of whales available to be seen instantaneously

We used the delta method to calculate the variance (Buckland et al. 2001: 52) (eq. 7).

(7) $$\mathrm{var}(C_I) = C_I^{\,2} \times \left(\frac{\mathrm{var}(p_{aI})}{P_{aI}^{\,2}} \right)$$

To correct for availability bias, C_I is used as a correction factor when sightings are instantaneous (e.g., for photographic surveys). If sightings are not instantaneous, the use of this correction factor leads to a positive bias of the estimate. McLaren (1961) developed a correction factor (C_M) that incorporates the dive cycle of the animal and the search time of the observer (eq. 8).

(8) $$C_M = \frac{t_d}{t_o + t_s}$$

Where: t_d = average time for a complete dive cycle
t_o = time available for an observer to see a group ('Time in View')
t_s = average time at the surface per dive cycle

Using data from three ATDRs deployed on narwhals in Tremblay Sound in August 1999 (n=1) and in Creswell Bay in August 2000 (n=2) (Laidre et al., 2002), Richard et al. (2010) calculated the average time for a complete dive cycle (t_d) (depths>2 m) and the average time at the surface per dive cycle (t_s) (depths 0-2 m) (Table 2). For 'Time in View' (t_o), we examined the length of time from the initial recording of a detection (spot time) to the recording of the abeam declination angle measurement (abeam time) for all sightings with both a spot and an abeam time (n=155) (Fig. 6). This resulted in an average 'Time in View' of 5.71 seconds (SE=0.25).

Table 2. Average duration of the surface (≤2 m) interval per dive cycle ($\bar{t}_s$) and complete dive cycle ($\bar{t}_d$) from three archival time-depth recorders (ATDRs) deployed on narwhals (data from Laidre et al. 2002; Richard et al. 2010).

ATDR	**Year**	**Location**	$\bar{t}_s$ **(sec)**	$\bar{t}_d$ **(sec)**
Cres1	2000	Creswell Bay	42	110
Cres 2	2000	Creswell Bay	40	145
Trem3	1999	Tremblay Sound	46	134
		Mean	**43**	**130**
		SE	1.764	10.333
		CV	0.041	0.080

