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 2015/060

Central and Arctic, Quebec, and Newfoundland and Labrador Regions

Abundance estimates of narwhal stocks in the Canadian High Arctic in 2013

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November 2015 (Erratum April 2022)

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.

Research documents are produced in the official language in which they are provided to the Secretariat.

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

Correct citation for this publication:

Doniol-Valcroze, T, Gosselin, J.F., Pike, D., Lawson, J., Asselin, N., Hedges, K., and Ferguson, S. 2015. Abundance estimates of narwhal stocks in the Canadian High Arctic in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/060. v + 36 p. (Erratum April 2022)

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ABSTRACT

In summer, narwhals of the Baffin Bay population migrate to the fiords and inlets of northeastern Canada and northwest Greenland. Numerous Inuit communities across Nunavut hunt narwhals on their summering grounds or along their fall migration routes for subsistence. To prevent localized depletion, management of this population is based on summering aggregations. Abundance estimates for most of these stocks were dated while others were totally lacking or known to be incomplete. DFO conducted the High Arctic Cetacean Survey (HACS) in August 2013 to estimate abundance of all four Canadian Baffin Bay narwhal summer stocks as well as putative stocks in Jones Sound and Smith Sound. This is the first survey to count all of the narwhal stocks in the Canadian High Arctic during one summer. This document presents the results of the survey and new abundance estimates for the stocks, as well as updated estimates of Potential Biological Removals (PBR).

Narwhal abundance was estimated using a double-platform aerial survey. Three aircraft were used simultaneously to cover the vast survey area within a short time frame. Each stock range was divided in several strata, based on geographic boundaries as well as observed densities of narwhals from past surveys. Distance sampling methods were used to estimate detection probability away from the track line. Mark-recapture methods were used on the sighting data from two observers on each side of the aircraft to correct for the proportion of narwhals missed by visual observers (i.e., perception bias). Abundance in fiords was estimated using density spatial modelling to account for their complex shape and uneven coverage. Estimates were corrected for availability bias (narwhals that are not available for detection because they are submerged when the plane passes overhead) using a new analysis of satellite-linked time depth recorders transmitting information on the diving behaviour of narwhals in August.

Fully corrected abundance estimates were 12,694 (Coefficient of Variation [CV] 33%) for the Jones Sound stock, 16,360 (CV 65%) for the Smith Sound stock, 49,768 (CV 20%) for the Somerset Island stock, 35,043 (CV 42%) for the Admiralty Inlet stock, 10,489 (CV 24%) for the Eclipse Sound stock, and 17,555 (35%) for the East Baffin Island stock. Sources of uncertainty arise from the high level of clustering observed, particularly in Admiralty Inlet, Eclipse Sound and East Baffin Island, as well as the difficulty in identifying duplicate sightings between observers in large aggregations.

Estimation de l’abondance des stocks de narvals dans les eaux canadiennes de l’Extrême-Arctique en 2013

RÉSUMÉ

En été, la population de narvals de la baie de Baffin migre vers les fjords et les bras de mer du nord-est du Canada et du nord-ouest du Groenland. De nombreuses communautés inuites du Nunavut chassent les narvals à des fins de subsistance dans leur aire d'estivage ou le long de leur route de migration automnale. Afin d'éviter l'épuisement local des ressources, la gestion de cette population est fondée sur les regroupements estivaux. Les estimations de l'abondance pour la plupart de ces stocks étaient désuètes, tandis que d'autres étaient incomplètes ou inexistantes. Le MPO a effectué un inventaire des cétacés dans l’Extrême-Arctique (ICE-A) en août 2013 afin d'estimer l'abondance des quatre stocks estivaux canadiens de narvals de la baie de Baffin ainsi que des stocks présumés du détroit de Jones et du détroit de Smith. Il s'agit du premier relevé à comptabiliser tous les stocks de narvals dans l’Extrême-Arctique canadien au cours d'un même été. Ce document présente les résultats du relevé et les nouvelles estimations de l'abondance des stocks, ainsi que des estimations mises à jour des retraits biologiques potentiels (RBP).

