Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2020/073

Central and Arctic Region

Narwhal (*Monodon monoceros*) abundance estimate from the 2018 aerial survey of the Northern Hudson Bay population

Cortney A. Watt, Claire Hornby, and Justine Hudson

Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, Manitoba, R3T 2N6

November 2020

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Watt, C.A., Hornby, C., and Hudson, J. 2020. Narwhal (*Monodon monoceros*) abundance estimate from the 2018 aerial survey of the Northern Hudson Bay population. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/073. iv + 15 p.

Aussi disponible en français :

*Watt, C.A., Hornby, C., et Hudson, J. 2020. Estimation de l'abondance de narvals (*Monodon monoceros*) d'après le relevé aérien de la population du nord de la baie d'Hudson réalisé en 2018. Secr. can. de consult. sci. du MPO, Doc. de rech. 2020/073. iv +16 p.*

TABLE OF CONTENTS

ABSTRACT

Northern Hudson Bay narwhal (*Monodon monoceros*) form a distinct genetic and geographically isolated population. Visual aerial surveys were conducted from 3–14 August 2018 in order to estimate the abundance of this narwhal population. This survey was designed to repeat the 2011 survey design, with one change to increase coverage in Wager Bay, as recommended by the Arviq Hunters and Trappers Organization in Naujaat. The survey covered four key areas commonly used by narwhal: Wager Bay, Roes Welcome Sound, Repulse Bay and the northern bays of Gore Bay and Lyon Inlet. The surface abundance estimate for narwhal was 5,055 (CV = 0.270) individuals. After adjustment for availability bias to account for whales not seen due to diving (adjustment factor Ca = 2.80 [CV = 0.05]) and perception bias, which occurs when some observers miss whales (adjustment factor Cp = 1.36 [CV = 0.092]), the estimated adjusted abundance is 19,232 (CV = 0.278, 95% CI = 11,257–32,856) narwhals.

INTRODUCTION

Narwhals (*Monodon monoceros*) from northern Hudson Bay form one of two narwhal populations in Canada, and are genetically and geographically distinct from narwhals of the Baffin Bay population (Richard 1991, Petersen et al. 2011). Narwhals from the Northern Hudson Bay (NHB) population summer near the community of Naujaat (formally Repulse Bay), Nunavut, from approximately June until October, when they travel ~ 1,250 km to their wintering grounds, just east of Hudson Strait (Richard 1991, Westdal et al. 2010, Elliott et al. 2013, Heide-Jørgensen et al. 2013, Westdal et al. 2013).

In the summer, NHB narwhal are hunted for subsistence by the community of Naujaat and other communities in the Qikiqtaaluk and Kivalliq regions (Figure 1). NHB narwhal can also be hunted on their migration to and from their summering areas by communities in Hudson Strait. From 2000–2017, approximately 90 narwhals on average were harvested each year from the NHB population (DFO, unpublished data). The habitat of NHB narwhal is also experiencing changes; notably, there has been a decline in summer sea ice since 1968 (Tivy et al. 2011), changes in trophic dynamics, including increases in capelin (*Mallotus villosus*) and concurrent decreases in Arctic cod (*Boreogadus saida*) (Gaston et al. 2003), as well as increased presence of killer whales (*Orcinus orca*) (Higdon and Ferguson 2009).

Systematic aerial surveys of NHB narwhals were conducted in the early 1980's (Richard 1991), as well as in 2000 (Bourassa 2003) and 2011 (Asselin et al. 2012). In 2011, a combination of visual and photographic surveys resulted in a population estimate of 12,485 (CV = 0.26, 95%, 95% CI = 7,515–20,743) narwhal (Asselin et al. 2012). To ensure the subsistence hunt is managed effectively, abundance estimates at regular intervals are needed. The objective of this study was to provide an updated abundance estimate for the NHB narwhal population based upon a survey carried out in 2018.

METHODS

STUDY AREA

The 2018 study area and survey coverage were designed to replicate the areas flown in the 2011 aerial survey and was divided into four strata: Wager Bay, Roes Welcome Sound, Repulse Bay and North Bays, which included Gore Bay and Lyon Inlet (Figure 1). Compared to the previous survey, coverage was increased in Wager Bay; in 2011 a zig-zag design was employed whereas systematic parallel transects, spaced 10 km apart were used in the 2018 survey to increase coverage, as recommended by the Arviq Hunters and Trappers Organization (HTO). In Repulse Bay and North Bays strata, a systematic survey design was also used with transects 13 km and 5.6 km apart, respectively, to provide uniform coverage probability (Buckland et al. 2001). In Roes Welcome Sound we used a 15 km zig-zag design to maximize coverage and reduce travel time between transects (Buckland et al. 2001). All strata were surveyed visually; however, photographs were taken throughout the survey to cross check detections and potential duplicates, and as a backup in case observers were unable to record distances to sightings.