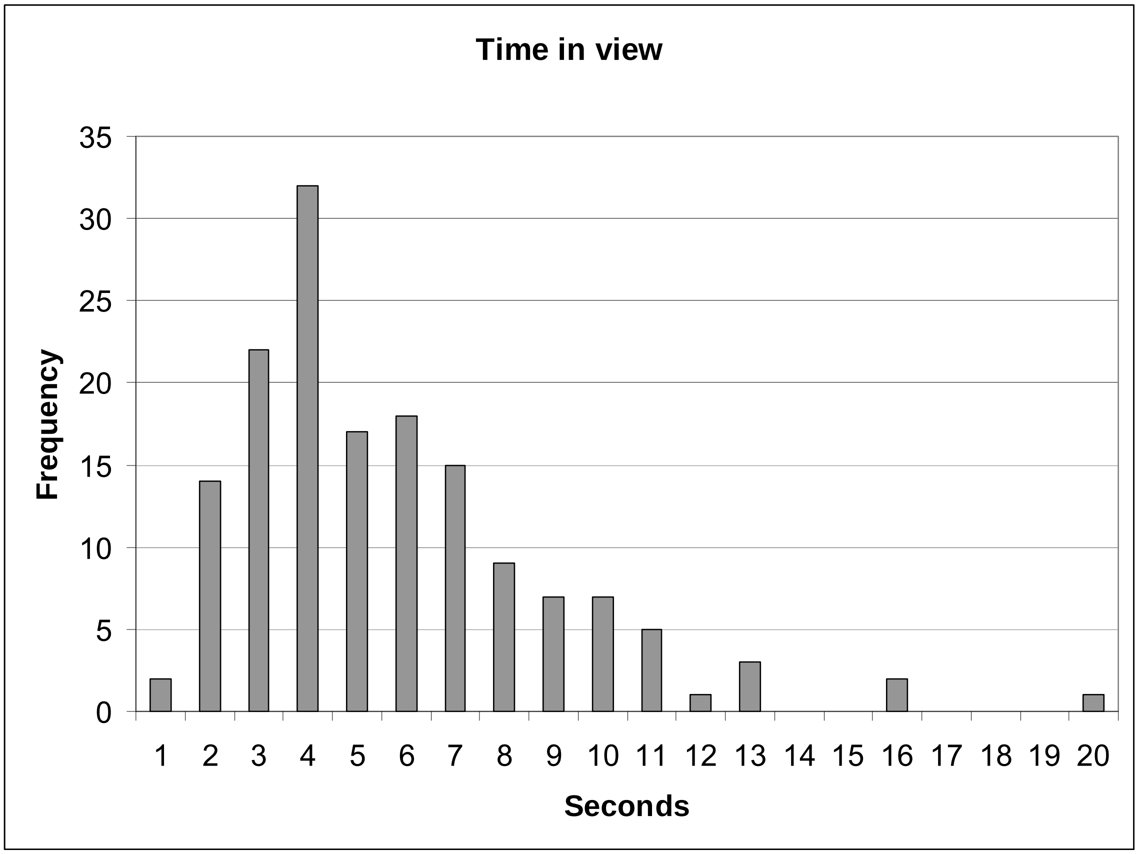

Figure 6. Histogram of Time in View for narwhal groups.

Following the technique proposed by Richard et al. (2010) and used by Asselin and Richard (2011), we used a weighted availability bias correction factor (C_a) which combines the data from the ATDRs, the nine STDRs and the 'Time in View' from our survey (eq. 9) (Table 3).

(9)
$$C_a = C_I \times \frac{\sum_{i=1}^{n} f_i (1 - b_i)}{\sum_{i=1}^{n} f_i}$$

Where: f_i =frequency of times in view of duration i sec

$$b_i = \frac{C_{M(0\,\text{sec})} - C_{M(i\,\text{sec})}}{C_{M(0\,\text{sec})}} \times 100$$ =percent bias of an instantaneous correction C_I

The variance of C_a was calculated using the delta method (Buckland et al. 2001: 52) with C_I contributing to the variance (eq. 10):

(10)
$$\text{var}(C_a) = {C_a}^2 \times \left(\frac{\text{var}(C_I)}{{C_I}^2} \right)$$

Table 3. Correction factor for time in view (t_o) from McLaren (1961) (C_M), instantaneous correction from McLaren (1961) ($C_{M(0\sec)}$), percent bias of an instantaneous correction (b_i), frequency of times in view (f_i), instantaneous correction (C_I) and the resulting weighted availability correction factor (C_a).

t_o (sec)	C_M	$C_{M(0\sec)}$	b_i	f_i
1	2.95	3.02	2.27%	2
2	2.89	3.02	4.44%	14
3	2.83	3.02	6.52%	22
4	2.77	3.02	8.51%	32
5	2.71	3.02	10.42%	17
6	2.65	3.02	12.24%	18
7	2.60	3.02	14.00%	15
8	2.55	3.02	15.69%	9
9	2.50	3.02	17.31%	7
10	2.45	3.02	18.87%	7
11	2.41	3.02	20.37%	5
12	2.36	3.02	21.82%	1
13	2.32	3.02	23.21%	3
14	2.28	3.02	24.56%	0
15	2.24	3.02	25.86%	0
16	2.20	3.02	27.12%	2
17	2.17	3.02	28.33%	0
18	2.13	3.02	29.51%	0
19	2.10	3.02	30.65%	0
20	2.06	3.02	31.75%	1
			n	155
			C_I	3.16
			C_a	**2.80**
			SE	0.15
			CV	0.05

Following Richard et al. (2010) and Asselin and Richard (2011) the surface abundance estimate ($\hat{N}_s$) was corrected for availability bias to give a total abundance estimate ($\hat{N}^*$) (eq. 11).

(11) $$\hat{N}^* = \hat{N}_S \times C_a$$

With variance calculated using the delta method (Buckland et al. 2001: 52) (eq. 12):

(12) $$\mathrm{var}(\hat{N}^*) = \hat{N}^{*2} \times \left\{ \frac{\mathrm{var}(\hat{N}_S)}{\hat{N}_S^{\,2}} + \frac{\mathrm{var}(C_a)}{C_a^{\,2}} \right\}$$

Total Allowable Landed Catch (TALC)

As in Richard (2008), and Asselin and Richard (2011), a Total Allowable Landed Catch (TALC) was calculated using the Potential Biological Removal (PBR) method (Wade, 1998) and factoring out the estimated hunting loss rate (eq. 13).