L'abondance des narvals a été estimée à l'aide d'un relevé aérien à double-plateforme. Trois aéronefs ont été utilisés simultanément pour couvrir la vaste zone du relevé dans un court délai. L’aire de répartition de chaque stock a été divisée en plusieurs strates, en fonction des limites géographiques et des densités de narvals déduites à partir des relevés précédents. Des méthodes d’échantillonnage avec mesure des distances ont été utilisées pour estimer la probabilité d'observation en fonction de la distance au transect. Des méthodes de marquage et recapture ont également été utilisées sur les données d'observation provenant des paires d’observateurs de chaque côté des aéronefs afin d’estimer la proportion de narvals non-détectés (biais relatifs à la perception). L'abondance dans les fjords a été estimée au moyen d'une modélisation spatiale de la densité afin de tenir compte de leur forme complexe et de la couverture irrégulière. Les estimations ont été corrigées pour tenir compte des biais de disponibilité (narvals qui ne peuvent être observés parce qu'ils sont sous l'eau lorsque l'aéronef passe au-dessus) au moyen d'une nouvelle analyse des enregistreurs de temps et de profondeur reliés à des satellites qui transmettent de l'information sur le comportement de plongée des narvals en août.

Les estimations de l'abondance entièrement corrigées étaient de 12 694 (coefficient de variation [CV] de 33 %) pour le stock du détroit de Jones, 16 360 (CV de 65 %) pour celui du détroit de Smith, 49 768 (CV de 20 %) pour celui de l'île Somerset, 35 043 (CV de 42 %) pour celui de l'inlet de l'Amirauté, 10 489 (CV de 24 %) pour celui du détroit d'Eclipse et enfin 17 555 (CV de 35 %) pour celui de l'est de l'île de Baffin. Le niveau élevé de concentration des narvals en quelques endroits, en particulier dans l'inlet de l'Amirauté, le détroit d'Eclipse et l'est de l'île de Baffin, ainsi que la difficulté à identifier les observations faites en double par les observateurs lorsqu'il y avait de grands rassemblements constituent les principales sources d'incertitude.

INTRODUCTION

A large meta-population of narwhals (*Monodon monoceros*) overwinter in Baffin Bay and Davis Strait (Heide-Jørgensen et al. 2013). In late spring, these narwhals migrate to the fiords and inlets of northeastern Canada and northwest Greenland, where they spend the summer before migrating back to their wintering grounds in Davis Strait and Baffin Bay in late fall. Numerous Inuit communities across Nunavut hunt narwhals on their summering grounds or along their fall migration route for subsistence, particularly in the Qikiqtaaluk and Kitikmeot regions, which include the Boothia Peninsula, Baffin Island and the Canadian High Arctic communities (Priest and Usher 2004). Sustainability of the subsistence hunt, which is of great importance for economic and cultural reasons, relies on obtaining up-to-date estimates of abundance.

Narwhals residing in the Canadian High Arctic are designated as Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and are a key priority fishery for Fisheries and Oceans Canada (DFO). Narwhal are listed on Appendix II of the Convention on International Trade in Endangered Species (CITES), and a non-detrimental finding (NDF) decision from the DFO Scientific Authority is required to obtain a CITES permit to export narwhal products internationally. Canadian management units are considered to be ineligible for international trade if the harvest exceeds the Total Allowable Landed Catch recommendation for a stock. Under CITES requirements, updated science and a documented management approach are required to confirm sustainable narwhal management to allow for international trade.

Telemetry studies indicate that tracked narwhals tend to remain in the summer aggregation areas where they were tagged and rarely visit other summering areas (Dietz et al. 2001; Dietz et al. 2008). Narwhals are also believed to exhibit inter-annual site fidelity by returning to the same summering areas every year (Dietz et al. 2008; Heide-Jørgensen et al. 2003), although there have been exceptions (Heide-Jørgensen et al. 2013). It is possible to have localized depletions or extinctions if site fidelity is not considered when harvesting occurs (Cope and Punt 2009). The population in Baffin Bay and surrounding waters has therefore been divided into smaller management units that represent seasonally spatially discrete stocks, believed to have little or no exchange during summer. The use of summering stocks as management units is considered precautionary.