SURVEY

Surveys were flown in a DeHavilland Twin Otter (DH-6) equipped with four bubble windows and an optical glass covering a camera hatch at the rear underbelly of the plane. Survey transects were flown at a target altitude of 1,000 ft (305 m) and a ground speed of 110 knots (204 km/hr). A Global Positioning System unit (Bad Elf GPS pro+) was used to log the position, altitude, speed, and heading of the aircraft every second. Two synchronized iPads running Foreflight (an aviation navigation application) were also connected to the Bluetooth GPS, and used by the survey coordinator and pilots to input/edit waypoints for each stratum. This programme also provided navigation tools and base maps, and recorded daily flight tracks. Surveys were only flown under the following environmental conditions: no rain, no risk of icing, ceilings of 2,500 ft or higher with no fog over the water in the survey area, and a Beaufort Sea State of 0–3. A double platform design, in which two observers were seated at the two bubble windows on each side of the aircraft, was used for all visual surveys (Buckland et al. 2001). All four observers remained in their respective positions in the plane throughout the survey and the two observers on the same side of the aircraft were visually and acoustically isolated from one another to ensure independent observations. The two primary observers at the front of the aircraft recorded the following environmental conditions at the start and end of each transect (or when any changes occurred): ice concentrations (in tenths), sea state (Beaufort scale), fog (% of field of view), glare (% of forward field of view), and cloud cover (%). Narwhal sightings were recorded through a Sony PCM-D50 audio recorder, as well as other observed species, group size, and perpendicular declination angle to the centre of each group, which was measured using a Peco DCC1 Digital Compass/Clinometer when the individual or group was abeam to the observer. A 'group' was defined as animals within one body length of each other and behaving cohesively. Photographs of the area below the aircraft were also taken during the visual surveys. Two Nikon D850 cameras, equipped with 25 mm lenses, were mounted at the rear of the aircraft and directed straight down, with the longest side perpendicular to the track line. To georeference photographs, cameras were linked via Bluetooth to a single Bluetooth GPS receiver (Bad Elf GPS Pro+) using a Bluetooth module accessory (Foolography Unleashed D200+ Bluetooth Module). Each camera was also connected to a laptop computer to control exposure settings, the photograph interval, and to save high resolution RAW and JPEG photographs to the computer's hard drive.

ANALYSIS

Visual line-transect survey data were analysed using Distance 7.2 software (Thomas et al. 2010), which requires the measure of perpendicular distance of each observation from the trackline. This distance is calculated using the declination angle (and taking into consideration the curvature of the earth [Lerczak and Hobbs 1998]), which was measured for all but four of the observations. The perpendicular distance of three observations were estimated from the aerial photographs using:

$$D_s = \left(\frac{W_v}{W_i}\right) * D_o$$

Where D_s is the distance of the sighting, W_v is the total field of view in meters (m) widthwise, W_i is the total number of millimeters (mm) in the image widthwise, and D_o is the distance from the trackline (which is centred on the photo) to the object in mm. One observation, which occurred out of the field of view of the photographs, did not have a recorded distance and so was not used to fit the detection function, but was used in abundance estimation.

Conventional distance analysis assumes the probability of detection on the trackline (p(0)) is 1; however, observers may miss some whales that are visible at the surface (Richard et al. 2010). Double observer methods, like those used in this study, allow for estimation of perception bias. To determine the value of p(0), duplicate sightings between the primary and secondary observers on each side of the aircraft were identified as occurring within 10 seconds of one another and less than a 10 degree declination difference (Southwell et al. 2002, Pike and Doniol-Valcroze 2015). In three cases, the declination angles differed by > 10 degrees (11–13 degrees), but the times were < 5 seconds apart and these were also classified as duplicates. When possible, potential duplicates were also confirmed by evaluating photographs (n = 26 pairs) and all were confirmed as duplicates. Primary observers on the left and right side of the aircraft were referred to as observer 1, and the two rear observers were considered together as observer 2. A point independence model, which assumes that detections were independent only on the track line (Buckland et al. 2009), was conducted in the MRDS package in R (R Core Team 2013, Laake et al. 2020).

DETECTION FUNCTION

A global detection function was calculated using combined observation data from all strata, which were all surveyed from the same platform by the same observers under similar conditions. Fits of key candidate detection functions (half-normal, hazard-rate), in various combinations with candidate series expansions (cosine, simple polynomial, and hermite polynomial) to ungrouped perpendicular distances from all observers, were assessed by Akaike information criterion (AIC) values. Conventional distance sampling assumes detection of all objects on the transect line (i.e., zero distance), which is not the case with aerial surveys since the area immediately under the aircraft may be obscured to observers. To eliminate having to truncate the data and exclude some observations, a gamma detection function was also considered. Data were right-truncated at 1000 m, and one observation with a missing perpendicular distance was excluded prior to model fitting using the package MRDS (Laake et al. 2020) in the statistical software R. Fog (%) and cloud cover (%) was recorded as 0% throughout the survey, and there was no ice observed during detections; thus, covariates, including observer, Beaufort sea state, sun glare, time of day (defined as afternoon [12:00–18:00] or evening [18:00–24:00]), time before last observation (defined as 0–10 s, 10–20 s, 20–30 s, 30–60 s, 60–300s, 300–600 s and > 600 s), and group size were modelled individually, and in combination.

MARK-RECAPTURE MODEL

MRDS models were built with different combinations of covariates, fitted to the data and compared using AIC. By definition, all point-independent models included perpendicular distance as a covariate. We used the distance recorded by observer 1. Other covariates included environmental variables, sighting rate, as well as observer (1 versus 2) and side of the aircraft. The best-fitting MRDS model yields estimates of p(0) for each observer platform and an estimate of p(0) for both observers combined, which is used as an adjustment factor for the perception bias.