(13) $$TALC = \frac{PBR}{LRC}$$

Where: $PBR = 0.5 \times R_{Max} \times \hat{N}_{Min} \times F_r$

$LRC =$ Loss rate correction

$R_{Max} =$ Maximum rate of increase for the stock

$\hat{N}_{Min} =$ 20th percentile of the log-normal distribution of $\hat{N}$ *

$F_r =$ Recovery factor

We used a loss rate correction of 1.28 (Richard, 2008). As the maximum rate of increase for the stock (R_{Max}) is unknown, we used the default for cetaceans of 0.04 (Wade, 1998). The recovery factor (F_r) can be set to 0.1 for a critically low stock status, 0.5 for a depleted status and 1.0 for a healthy status (Wade and Angliss, 1997).

RESULTS

OVERALL SURVEY CONDITIONS

Surveys were conducted on 4 August, 6 August, 8 August and 14 to 17 August and a range of survey conditions were encountered during the seven days of surveying (Appendix A). From 4 August to 8 August, wind and fog prevented extensive surveying. Beaufort Sea States up to 4.5 were reported while some transects were cut short due to the presence of fog. Following five days without surveying due to high winds and low clouds, survey conditions were much improved for the 14 August to 17 August surveys. Beaufort Sea States were largely below 3 with many transects with Beaufort Sea States below 2. Ice concentrations were highest in the Foxe Channel stratum and the southern portion of the Northern Bays stratum. Glare was reported, at various levels, on and off throughout the surveys. Some fog was reported but only on 11 transects and mainly light in intensity.

NARWHAL ABUNDANCE ESTIMATE

From 4 August to 8 August, only one stratum (Roes Welcome Sound) was surveyed in its entirety but no narwhals were observed. An aggregation of narwhals was surveyed in Gore Bay (435 km^2) on 8 August. An estimated 521 (CV =0.55) narwhals were at the surface in this one small bay (Table 4). A partial survey of Repulse Bay on 4 August yielded four sightings. From 14 to 17 August, more favorable surveying conditions enabled us to cover practically the entire study area within a four-day period. Only two transects, located at the southern end of the Roes Welcome Sound stratum (Fig. 2.e.), were not flown. The Repulse Bay stratum was surveyed twice, on 14-15 August and on 17 August, and 20 groups of narwhals were spotted each time. Wager Bay and the Northern Bays strata also contained concentrations of narwhals with 19 and 49 sightings respectively. Only three narwhal groups were spotted in each of the Roes Welcome Sound and Foxe Channel strata.

The aerial photos were used to confirm the species identification for nine sightings: five narwhal sightings, three walrus sightings and one seal sighting. The photos were also used to confirm the presence of three narwhal sightings for which the observer expressed uncertainty. In total, 195 narwhal groups were sighted throughout the surveys. For three sightings, the observers did not give a declination angle and we were unable to find the animals on the aerial photos. These sightings were omitted from further analysis. We used the photos to measure or confirm the perpendicular distance for 17 sightings. These included sightings for which observers did not give a declination angle and sightings made by one observer who demonstrated bad technique while measuring angles in the field. This left us with 192 sightings, of which 135 were farther than 200 m from the trackline and included in the analysis (Table 4).

Using Distance 6.0, we found that using a Hazard Rate detection function with distance, observer (primary or secondary), side of aircraft (left or right) and ice concentration as covariates of the Mark-Recapture model and cloud cover as a covariate of the Distance model resulted in a good fit of the detection curve and an AIC within 2 of the lowest (Delta AIC=1.63) and ranked third overall using AIC (Table 5). In comparing the three models with the lowest AICs (Table 5), the second ranked model (Delta AIC=0.55) was not selected as the fit of the detection curve was not as good as the models ranked first and third, as determined by the Kolmogorov-Smirnov (k-s) statistic (k-s=0.069, p=0.54) and inspection of the detection curve. The model ranked first (Delta AIC=0) was very similar to the third-ranked model (Delta AIC=1.63) with the addition of Beaufort Sea State as a covariate of the Mark-recapture model. In comparing the first and third ranked models, their k-s statistics were the same (k-s=0.056, p=0.76) and their global density estimates were very similar. The model ranked first was not selected due to the correlation between ice cover and Beaufort Sea State, as ice cover lessens the effect of wind on wave action. Observer and side of aircraft plus all of their interactions were included as covariates. Using this covariate detection model in Distance's MRDS, we estimated that both the primary and secondary observers missed observations at the track line [g(0)]. The primary and secondary observers had probabilities of detection [p(0)] of 0.80 (CV=0.06) and 0.62 (CV=0.10), respectively. The estimated p(0) of the two observers combined was 0.91 (CV= 0.04). Only two groups of narwhals were seen at distances in excess of 800 m from the track line and examination of the detection curves (Fig. 7) indicates that animals were increasingly missed beyond 300-400 m.