The four recognized Baffin Bay narwhal summering aggregations in Canadian waters are the Somerset Island (SI), Admiralty Inlet (AI), Eclipse Sound (ES) and East Baffin Island (EB) stocks (Fig.1). Based on genetic analyses (de March and Stern 2003), traditional knowledge, as well as reconnaissance surveys flown by DFO in 2012, it is apparent that there are also large numbers of summering narwhals around Ellesmere Island that range over Jones Sound, Smith Sound, Norwegian Bay, and adjacent bays and fiords. These narwhals have been aggregated as the Jones Sound (JS) and the Smith Sound (SS) stocks (Richard 2010), for which there are no survey abundance estimates available. These six Canadian stocks are the focus of this document. Melville Bay and Inglefield Bredning are also considered Baffin Bay summering aggregations but occur in Greenland and therefore are not considered here.

Several narwhal surveys were conducted by DFO in the eastern Canadian Arctic from 1975 to 2011 (Table 1). Some stocks have been surveyed numerous times and have recent abundance estimates (e.g., AI, five surveys in total, most recently in 2010), while others have only have been surveyed once or have dated estimates. Several narwhal summer stocks cover large areas and may have further sub-structuring. For instance, the SI stock is the largest summering stock (in area) of the Baffin Bay population, and includes Prince Regent Inlet, Gulf of Boothia, Peel Sound, Barrow Strait, and northern Foxe Basin. Systematic surveys of this summer stock, or parts thereof, were conducted in 1981 (Smith et al. 1985), 1984 (Richard et al. 1994), 1996 (Innes et al. 2002), and 2002-2004 (Richard et al. 2010). No survey has covered the entire stock area, and the number of surveys within each sub-area ranges from zero (northern Foxe Basin) to four (Prince Regent Inlet). For JS and SS stocks, information on summer abundance is lacking altogether. Narwhals are also known to occur elsewhere in small numbers in the Canadian High Arctic during summer (e.g., Parry Islands, Cambridge Bay), but no narwhal surveys have been conducted in these areas. On the Greenland side, the Melville Bay and Inglefield Bredning are estimated to number approximately 6,000 and 8,000 narwhals, respectively (Heide-Jørgensen et al. 2013).

The objective of the High Arctic Cetacean Survey (HACS), a large-scale aerial survey conducted in August 2013, was to obtain new abundance estimates, in the same year, for all six of the narwhal summering stocks present in the Canadian High Arctic. This information will allow us to update the Potential Biological Removal (PBR) estimates that are used for management advice.

METHODS

STUDY AREA AND SURVEY TIMING

The extent of the HACS study area was based on the aerial abundance surveys done since the 1970s, telemetry tracking studies, reports of traditional knowledge and recent observations by Inuit hunters (Priest and Usher 2004). The six major summering stocks in the Canadian High Arctic cover a vast range from the east coast of Baffin Island to the Central Arctic Archipelago, and possibly further west (Richard 2010). Because of assumed inter-annual fidelity to summering sites and logistical challenges, previous surveys of Baffin Bay narwhal stocks were conducted by covering summering areas separately over several years (Richard et al. 2010). However, recent concerns about potential exchanges among neighboring summering areas (Dietz et al. 2001; Heide-Jørgensen et al. 2002; Watt et al. 2012) have made it desirable to attempt to survey all stocks simultaneously.

Therefore it was decided that HACS would attempt to cover the summering areas of each stock in the same year, with a priority on the Jones Sound, Smith Sound and Somerset Island stocks (Fig. 1). Since little was known of the distribution of narwhals in the waters around Ellesmere Island (i.e., Jones Sound and Smith Sound stocks), a reconnaissance aerial survey was performed in late August 2012 with members of the Grise Fiord community. Although fog prevented coverage of the offshore areas, numerous narwhals were observed in coastal waters and deep inside fiords, as far north as Alexandria Fiord, which was taken into account when planning the extent of the survey study area (Fig. 2). For the Somerset Island stock, it was considered unrealistic to cover the entire known distribution range, which potentially extends at low densities far to the west and southwest of Prince of Wales Island, and it was decided to focus instead on the presumed core areas of Prince Regent Inlet, Peel Sound and the Gulf of Boothia.

Dates for the survey were established based on the short window of relatively ice-free waters in the Arctic Archipelago and the historical timing of narwhal aggregations in their summering areas. The best time was determined to be August, when telemetry studies show that whales are relatively sedentary within their summering range and the weather is most favorable. Later than August, there was a risk that some narwhals would begin migrating and move to other areas (Watt et al. 2012). Three aircraft were used to cover the entire survey area in a relatively short period of time and reduce the potential of bias due to directed movements of animals between survey areas.