During the first survey of the North Bays stratum (August 3), one observer on the right side of the aircraft was ill, while one observer on the left side of the aircraft faced a technical issue and their sightings were not recorded. As a result, the first survey of the North Bays stratum was analysed with only a single observer and perception bias was calculated excluding this flight, but after calculation using other effort, the perception bias estimate was applied to all strata.

AVAILABILITY BIAS

Near-surface abundance estimates were also adjusted to account for narwhals that were diving and therefore unavailable to observers (i.e., availability bias) using the same values used to adjust the 2011 survey (Asselin et al. 2012). Experiments with narwhal shaped models showed that narwhals could be seen and identified by observers at depths of 2 m but not deeper (Richard et al. 1994), and this depth threshold for visibility has been used to correct for availability bias in previous narwhal surveys (Richard et al. 2010, Asselin et al. 2012). In brief, availability bias was estimated using data from nine narwhals equipped with satellite-linked time-depth recorders (STDR) near the community of Naujaat in 2006 and 2007. The proportion of time narwhals spent within 2 m of the surface in the month of August was estimated as 0.316 (CV = 0.053). This is the proportion of whales available to be seen when sightings are instantaneous, such as in a photograph. However, for visual surveys sightings are not instantaneous and using this adjustment factor may result in a positive bias. Using tags from three archival time-depth-recorders (ATDR) deployed on narwhals in 1999 and 2000 (Laidre et al. 2002), Richard et al. (2010) calculated the average time of a dive cycle and the average time spent within 0–2 m. The time that a whale is in view was estimated as 5.71 seconds from survey data where spot time (initial sighting of whale) and time the whale was abeam was recorded (Asselin et al. 2012). Using this information, Asselin et al. (2012) calculated a weighted availability bias factor that combined data from the STDRs (n = 9), the ATDRs (n = 3), and the estimated time in view of 2.80 (CV = 0.05).

DENSITY AND ABUNDANCE ESTIMATES

Density, group size, and encounter rate estimates were calculated for each stratum. Whale density ($\widehat{D}$) was estimated by:

$$\widehat{D} = \frac{n * \hat{E}(s)}{2 * L * ESHW}$$

with variance:

$$var(\widehat{D}) = \widehat{D}^2 \; x \left\{\frac{var(n)}{n^2} + \frac{var(ESHW)}{ESHW^2} + \frac{var(\hat{E}(s))}{\hat{E}(s)^2}\right\}$$

Where n is the number of groups detected, $\hat{E}(s)$ is the expected cluster size in the stratum, L is the sum of lengths of all transects in the stratum, and ESHW is the estimated strip half width from the model. The abundance ($\widehat{N}$) was then calculated by:

$$\widehat{N} = \widehat{D} * A$$

where A is the area of the stratum.

Encounter rate and its variance were estimated using a post-stratification scheme (variance estimator ‘S2’; Fewster et al. 2009).

The total estimate of narwhals at or near the surface was adjusted to account for perception and availability biases using:

$$\widehat{N} = \widehat{N}_{sur} * C_p * C_a$$

The final abundance estimate had an associated variance calculated using the delta method (Buckland et al. 2001) where:

$$var(\widehat{N}) = \widehat{N}^2 \times \left\{\frac{var(n/L)}{(n/L)^2} + \frac{var(\hat{E}(s))}{(\hat{E}(s))^2} + \frac{var(C_p)}{{C_p}^2} + \frac{var(C_a)}{{C_a}^2}\right\}$$

Confidence intervals were calculated assuming a log-normal distribution as suggested in Buckland et al. (2001).

RESULTS

SURVEY

Visual surveys of all four strata were conducted from 3–14 August, and the North Bays stratum was surveyed a second time on 14 August (Table 1). Conditions were good throughout the survey and Beaufort sea state varied from 0–3 (Table 1).

DETECTION FUNCTION

Histograms of the distribution of distances indicated that fitting a gamma detection function was the most appropriate (Figure 2). The best model fit based on AIC included glare as a covariate with a mean detection probability of 0.41 ± 0.021 SE (Table 2) and an ESHW of 409 m (not including perception bias).

MARK-RECAPTURE MODEL

After right truncation at 1,000 m, which eliminated a single detection, there were 184 unique observations (131 seen by primary observers, 123 by secondary observers, and 70 by both; Figure 3). Selection among mark-recapture models which all included distance, was performed on all combinations of environmental covariates, observer and group size. The best model (lowest AIC) included only distance and resulted in a p(0) for observers 1 and 2 of 0.49 ± 0.076 SE and a combined p(0) of 0.74 ± 0.080 SE (Table 2). This resulted in an adjustment factor of 1.36 (CV = 0.092).

ABUNDANCE ESTIMATES

An average, weighted by the CV, of the two replicates of the North Bays stratum was used for final abundance estimation. The estimated number of narwhal at the surface for all strata was 5,055 (CV = 0.270; Table 3). Adjusting for perception and availability bias gives an estimate of 19,232 (CV = 0.278, 95% CI = 11,257–32,856; Table 3) narwhals in 2018.

DISCUSSION

The abundance estimate for the 2018 survey of NHB narwhal is 19,232 narwhal with a 95% CI range from 11,257–32,853, which is not statistically different than the 2011 survey, which estimated 12,485 narwhals with a 95% CI range from 7,515–20,743 individuals. A trend analysis on abundance estimates for the NHB narwhal population has not yet been conducted, and although higher mean abundance was reported in 2018, this does not necessarily mean that there is an increasing trend in this population. A full analysis incorporating all of the available data is needed to determine population trends.