Table 4. Survey coverage, sightings and surface estimates by stratum (CVs are shown in parentheses, surveys in bold were used in the population abundance estimate).

	Date	Area (km^2)	Total Transect Distance (km)	Surveyed Area (km^2)[1]	Sightings with Distance	Average Group Size	Average Probable Detection over Distance *g(x)*	Estimated Coverage (%)[2]	Average Probable Detection at Track Line *p(0)*	Surface Estimate
Repulse Bay (Partial)	4-Aug	6884	326	399	4	1.5 (0.3)	0.41 (0.04)	2.4	0.91 (0.03)	335 (0.60)
Roes Welcome Sound	6-Aug	4706	313	384	0	0 (0)	0.41 (0.04)	3.4	0.91 (0.03)	0 (0)
Gore Bay	8-Aug	435	63	77	13	3.4 (0.4)	0.41 (0.04)	7.2	0.91 (0.03)	521 (0.55)
Wager Bay	**14-Aug**	**2819**	**150**	**184**	**19**	**1.8 (0.1)**	**0.41 (0.04)**	**2.7**	**0.91 (0.03)**	**1095 (0.63)**
Repulse Bay (1)	**14+15 Aug**	**6884**	**539**	**660**	**20**	**2.5 (0.2)**	**0.41 (0.04)**	**3.9**	**0.91 (0.03)**	**1692 (0.34)**
Northern Bays (Partial)	15-Aug	1233	34	42	4	3.5 (0.4)	0.41 (0.04)	1.4	0.91 (0.03)	933 (1.09)
Foxe Channel	**15+16 Aug**	**6689**	**533**	**653**	**3**	**1 (0)**	**0.41 (0.04)**	**4.0**	**0.91 (0.03)**	**76 (0.52)**
Roes Welcome Sound (Partial)	**16-Aug**	**3407**	**220**	**269**	**3**	**1.3 (0.2)**	**0.41 (0.04)**	**3.3**	**0.91 (0.03)**	**107 (0.77)**
Northern Bays	**16-Aug**	**1233**	**226**	**277**	**49**	**2.7 (0.1)**	**0.41 (0.04)**	**9.3**	**0.91 (0.03)**	**1746 (0.44)**
Repulse Bay (2)	**17-Aug**	**6884**	**529**	**648**	**20**	**2.1 (0.1)**	**0.41 (0.04)**	**3.9**	**0.91 (0.03)**	**1160 (0.69)**

[1] total transect distance multiplied by twice the largest perpendicular distance (note: the largest perpendicular distance was first truncated by 200 m)
[2] [(Surveyed Area * g(x)) / Area] * 100

Table 5. Detection functions, Mark-Recapture model covariates, Distance model covariates AIC, Delta AIC, Global density estimate pooled across strata (CV shown in parentheses) and the Kolmogorov-Smirnov (k-s) statistic for the top five ranked models tested in Distance 6.0. The model shown in bold was used in the analysis.

Ranking	Detection function	Mark-recapture model covariates	Distance model covariates	AIC	Delta AIC	Global density estimate	k-s
1	Hazard Rate	(Observer * Side) +Ice + Beaufort Sea State	Cloud	1908.04	0.00	0.190(0.25)	0.057 (p=0.76)
2	Hazard Rate	(Observer * Side)	Cloud + Ice	1908.59	0.55	0.166(0.23)	0.069 (p=0.54)
3	**Hazard Rate**	**(Observer * Side) + Ice**	**Cloud**	**1909.67**	**1.63**	**0.186(0.25)**	**0.057 (p=0.76)**
4	Hazard Rate	(Observer * Side) + Ice	Cloud * Side	1910.14	2.10	0.252(0.26)	0.058 (p=0.75)
5	Hazard Rate	(Observer * Side) + Ice	Cloud + Beaufort Sea State	1911.65	3.61	0.166(0.23)	0.062 (p=0.68)