SURVEY DESIGN

The survey was designed to balance two conflicting objectives: to cover the largest possible proportion of the summering areas of narwhal stocks while improving on the precision of past estimates, which required coverage at a higher intensity than previous surveys. To minimize the sampling error, we divided each stock range in several strata (Fig. 2) based on geographic boundaries, telemetry studies and observed densities of narwhals from past surveys (Asselin and Richard 2011; Richard et al. 2010; Dietz et al. 2001). For instance, the Somerset Island stock comprised the strata Prince Regent Inlet, Peel Sound high intensity, Peel Sound low intensity and Gulf of Boothia. When no data from previous studies were available, we relied on traditional knowledge and the observations made during the 2012 reconnaissance survey.

Transect design was performed in Distance (version 6.1, Thomas et al. 2010), using precise coastline shapefiles. Projection for each stratum was selected using Young's rule (Maling 1992) to minimize distortions of area. The first transects of each stratum were chosen at random and the others were spaced at regular interval (i.e., the design was systematic with a random start). As much as possible, transect lines were oriented in a direction perpendicular to the longest axis of the stratum to provide a maximum number of lines (sampling units) per stratum. For presumed high density strata, we used systematic parallel transects with greater coverage (7-15%) than had been used in the past. Areas where we expected lower densities of narwhals were covered using zigzag transects with equally spaced endpoints (Strindberg and Buckland 2004). Parallel line transects are preferred over zigzag, especially in high coverage area, as they maintain uniform coverage probability, and the spacing between adjacent lines allows resting time for the observers. However, zigzag transects are more efficient to cover wide areas as transit time between transects is reduced (even if some time must be allotted for observers to rest between transects). Some low coverage strata had complex geographic shapes that were divided in subareas where equally spaced zigzag designs were created using the same spacing for the whole stratum. Using convex hull shapes and the longest axis of the subareas as main design axis allowed us to maintain a relatively equal coverage probability within these strata.

The sequence of stratum coverage was designed to survey High Arctic narwhal summer aggregation areas in order of decreasing priority, with high priority given to strata with presumed highest densities, older survey estimates and high management concerns, and with the condition that adjacent strata considered to be part of the same summering stock be covered within a short time window to avoid significant animal movements among strata. Weather permitting, the strata were to be surveyed in the following order:

1) Jones Sound/Smith Sound/Norwegian Bay (high densities and numbers, never surveyed systematically, and a high management priority);
2) Prince Regent Inlet (highest density and numbers of all stocks, old estimate) and the neighboring Peel Sound (high narwhal numbers seen in the past, exchange of narwhals from Prince Regent Inlet through Bellot Strait);
3) Admiralty Inlet and Eclipse Sound (high density and numbers but more recent estimate; both must be done at same time as it was recently demonstrated that they can share animals in August, Watt et al. 2012);
4) East Baffin Island (high densities and numbers, old estimate); and
5) Gulf of Boothia (presumed low density area for Somerset Island stock).

In an effort to avoid the effect of potential directed movements of narwhals within strata, attempts were made at surveying each stratum in a day or two. Unpredictable weather also makes single-day stratum coverage desirable. For large or remote areas, this often required the use of more than one aircraft. All three survey aircraft initially based in Resolute combined their effort to complete surveys of priority items 1 and 2 in the list above. Each plane then deployed north (item 3), east (item 4) or west (item 5) of Baffin Island.

Narwhals are believed to prefer deep water if there is ice cover, but aggregate in fiords in the absence of ice during the summer (Heide-Jørgensen et al. 2003; Dietz et al. 2001; Laidre and Heide-jørgensen 2011). This meant that, depending on ice conditions, there was a possibility that a significant number of narwhals would be in the fiords (as was the case during the 2012 reconnaissance survey). It is difficult to obtain correct densities when narwhals are found near shore for several reasons. First, most fiords cannot be surveyed with systematic lines because they are often too narrow and too steep-walled. Second, fiords vary in width, which means that in some cases, the entire fiord can be seen from the aircraft and clipping of the observation field-of-view occurs at various points along the shoreline. Standard distance analysis is then made complex because of unequal coverage probability for different segments of areas surveyed. In addition, these fiords are numerous and sometimes separated by large distances. Therefore, a separate design and methodology was used for the fiord strata in this survey (for details on the methods and resulting abundance estimates, see Doniol-Valcroze et al. 2015).