Adjustment factors to account for availability and perception biases, can have a large impact on the resulting abundance estimate. The same adjustment for availability bias was used for both the 2011 and 2018 NHB narwhal surveys as there has been no additional data collected on the time narwhals spend at depth for this population. The adjustment for perception bias varied between the two surveys. Asselin et al. (2012) reported the estimated p(0) of the two observers combined as 0.91 while the p(0) was lower in our study (0.74). Three of the four observers in our study have conducted surveys previously, however, including observer as a covariate in the mark-recapture model did not improve the model fit. Weather conditions were optimal throughout the survey, reported cloud and fog cover did not vary, and there was very little ice reported in the region. Perception bias may have varied between surveys due to difficulties associated with the identification of narwhal versus beluga whales. This is one of the few places in Canada where observers need to be able to accurately distinguish between the two species, which can both appear white when at, or near, the surface. There were 19 beluga sightings during the survey and three of these did occur within five seconds of a narwhal sighting, with two of them within a five degree declination difference (the third differed by > 30 degrees); however, in both cases, the observer recorded that they were certain of the species identification. If these two observations are identified as duplicates of narwhal sightings there is no effect on the estimated p(0) for the survey. There is also a possibility that walrus in the area may have been identified as narwhal. Although there is no way to be certain about all sightings, over 70 sightings that were captured in photographs were reviewed and walrus were not identified as narwhal. Perception bias can also vary due to differences in group size (although our mean group size of 1.50–2.72 did not vary significantly from the 2011 survey, which reported a mean group size of 0–3.5 [Asselin et al. 2012]), survey aircraft, varying environmental conditions, surveyor experience, and different survey methods. This highlights the importance of measuring perception bias for each survey.

In visual surveys, the observers have a few seconds to detect whales at the surface and the use of an instantaneous availability bias may over-estimate abundance; therefore, we used an adjustment factor that considered the time narwhals are in view. This adjustment factor is the best value currently available for NHB narwhal; however, it is derived from only nine whales satellite tagged in 2006–2007 in the month of August. Time in view was calculated as 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 155 sightings from the 2011 survey, and data from three whales equipped with ATDR tags in 1999 and 2000 in Eclipse Sound and Creswell Bay (Laidre et al. 2002). In the future, it would be ideal to have adjustment factors that overlap spatially and temporally with the survey, or an increase in the sample size of satellite tagged NHB narwhals to get a better representation of their behaviour. In addition, ATDR data from narwhals from the NHB population would be helpful as their dive cycle may vary from narwhals from the Baffin Bay population. We did not update the time in view data to include information from the 2018 survey because < 50% of sightings in 2018 had recorded spot and beam times compared to 80% in the 2011 survey (Asselin et al. 2012). However, the difference between spot and beam time in 2018 was only slightly lower (4.6 seconds versus 5.7 seconds in the 2011 survey [Asselin et al. 2012]), which would change the availability bias adjustment factor by 0.08. As a result of the small difference, the fact that the 2018 survey had fewer data points, and to maintain consistency, the availability bias adjustment factor used for the 2011 survey was also applied to the 2018 estimate of narwhal abundance. Future surveys should ensure all sightings have recorded spot and beam times.

It is possible that over the 12 days of the survey there was movement among strata. If this occurred it could over-estimate abundance if whales were counted in more than one stratum, or under-estimate abundance if whales moved out of one stratum and into another on the day that stratum was surveyed. However, we assume movement among strata is random, and when observers recorded travel direction of whales there was no evident pattern of movement of individually sighted whales in any particular direction (data on file). Due to movement of narwhal among strata on different days, it is desirable to fly repeat surveys of individual stratum. Unfortunately, weather only permitted a repeat of the North Bays stratum; however, this was an important stratum to repeat since it was the first surveyed stratum and there had been some technical issues, which resulted in only a single observer platform being used. The repeat of this stratum provided data to assess perception bias in this area and was included in the overall perception bias calculation. The two repeats of the North Bays stratum did have different surface abundance estimates of narwhal (142 versus 82), which is anticipated based on what we know about movement and variability in abundance estimates for cetaceans on different days (Gosselin et al. 2017). As a result of this variability we used a weighted average, weighted by the CV, of the two estimates for the North Bays stratum to estimate total abundance.

The 2018 survey covered the same area surveyed in 2011, and we assumed it included the entire area used by NHB narwhal in the summer. However, in the 2018 survey there were sightings at the south-eastern extent of the Repulse Bay stratum, which may indicate a larger or different summer distribution. Future surveys, in consultation with the Arviq HTO, may consider expanding or changing the survey extent, particularly given the changes in abiotic and biotic conditions in this area (Gaston et al. 2003, Higdon and Ferguson 2009, Tivy et al. 2011,).

Under the Precautionary Approach (PA) framework (Stenson and Hammill 2008, Stenson et al. 2012) and new legislative requirements of Bill C-68, DFO is required to collect adequate data to assess marine mammal stocks and define limit reference points to generate advice for Total Allowable Landed Catch (TALC) using population trends rather than Potential Biological Removal (PBR). In this way, harvest advice is based on long-term population trends derived from time series of abundance estimates and harvest removals rather than single survey estimates, which can be quite variable, and can result in PBR estimates that fluctuate more than would be expected given the dynamics of narwhal populations. The survey in 2018 may add sufficient information to the series of survey data for NHB narwhal to enable assessment using a population dynamics model that considers the series of population abundance estimates.