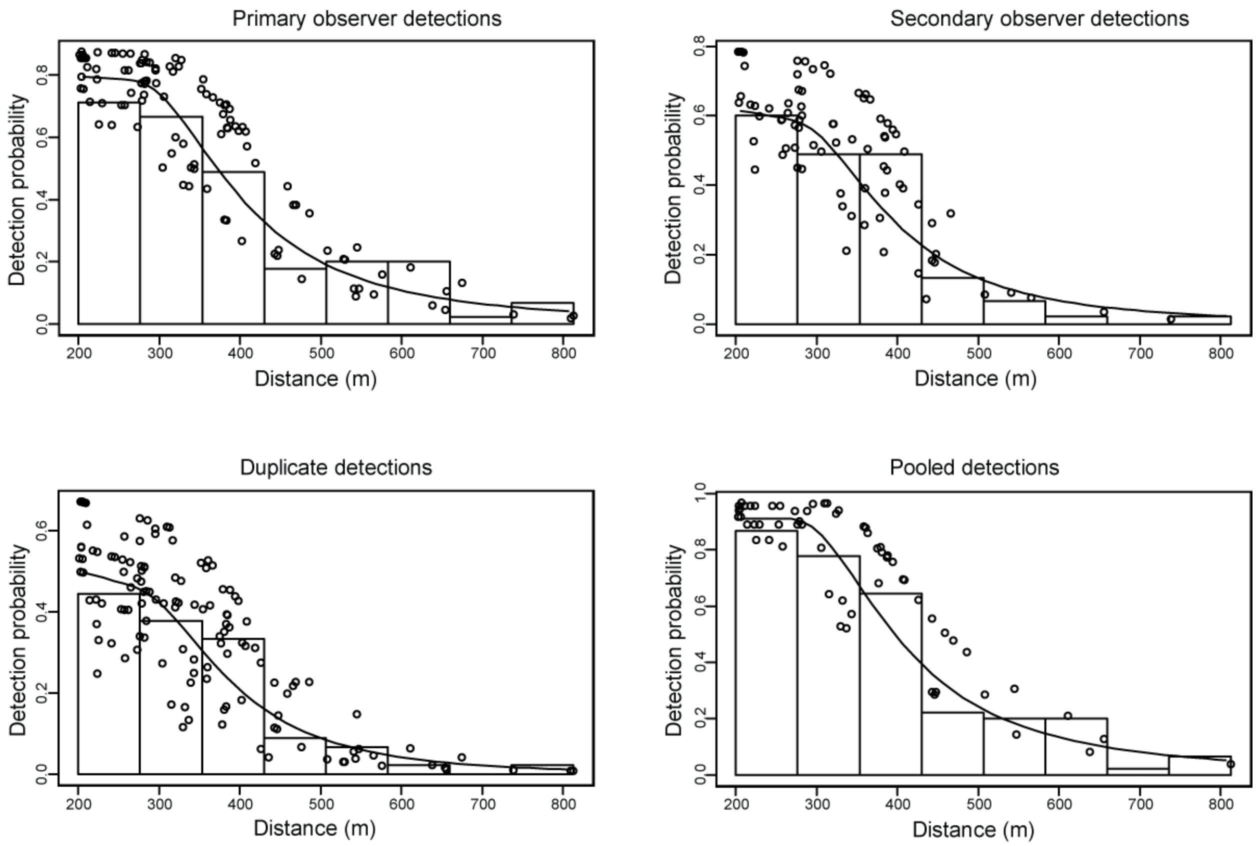

Figure 7. Probability of detection of each narwhal sighting, histograms of frequency of sightings and fitted detection functions for single observers (top), both observers (bottom left) and pooled detections (bottom right).

The weighted average surface estimate from the two surveys of Repulse Bay conducted on August 14/15 and August 17 was 1429 (CV=0.35) narwhals. Summing that average surface estimate to single estimates for the Foxe Channel (August 15/16) Wager Bay (August 14), Roes Welcome Sound (August 16) and the Northern Bays (August 16) strata resulted in a total surface estimate of 4452 (CV=0.26). Finally, correcting the surface estimate for availability bias resulted in a total population estimate of 12,485 narwhals (95% C.I. 7,515-20,743) (Table 6).