SURVEY METHODOLOGY

The aerial survey was flown at an altitude of 1,000 feet (305 m) and a target speed of 100 knots (185 km/h) using three deHavilland Twin Otter 300 aircraft, each equipped with four bubble windows on the sides that allowed the observers to view the track line directly below the aircraft, and a large belly window used for cameras. Four observers were stationed at the front and rear bubble windows, with a fifth team member acting as a navigator and camera operator. The visual surveys were conducted as a double-platform experiment with independent observation platforms at the front (primary) and rear (secondary) of the survey plane. The two observers stationed on the same side of the aircraft were separated visually and acoustically to ensure independence of their conditional detections.

The fifteen team members gathered at the Polar Continental Shelf Project base in Resolute on August 1, 2013. During the first two days, all observers were given extensive training sessions to familiarize them with the protocols and prepare them for data collection. These sessions included classroom presentations, on-the-ground training and practice flights around Resolute, which also allowed testing of on-board equipment.

Speaking into hand-held Sony PCM-D50 recorders, observers noted the time at which they sighted groups of narwhals (“spot time”) and then the time at which the animals passed abeam (“beam time”) as well as the perpendicular declination angle of each sighting relative to the horizontal plane using inclinometers (Suunto). A group was defined as two or more animals that are within one or a few body lengths of each other and oriented or moving in a similar direction. Observers were instructed to give priority to the estimation of group size, especially when densities were high, followed by perpendicular distance and other variables (direction of movement, presence of young, number of tusks) if time permitted. Position and altitude of the plane were recorded every 2 seconds using a GPS connected to a laptop running an electronic map software (Fugawi). Recorders were recording continuously along transects and the time of the recording was synchronised (time stamped) with the GPS time.

Primary observers recorded weather and observation conditions at the beginning, at the end and at regular intervals along the lines or whenever changes in sighting conditions occurred. The conditions noted included sea state (Beaufort scale), ice concentration (in tenths), cloud cover (%), fog (% cover and intensity), angle of searching area affected by sun reflection along with sun reflection intensity (4 levels: “intense” when animals were certainly missed in the center of reflection angle; “medium” when animals were likely missed in the center of reflection angle, “low” when animals were likely detected in center of reflection angle and “none” when there was no reflection).

In addition to visual observations, the three aircraft collected continuous photographic records below the aircraft using dual oblique cameras pointing downwards towards either side of the track line. A 3-second interval between photographs allowed a target overlap of 20% between successive photographs along the direction of the aircraft at the survey altitude. The digital camera system was comprised of two digital cameras (Nikon D-800) mounted in a custom frame and aimed through the belly window in the rear of the aircraft. A GPS unit was connected to each camera which was in turn connected to a laptop. Geo-referenced images were thus saved on the laptop in real time. The cameras were oriented ‘width-wise’ (i.e., long side perpendicular to the track line), at an angle of 27°. At an altitude of 305 m, the swath width of the pictures taken was 420 m, for a total strip width of 840 m at the surface of the water.

DATA MANAGEMENT AND PHOTO VERIFICATION

Audio recordings of visual observers were transcribed and combined. Each whale sighting was georeferenced by matching the observed time with the synchronised GPS time to the nearest second and the corresponding location. Narwhal sightings and aircraft flight tracks were mapped using ArcGIS 9.2 (ESRI Inc.). Transect lengths and stratum areas were determined in ArcGIS. Declination angles of abeam sightings were transformed into perpendicular distances by dividing the recorded altitude by the tangent of the angle.

Sightings where angles of declinations had not been recorded, or were coded as “uncertain”, were compared to the photographic records. The perpendicular distance was retrieved from the pixel position of the sighting on the photo if a visual sighting could be identified without ambiguity on the corresponding photo. If the sighting was not made within the swath width of the picture, could not be found, or could not be told apart from other sightings unambiguously, it was coded as missing distance (these sightings were not used in fitting the detection function, but were added to the total count per transect, as described below). Sightings where group size had not been recorded or was coded as uncertain were also compared to the photographic records, and group size was retrieved if a match could be made based on perpendicular distance. Otherwise, sightings with missing group size were given the average group size in that stratum (posterior to estimation of the expected group size so that it did not affect the estimation of its variance).