ACKNOWLEDGEMENTS

Thanks to D. Mablick, and the Naujaat HTA for their recommendations and assistance with the survey. Also thanks to H. Haqpi and D. Ammaq who assisted with the survey, and pilots P. Amos and B. Quinn. We thank the DFO observers C. Bartel, D. Boguski, C. Debets, L. Montsion, and P. Smith.

REFERENCES CITED

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.

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, QC. 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, USA, Oxford. 448 p.

Buckland, S.T., Laake, J.L., and Borchers, D.L. 2009. Double-observer line transect Methods: levels of independence. Biometrics 66(1): 169–177.

Elliott, R.E., Moulton, V.D., Raborn, S.W. and Davis, R.A. 2013. Hudson Strait marine mammal surveys, 10 March–2 April 2012. LGL Report No. TA8129-2. Prepared by LGL Limited, King City, ON for Baffinland Iron Mines Corporation, Toronto, ON. 87 p.

Fewster, R.M., Buckland, S.T., Burnham, K.P., Borchers, D.L., Jupp, P.E., Laake, J.L., and Thomas, L. 2009. Estimating the encounter rate variance in distance sampling. Biometrics 65(1): 225–236.

Gaston, A.J., Woo, K., and Hipfner, J.M. 2003. Trends in forage fish populations in northern Hudson Bay since 1981, as determined from the diet of nestling thick-billed murres *Uria lomvia*. Arctic 56: 227–233.

Gosselin, J.-F., Hammill, M.O., Mosnier, A., and Lesage, V. 2017. Abundance index of St. Lawrence Estuary beluga, *Delphinapterus leucas*, from aerial visual surveys flown in August 2014 and an update on reported deaths. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/019. v + 28 p.

Heide-Jørgensen, M.P., Richard, P.R., Dietz, R., and Laidre, K.L. 2013. A metapopulation model for Canadian and West Greenland narwhals. Anim. Conserv. 16(3): 331–343.

Higdon, J.W., and Ferguson, S.H. 2009. Loss of Arctic sea ice causing punctuated change in sightings of killer whales (*Orcinus orca*) over the past century. Ecol. Appl. 19: 1365–1375.

Laake, J., Borchers, D., Thomas, L., Miller, D., and Bishop, J. 2020. mrds: Mark-Recapture Distance Sampling. R package version 2.2.1.

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.

Lerczak, J.A., and Hobbs, R.C. 1998. Calculating sighting distances from angular readings during shipboard, aerial, and shore-based marine mammal surveys. Mar. Mamm. Sci. 14(3): 590–599.

Petersen, S.D., Tenkula, D., and Ferguson, S.H. 2011. Population Genetic Structure of Narwhal (*Monodon monoceros*). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/021. vi + 20 p.

Pike, D., and Doniol-Valcroze, T. 2015. Identification of duplicate sightings from the 2013 double-platform High Arctic Cetacean Survey. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/034. v + 22 p.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Richard, P.R. 1991. Abundance and distribution of narwhals (*Monodon monoceros*) in northern Hudson Bay. Can. J Fish. Aquat. Sci. 48(2): 276–283.

Richard, P., Weaver, P., Dueck, L., and Baber, D. 1994. Distribution and numbers of Canadian High Arctic narwhals (*Monodon monoceros*) in August 1984. Meddelelser Om Grønl. Biosci. 39: 41–50.

Richard, P.R., Laake, J.L., Hobbs, R.C., Heide-Jørgensen, M.P., Asselin, N. 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.

Stenson, G.B., and Hammill, M. 2008. Incorporating the precautionary approach into the provision of advice on marine mammals. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/079. iv + 12 p.

Stenson, G.B., Hammill, M., Ferguson, S., Stewart, R., and Doniol-Valcroze, T. 2012. Applying the Precautionary Approach to Marine Mammal Harvests in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/107. ii + 15 p.

Southwell, C., de la Mare, W., Underwood, M., Quartararo, F., and Cope, K. 2002. An automated system to log and process distance sight-resight aerial survey data. Wildlife Soc. Bull. 30(2): 394–404.

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:10.1111/j.1365-2664.2009.01737.x.

Tivy, A., Howell, S.E.L., Alt, B., McCourt, S., Chagnon, R., Crocker, G., Carrieres, T., and Yackel, J.J. 2011. Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive, 1960–2008 and 1968–2008. Journal of Geophysical Research 116: C03007. doi:10.1029/2009JC005855.

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. Edited by S.H. Ferguson, L.L. Loseto, and M.L. Mallory. Springer, Dordrecht, Netherlands. pp. 71–92.

Westdal, K.H., Richard, P.R., and Orr, J.R. 2013. Availability bias in population survey of Northern Hudson Bay narwhal (*Monodon monoceros*). Polar Biol. 36(9): 1235–1241.

TABLES AND FIGURES

Table 1. Summary of aerial survey work conducted in in Northern Hudson Bay in 2018.

Date	Stratum	Number of Transects	Beaufort Sea State
3-Aug	North Bays	1-18	1-3
3-Aug	Roes Welcome Sound	1-9	2
6-Aug	Wager Bay	1-16	0-1
6-Aug	Repulse Bay	1-10	0-2
11-Aug	Repulse Bay	11-15	0-1
14-Aug	Repulse Bay	16-23	0-1
14-Aug	North Bays (repeat)	1-18	0-2

Table 2. Mark-recapture (MR) distance sampling (DS) model selection based on AIC. The top 12 models are shown in order of increasing AIC.