Table 6. Narwhal surface estimates by stratum and the final abundance estimate corrected for availability bias.

	C.L. 2.5%	Mean	C.L. 97.5%	CV
Repulse Bay 1	852	1692	3361	0.34
Repulse Bay 2	307	1160	4381	0.69
Average Repulse Bay	740	1429	2758	0.35
Foxe Channel	29	76	199	0.52
Wager Bay	354	1095	3386	0.63
Roes Welcome Sound	28	107	406	0.77
Northern Bays	763	1746	3998	0.44
Total Surface Estimate	**2707**	**4452**	**7322**	**0.26**
C_a		2.80		0.05
Abundance Estimate	**7515**	**12,485**	**20,743**	**0.26**

TOTAL ALLOWABLE LANDED CATCH (TALC)

The 20th percentile of the log-normal distribution of the stock estimate ($\hat{N}_{Min}$) is 10,040. Following Richard (Richard, 2008), we used a Recovery factor (F_r) of 1 for this calculation as this new abundance estimate confirms the stock is healthy. The PBR is the product of 0.5, 0.04 (R_{Max}), 10,040 ($\hat{N}_{Min}$) and 1 (F_r) and equals 201 (Table 7). The TALC is the PBR divided by 1.28 (LRC) and equals 157.

Table 7. PBR and TALC calculations for Northern Hudson Bay narwhals based on the 2011 survey.

Mean Abundance Estimate	$\hat{N}_{Min}$	R_{Max}	F_r	**PBR**	**LRC**	**TALC**
12,485	10,040	0.04	1	201	1.28	157

DISCUSSION

Prior to our 2011 surveys, NHB narwhals had been the subject of three population surveys (Richard, 1991; Bourassa, 2003; Richard, 2010), two studies aimed at collecting Traditional Ecological Knowledge (Gonzalez, 2001; Westdal, 2008) and one project studying the movements of narwhals equipped with satellite linked-transmitters (Westdal et al., 2010). This published information allowed us to design an aerial survey that captured a large portion of the population. By consulting Repulse Bay's Arviq Hunters and Trappers Organization, we extended the study area to include Wager Bay, where 19 groups of narwhals were spotted. Following initial surveys of Gore Bay, Lyon Inlet and the northern inlets, where a high density of narwhals were observed, we re-surveyed this portion of the study area with higher coverage to increase the accuracy and precision of the abundance estimate for this stratum. We also separated the Main stratum into two strata, to reflect differences in ice conditions during the 14-17 August surveys. After observing higher narwhal densities in the Repulse Bay stratum, we conducted an additional survey of that stratum to increase the precision of our estimate by averaging two surveys.

Accurate abundance estimates require that all individuals in the group for which an estimate is sought have a possibility of being sampled. Correctly establishing the study area is the first step towards accurately estimating the abundance of a population using Distance (Buckland et al., 2001). As NHB narwhals move in response to killer whales (Gonzalez, 2001; Westdal, 2008) and ice conditions (Gonzalez, 2001; Westdal, 2008), their locations at a given time are difficult to predict. By expanding the study area beyond what had been previously sampled, we increased our chances of capturing a larger portion of the population from which we could estimate an accurate abundance estimate. We do not however claim to have covered all of the areas used by NHB narwhals in August 2011. For example, after the survey, we learned that narwhals had been spotted near Chesterfield Inlet, approximately 170 km south of our study area (letter from Kivalliq Wildlife Board dated 16 August 2011, received 17 August 2011). It is impossible to know how many narwhals were outside of our study area at the time of our surveys and thus not possible to quantify the extent to which our results may have been negatively biased (i.e. underestimated). Nonetheless, our results are the best estimate of the abundance of NHB narwhals based on knowledge of their aggregation areas at this time.

Prior to the 2011 surveys, the 2000 NHB narwhal survey estimate of 1778 (90% C.I. 1688-2015) (Bourassa, 2003), corrected to 5053 (CV=0.40) to account for submerged animals (Richard, 2008), was the best abundance estimate available. Our 2011 estimate of 12,485 (CV=0.26) is notably higher. Our larger study area likely accounts for part of the difference. The 2000 survey did not include Wager Bay (Bourassa, 2003) where we observed 19 narwhal groups and estimated 1095 (CV=0.63) narwhals at the surface. Similarly, our survey extended farther north in Lyon Inlet than the 2000 survey (Bourassa, 2003). The narwhals we observed in the Northern Bays stratum accounted for nearly 40% of our overall surface abundance estimate (1746 of 4452). Our 8 August survey of Gore Bay resulted in an estimate of 521 (CV=0.55) narwhals at the surface. While this survey could not be included in the overall abundance estimate, it highlights the importance of fully surveying the study area to ensure that small areas with high densities of narwhals are not missed.