DATA ANALYSIS

Statistical Framework

The estimated index of density $(\widehat{D})$ and abundance $(\widehat{N})$of narwhals at the surface during systematic survey of each stratum are estimated by:

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

and

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

where n is the number of groups detected, $\hat{\mathrm{E}}(s)$ is the expected cluster size in the stratum, L is the sum of lengths of all transects in the stratum, ESHW is the estimated effective strip half width and A is the area of the stratum. The associated variance of density of animals at the surface during systematic survey is estimated by:

$$var(\hat{D}) = \hat{D}^2 \cdot \left[\frac{var(n)}{n^2} + \frac{var(ESHW)}{ESHW^2} + \frac{var\left(\hat{E}(s)\right)}{\hat{E}(s)^2}\right]$$

The distribution of density is assumed to be log-normally distributed, and the 95% Confidence interval (CI) was estimated using $(\hat{D}/C\,, \hat{D} \cdot C)$ where

$$C = exp\left[t_{df}(\alpha) \cdot \sqrt{var(\ln \hat{D})}\right]$$

and

$$var(\ln \hat{D}) = \ln\left[1 + \frac{var(\hat{D})}{\hat{D}^2}\right]$$

and where $t_{df}(\alpha)$ is the critical value of Student's *t*-distribution at α= 0.05. To consider the few degrees of freedom of some component of variance, the degrees of freedom were computed according to the Satterthwaite method adapted by Buckland et al. (2001):

$$df = \frac{\left[\sum_q (cv_q)^2\right]^2}{\sum_q (cv_q)^4 / df_q}$$

where the coefficient of variation and degrees of freedom are estimated for each of the *q* components of the estimation of density, which are: *n, ESHW* and $\hat{\mathrm{E}}(s)$.

Mark-Recapture Distance Sampling

Distance sampling (DS) methods can be used to estimate detection probability away from the track line while assuming that detection on the track line is certain (denoted by g(0)=1). However, aerial survey observers miss some of the narwhals visible at the surface (Richard et al. 2010). This “perception bias” (*sensu* Marsh and Sinclair 1989) can be corrected for by using mark-recapture (MR) methods on the sighting data from two observers on the same side of the plane (Laake and Borchers 2004). Thus, the combination of MR and DS (MRDS) methods can be used to estimate abundance without assuming that g(0)=1. Here, the two observers in the front of the plane were considered to be the first platform and are referred to as “observer 1”, and the two observers in the rear were considered to be the second platform (i.e., “observer 2”).

To conduct MRDS analysis, duplicate sightings (those seen by both the primary and secondary observer) must be identified. The criteria used to identify duplicate sightings are described in Pike and Doniol-Valcroze (2015). Briefly, a series of covariates based on the differences between platforms (timing, distance, group size and species) was used to assign a dissimilarity score to each possible pair of sightings made by primary and secondary observers within 10 seconds of one another. If this dissimilarity score was higher than a given threshold, the sighting pair was not considered a duplicate. When there was more than one candidate pair, the one with the lowest dissimilarity score was selected as a duplicate.

Although observers 1 and 2 were acting independently, detection probabilities of observers can be correlated because of factors such as group size (for example, both observers are more likely to see only large groups at long distances). Buckland et al. (2009) developed a point-independence model, which assumes that detections were independent only on the track line. This model is usually more robust than a model assuming that detections were independent at all perpendicular distances.

Line-transect analyses to estimate density and abundance were performed with the *mrds* package in R. A point-independence model involves estimating two functions: a multiple covariate DS detection function for detections pooled across platforms, assuming certain detection on the track line, and a MR detection function to estimate the probability of detection on the track line.

Detection function

A single, global detection curve was fitted to narwhal sightings from all strata. The analyses were performed on the perpendicular distances of unique sightings (i.e., duplicate sightings, plus sightings made only by observer 1 plus sightings made only by observer 2). Distances were not binned prior to analysis. The overall distribution of perpendicular distances was examined for right truncation to remove outliers at great distances. We used AIC to select the best-fitting detection function among half normal, hazard rate, gamma and uniform models, with and without adjustment series (Buckland et al. 2001).

AIC was also used to select among models with covariates (Marques et al. 2007). In addition to the environmental covariates ice cover, cloud cover, sea state and glare, we tested the impact of a “sighting rate” covariate, which was computed as a rolling average of the number of sightings made by the observer in a 30-second window prior to each sighting.