Detection	DS model	AIC_{DS}	Average p_{DS}	MR model	AIC_{MR}	p(0) observers combined	Combined AIC	ΔAIC
gamma	**~glare**	**3732.46**	**0.41 ± 0.021**	**~distance**	**404.92**	**0.74 ± 0.080**	**4137.38**	**0.00**
gamma	-	3733.27	0.41 ± 0.022	~distance + cluster size	405.51	0.73 ± 0.081	4138.78	1.40
gamma	~beaufort	3733.71	0.41 ± 0.022	~distance + time	405.54	0.73 ± 0.081	4139.25	1.87
gamma	~beaufort + glare	3733.96	0.41 ± 0.022	~distance + time between observations	405.67	0.73 ± 0.080	4139.63	2.25
gamma	~beaufort + observer	3734.24	0.40 ± 0.022	~distance + beaufort	406.14	0.73 ± 0.082	4139.86	3.01
gamma	~glare + group size	3734.3	0.41 ± 0.022	~distance + observer	406.36	0.74 ± 0.080	4140.31	3.28
gamma	~observer	3734.45	0.41 ± 0.022	~distance + glare	406.84	0.73 ± 0.081	4141.08	3.91
gamma	~glare + observer	3734.64	0.40 ± 0.022	~distance + beaufort + size	406.91	0.73 ± 0.083	4141.22	4.18
gamma	~group size	3735.14	0.41 ± 0.022	~distance + size + observer	406.97	0.73 ± 0.081	4141.42	4.73
gamma	~time	3735.25	0.41 ± 0.022	~distance + size + glare	407.42	0.73 ± 0.082	4142.06	5.30
gamma	~time between observations	3735.27	0.41 ± 0.022	~distance + beaufort + observer	407.58	0.73 ± 0.082	4142.72	5.48
gamma	~beaufort + glare + observer	3735.42	0.40 ± 0.022	~distance + beaufort + glare	408.14	0.73 ± 0.082	4143.56	6.19

Table 3. Survey coverage of each visual stratum; North Bays (NB), Roes Welcome Sound (RWS), Wager Bay (WB) and Repulse Bay (RB). North Bays stratum was repeated (NB_{REP}), and the weighted average (weighted by the CV) for the two replicates is presented (NB_{AVG}) and was used in final estimation of abundance. The RB stratum was completed over three days. Encounter rate, CV of encounter rate (CV_{ER}), mean group size, and CV of group size (CV_{GS}) are provided for visual strata. Surface abundance and CV (CV_{SA}) and corrections for perception (C_p) and availability bias (C_a) are shown with their respective CVs, as well as fully adjusted abundance ($\hat{N}$) and CV of abundance ($CV\hat{N}$). All CVs are presented as a percentage (%). The effective strip half-width is 409 m (not including perception bias).

Stratum	**Area (km^2)***	**Effort (km)**	**# Groups**	**Encounter Rate**	**CV_{ER}**	**Mean Group Size**	**CV_{GS}**	**$\hat{N}_s$**	**CV_{SA}**	**C_p**	**CV_{Cp}**	**C_a**	**CV_{Ca}**	**$\hat{N}$**	**$CV\hat{N}$**
NB	1,254	335	13	0.0389	38.19	2.38	29.86	142	48.76	1.36	9.19	2.80	5.00	540	49.87
NB_{REP}	1,254	335	8	0.0239	22.05	2.25	13.93	82	26.60	1.36	9.19	2.80	5.00	312	28.58
NB_{AVG}	-	-	-	-	-	-	-	87	23.80	1.36	9.19	2.80	5.00	333	25.98
RWS	4,791	391	2	0.0051	77.23	1.50	33.33	45	84.28	1.36	9.19	2.80	5.00	171	84.93
WB	2,869	346	32	0.0925	24.26	1.59	11.57	517	27.38	1.36	9.19	2.80	5.00	1,967	29.31
RB_{1-10}	5,858	489	102	0.2087	37.20	2.09	6.01	3120	38.04	1.36	9.19	2.80	5.00	11,869	39.45
RB_{11-15}	3,284	293	18	0.0615	60.88	2.72	18.74	672	63.91	1.36	9.19	2.80	5.00	2,557	64.76
RB_{16-23}	4,673	381	24	0.0629	80.13	1.71	10.85	614	81.03	1.36	9.19	2.80	5.00	2,336	81.70
TOTAL	-	-	-	-	-	-	-	**5,055**	**27.00**	**1.36**	**9.19**	**2.80**	**5.00**	**19,232**	**27.84**

*Area of each stratum was calculated using a Lambert azimuthal equal-area (GRS80) projection in ArcGIS

Subscripts for the RB stratum represent the transect lines flown on each day (see Table 1).