The simultaneous collection of aerial photography and visual observations provided us with an additional source of information when observers did not provide detailed sighting information (e.g. missed angles) or when two observers disagreed on species identification. This additional source of information allowed us to use three uncertain sightings, seventeen sightings with missing or uncertain angles and to confirm the species identification of nine sightings. In this way, we were able to include additional sightings in our analysis that would have been lost without the use of the aerial photos. Innes et al. (2002) also proposed a technique to include sightings with missing perpendicular distances but their method relied on the assumption that observations with missing perpendicular distances were a random sample of all observations. Our method measures the actual distance of the sightings but can only be used in the area of overlap between the aerial photos and the visual survey strip: 200 m to 420 m from the trackline.

While these results are a notable improvement on prior attempts to estimate the abundance of NHB narwhals, there are still a number of sources of uncertainty with the estimation of the population size. The individual stratum estimates have large CVs associated with them which could be reduced by increasing the survey coverage. This is particularly true for Wager Bay which contributes 25% of the overall surface abundance estimate (1095 of 4452) with a CV=0.63. Another source of uncertainty is the correction factor for availability bias which has a large effect on the estimated size of the population but is currently based on records of the diving behaviour of a small number of narwhals. More research is required to include additional covariates into the availability bias model such as age, sex, bathymetry, week, and behavior (e.g., feeding or traveling). Also of concern is that the availability bias correction factor has a small associated variance and it is possible that the mean of the proportion of time narwhal instrumented with time-depth recorders spend at the surface does not fully account for the variation in behaviour of NHB narwhals during the surveys. This source of uncertainty requires further research to determine if it is a source of bias or causes an underestimation in the error variance of the estimated number of NHB narwhals. A source of uncertainty in the calculation of the TALC comes from the use of a fixed loss rate (1.28) derived from hunts throughout Nunavut (Richard, 2008) rather than one derived from observations of NHB narwhal hunts only. Such data are as yet not available but a correction factor derived from them should be applied to TALC calculations when obtained. We recommend the collection of independent hunt loss rate data for Northern Hudson Bay to compare current losses to the fixed loss rate used here.

ACKNOWLEDGEMENTS

We would like to acknowledge the community of Repulse Bay, Kivalliq Wildlife Board, Nunavut Tunngavik Inc., Repulse Bay's Arviq Hunters and Trappers Association, the Polar Continental Shelf Project, the Nunavut Implementation Fund (DFO) and the Nunavut Wildlife Management Board for their support of this project. Peter Mannik, Mary Tuktudjuk, Simeoni Kringayark, Holly Cleator and Elly Chmelnitsky served as observers during the aerial surveys and we thank them for their assistance.

REFERENCES

Asselin, N.C., and Richard, P.R. 2011. Results of narwhal (*Monodon monoceros*) aerial surveys in Admiralty Inlet, August 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/065. iv + 26 p.

Borchers, D.L., and Burnham, K.P. 2004. General formulation for distance sampling. *In* Advanced distance sampling: estimating abundance of biological populations. Edited by S.T. Buckland, D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers and L. Thomas. Oxford University Press, Oxford. p. 6-30.

Bourassa, M.N. 2003. Inventaires de la population de narvals (*Monodon monoceros*) du nord de la Baie d'Hudson et analyse des changements démographiques depuis 1983, Thesis (M.Sc.) Université du Québec, Rimouski, xii + 69 p.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., and Thomas, L. 2001. Introduction to distance sampling: estimating abundance of biological populations. Oxford University Press, Oxford. 432 p.

Burnham, K.P., and Anderson, D.R. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer, New York. 488 p.

Covington, M. 1985. Astrophotography for the amateur. Cambridge University Press, Cambridge. 168 p.

de March, B.G.E., and Stern, G. 2003. Stock separation of narwhal (*Monodon monoceros*) in Canada based on organochlorine contaminants. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/079. iii + 16 p.

de March, B.G.E., Tenkula, D.A., and Postma, L.D. 2003. Molecular genetics of narwhal (*Monodon monoceros*) from Canada and West Greenland (1982-2001). DFO Can. Sci. Advis. Sec. Res. Doc. 2003/080. i + 19 p.