Because observers were instructed to give priority to group size estimation, some observations were lacking a perpendicular distance measurement (usually when high densities of narwhals were encountered). These observations were not included in the selection of the detection function. However, these observations were all assumed to be within truncation distances as we expect that the effective searching width was narrowed in higher densities. Therefore, these observations were included in the estimation of encounter rates and expected cluster size for the estimation of density and abundance.

Mark-Recapture function

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, unless it was missing and available from observer 2. Other covariates included environmental variables, sighting rate, as well as observer (1 vs 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 a correction factor for the perception bias.

There were a few segments of the survey during which only one observer was active on either side of aircraft, due to logistic issues (e.g., recorder failure). On these segments, observations were recorded by a single platform, and accordingly they were corrected for perception bias using the p(0) for the corresponding platform (1 or 2) instead of the p(0) of the combined observers.

Encounter Rates

The number of unique sightings of narwhal clusters were summed by transect to estimate the average encounter rate for each stratum. Variance in encounter rates was estimated using a post-stratification scheme (i.e., variance estimator “S2” from Fewster et al. 2009).

Cluster Size

The expected cluster size in each stratum was estimated using the size bias regression method of the natural log of cluster size against the probability of detection, i.e., Ln(s) vs g(x). If the regression was significant at $\alpha = 0.10$, expected cluster size was calculated using regression coefficients; otherwise the mean cluster size was used (Buckland et al. 2001).

Fiord Strata

Fiord strata were sampled and surveyed as described in Doniol-Valcroze et al. (2015). Within each stratum, fiords were considered primary sampling units (PSU) and cluster sampling was used to select fiords to be surveyed. Within each fiord, flights were planned as continuous tracks and adjusted on site by the navigator to follow the main axis of each fiord, while aiming to spread coverage uniformly according to distance from the shore when the fiords were wide enough, and to minimize duplicate coverage of any area. Data were collected using the same protocol as non-fiord areas.

Data from fiord strata were analysed separately (see Doniol-Valcroze et al. 2015 for details). To account for the complex shape and uneven coverage of fiords, we used a density surface modelling (DSM) framework to model spatially-referenced count data with the additional information provided by collecting distances to account for imperfect detection. Modelling proceeds in two steps: a detection function is fitted to the perpendicular distance data to obtain detection probabilities for clusters of individuals. Counts are then summarised per segment (contiguous transect sections). A generalised additive model (GAM, Wood 2006) is then constructed with the per-segment counts as the response with segment areas corrected for detectability.

Surface Abundance Estimates per Stock

Total surface abundance estimates for each stock were obtained by the addition of the estimated abundances of all the strata that were part of that stock's summer range, including results from fiord strata (Doniol-Valcroze et al. 2015). Variance for the stock-wide abundance estimate was calculated by adding the variances of each stratum.

Sensitivity Analysis to Duplicate Identification Thresholds

As outlined in Pike and Doniol-Valcroze (2015), however, identification of duplicates in the HACS dataset was not a straightforward process due to a large proportion of missing measurements and highly aggregated narwhal groups. Choice of thresholds beyond which pairs of sightings would not be considered potential duplicates was somewhat arbitrary and had an effect on the resulting number of unique sightings. In turn, this has an impact on abundance estimates in three ways:

a) the number of unique sightings determines the raw number of individuals seen on transect from which the total population abundance is estimated;

b) the identity and characteristics of unique sightings (distance, count size) has an effect on estimation processes such as fitting a detection curve and calculating expected group size; and

c) the number, distance and size of unique and duplicate sightings has an effect on the mark-recapture distance model, and thus on p(0), which serves as a multiplier on the abundance estimate.

To take into account the effect of choosing thresholds for duplicate identification, we performed a sensitivity analysis and quantified the resulting uncertainty. As recommended in Pike and Doniol-Valcroze (2015), we estimated surface abundance of narwhals in all non-fiord strata for each of the sets of unique sighting obtained with threshold values of 3–7 seconds for time differences T and 5°–15° for declination angle differences D (the two covariates that had the largest effect on duplicate identification). We then calculated the variance in the abundance estimates resulting from these multiple analyses. This allowed us to include an additional variance component in the surface abundance estimate with a CV equal to that of the sensitivity analysis (CV_{dup}), thus leaving the point estimates unchanged but increasing the range of uncertainty. The inclusion of this correction factor allows us to incorporate all of the three effects described above simultaneously.