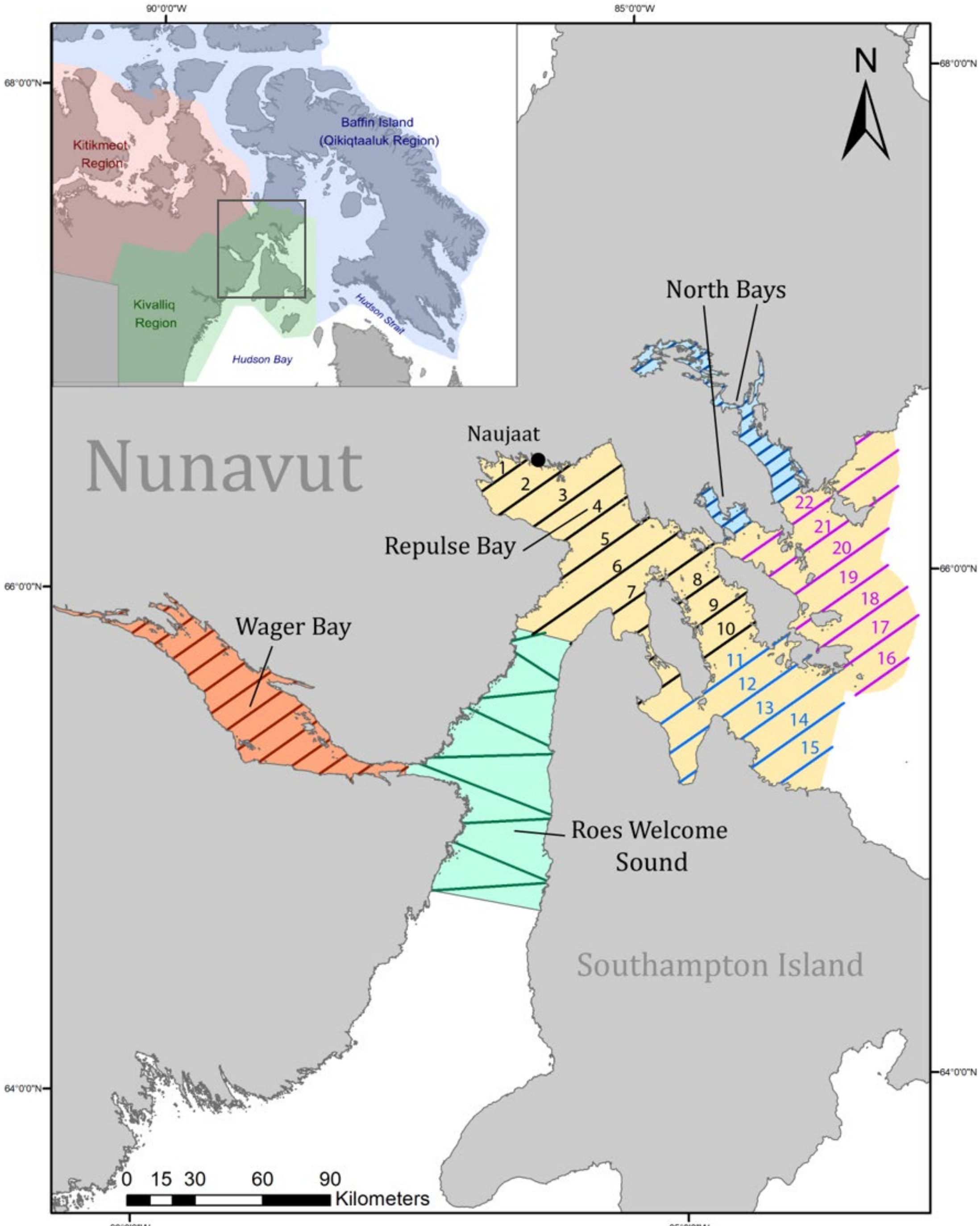

Figure 1. Map indicating four strata and transect lines surveyed in the 2018 visual aerial survey in Northern Hudson Bay. Different coloured lines on the Repulse Bay stratum indicate lines flown on three different days. Transect line numbers are included for the Repulse Bay stratum to correspond with transects flown on different days in Table 1.