Gonzalez, N. 2001. Inuit traditional ecological knowledge of the Hudson Bay narwhal (Tuugaalik) population. Rep. prepared for Fisheries and Oceans Canada, Iqaluit, Nunavut. http://www.dfo-mpo.gc.ca/Library/317649.pdf

Grenzdörffer, G.J., Guretzki, M., and Friedlander, I. 2008. Photogrammetric image acquisition and image analysis of oblique imagery. Photogrammetric Record 23(124): 372-386. doi:DOI 10.1111/j.1477-9730.2008.00499.x

Innes, S., Heide-Jorgensen, M.P., Laake, J.L., Laidre, K.L., Cleator, H.J., Richard, P., and Stewart, R.E.A. 2002. Surveys of belugas and narwhals in Canadian high Arctic in 1996. NAMMCO Scientific Publications 4: 169-190.

Laake, J.L., and Borchers, D.L. 2004. Methods for incomplete detection at distance zero. *In* Advanced distance sampling: estimating abundance of biological populations. Edited by S.T. Buckland, D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers and L. Thomas. Oxford University Press, Oxford. p. 108-189.

Laidre, K.L., Heide-Jørgensen, M.P., and Dietz, R. 2002. Diving behaviour of narwhals (*Monodon monoceros*) at two coastal localities in the Canadian High Arctic. Can. J. Zool. 80(4): 624-635. doi:10.1139/z02-041

Marsh, H., and Sinclair, D.F. 1989. Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. J. Wildl. Manag. 53(4): 1017-1024.

McLaren, I.A. 1961. Methods of determining the numbers and availability of ringed seals in the eastern Canadian Arctic. Arctic 14(3): 162-175.

Richard, P.R. 1991. Abundance and distribution of narwhals (*Monodon monoceros*) in northern Hudson Bay. Can. J. Fish. Aquat. Sci. 48: 276-283.

Richard, P.R. 2008. On determining the Total Allowable Catch for Nunavut odontocete stocks. DFO Can. Sci. Advis. Sec. Res. Doc.2008/022. iv + 12 p.

Richard, P.R. 2010. Survey index of the northern Hudson Bay narwhals, August 2008. DFO Can. Sci. Advis. Sec. Res. Doc.2010/021: iv + 17 p.

Richard, P.R., Weaver, P., Dueck, L., and Barber, D. 1994. Distribution and numbers of Canadian High Arctic narwhals (*Monodon monoceros*) in August 1984. Meddelelser om Grønland, Bioscience 39: 41-50.

Richard, P.R., Laake, J.L., Hobbs, R.C., Heide-Jorgensen, M.P., Asselin, N.C., and Cleator, H. 2010. Baffin Bay narwhal population distribution and numbers: aerial surveys in the Canadian high Arctic, 2002-04. Arctic 63(1): 85-99.

Strong, J.T. 1988. Status of the narwhal, *Monodon monoceros*, in Canada. Can. Field-Nat. 102(2): 391-398.

Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R.B., Marques, T.A., and Burnham, K.P. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. J. Appl. Ecol. 47(1): 5-14. doi:DOI 10.1111/j.1365-2664.2009.01737.x

Wade, P.R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. Mar. Mammal Sci. 14(1): 1-37. doi:10.1111/j.1748-7692.1998.tb00688.x

Wade, P.R., and Angliss, R.P. 1997. Guidelines for assessing marine mammal stocks. Report of the GAMMS Workshop 3-5 April, 1996, Seattle, WA., NOAA Technical Memorandum NMFS-OPR-12. 93 p.

Westdal, K.H. 2008. Movement and diving of Northern Hudson Bay narwhals (*Monodon monoceros*): relevance to stock assessment and hunt co-management, Thesis (M.Env.),University of Manitoba, Winnipeg, Manitoba. 103 p.

Westdal, K.H., Richard, P.R., and Orr, J.R. 2010. Migration route and seasonal home range of the northern Hudson Bay narwhal (*Monodon monoceros*). *In* A little less Arctic: Top predators in the world's largest northern inland sea. Edited by S.H. Ferguson, L.L., Loseto and M.L. Mallory. Springer London. p. 71-91.