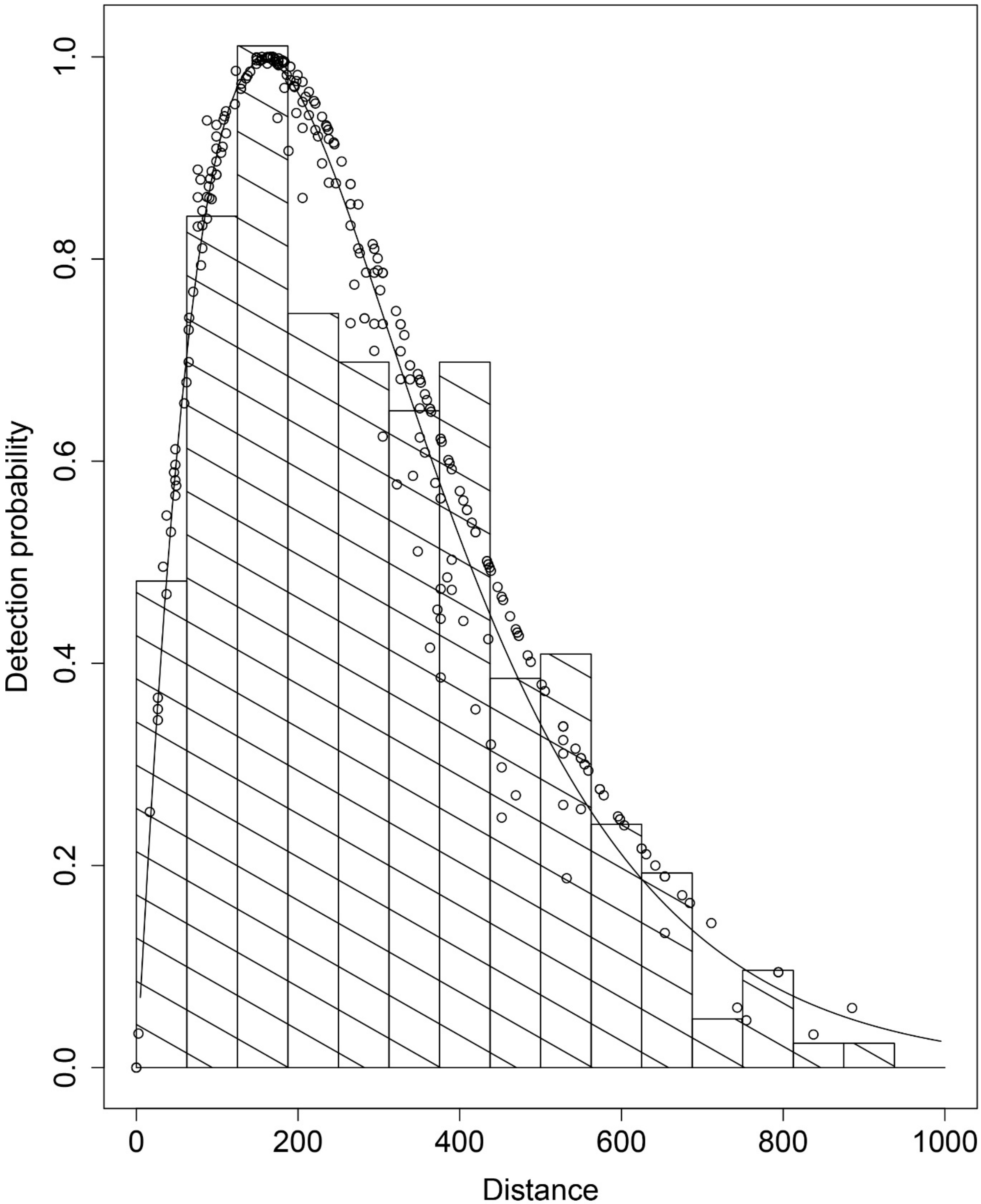

Figure 2. Histogram of the perpendicular distances of narwhal sightings for the 2018 visual aerial survey in Northern Hudson Bay.

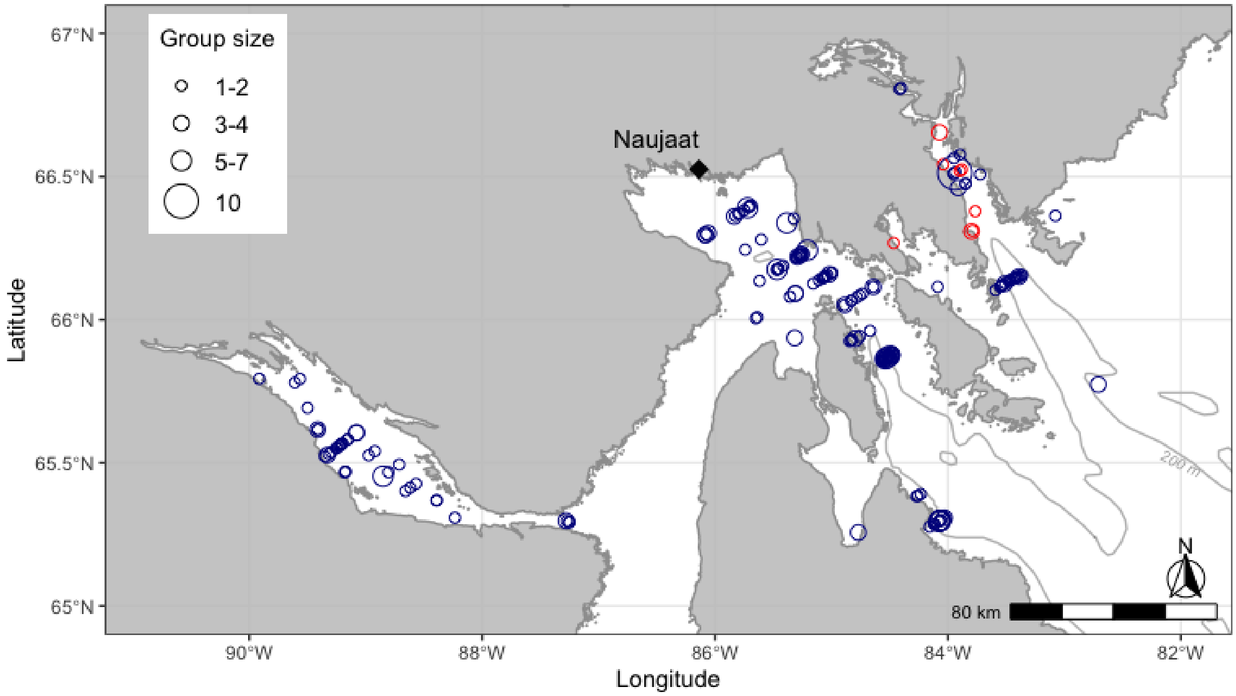

Figure 3. Map of all narwhal sightings in the first replicate survey (blue) and sightings during the repeat survey of the North Bays stratum (red) during the 2018 visual aerial survey in Northern Hudson Bay.