Availability Bias

To estimate species abundance, visual and photographic aerial surveys of aquatic marine mammals should be corrected for availability bias (Marsh and Sinclair 1989), i.e., animals in the study area, but not visible to observers because they are under water. Experiments with narwhal-shaped models showed that narwhals could be seen and identified by observers (i.e., were available) at depths of about 2 m but not deeper (Richard et al. 1994),and therefore this is the depth threshold that has been used to correct for availability bias in past narwhals surveys (Richard et al. 2010). However, during HACS, sightings in all the fiords of the East Baffin Island stratum were reported by observers as having occurred in murky or opaque waters, which was confirmed by examination of the photographs taken underneath the plane. This suggests that observers would not have been able to detect and identify narwhals as deep as 2 m, as is usually assumed. Therefore, for this stratum, a correction factor was calculated based on the assumption that narwhals could only be seen between 0 and 1 m.

The proportion of time P_a that narwhals spend within 2 m of the surface was estimated at 31.4 ± 1.06%, based on data from 23[1] narwhals fitted with satellite tags near the communities of Arctic Bay and Pond Inlet every August from 2009 to 2012[2] (Watt et al. 2015). The correction factor for availability bias when sightings are instantaneous is given by $C_I = 1/P_a = 3.18$ (CV 3.37%). Based on 24 narwhals[3], the proportion of time that narwhals spend within 1 m of the surface was estimated at 20.4 ± 0.78% and thus we used an instantaneous availability correction factor of 4.90 (CV 3.82%) for East Baffin Island fiords.

C_I is an appropriate correction factor when sightings are instantaneous (e.g., for photographic surveys). If sightings are not instantaneous, this correction factor positively biases the estimate. McLaren (1961) developed a correction factor that incorporates the dive cycle of the animal and the search time of the observer:

$$C_M = \frac{t_d}{t_0 + t_s}$$

Where: t_d is average time for a complete dive cycle, t_0 is the time available for an observer to see a group (i.e., “Time in View”), and t_s is the average time at the surface per dive cycle. The

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[1] Erratum April 2022 – 24 narwhals now reads 23

[2] Erratum April 2022 – 2013 now reads 2012

[3] Erratum April 2022 – Original text read as: Based on the same data, the proportion of time that narwhals spend within 1 m of the surface was estimated at 20.4 ± 0.78% and thus we used an instantaneous availability correction factor of 4.90 (± 0.187) for East Baffin Island fiords.

24 satellite tags used for estimating P_a could not be used to estimate t_d and t_s. Instead, we used values from Richard et al. (2010), which are based on data from three archival time-depth recorders (ATDRs) deployed on narwhals in Tremblay Sound in August 1999 (n=1) and in Creswell Bay in August 2000 (n=2).

To estimate the "Time in View" of the HACS sightings, we examined the length of time from the initial recording of a detection (i.e., spot time) to the recording of the abeam declination angle measurement (i.e., beam time). Following the technique proposed by Richard et al. (2010) we used a weighted availability bias correction factor C_a:

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

Where f_i is the frequency of times in view of duration *i* seconds and b_i was the percent bias of an instantaneous correction C_I:

$$b_i = \frac{C_{M(0\,sec)} - C_{M(i\,sec)}}{C_{M(0\,sec)}} \times 100.$$

We considered that only C_I contributed to the variance of C_a and that therefore their CVs were identical.

The surface abundance estimate of each stock $\widehat{N}_s$ was then multiplied by C_a to give a total abundance estimate $\widehat{N}_c$. The variance was calculated using the delta method (Buckland et al. 2001: 52):

$$var(\widehat{N}_c) = \widehat{N}_c \cdot \left\{ \frac{var(\widehat{N}_s)}{\widehat{N}_s^{\,2}} + \frac{var(C_a)}{C_a^{\,2}} \right\}$$

Recommended Total Allowable Landed Catch (TALC)

We used the Potential Biological Removal (PBR) method (Wade 1998), corrected to include hunting losses (i.e., animals that are struck and lost), to calculate the recommended Total Allowable Landed Catch (TALC):

$$TALC = \frac{PBR}{LRC}$$

where:

$$PBR = 0.5 \cdot R_{max} \cdot \widehat{N}_{min} \cdot F_r \ ,$$

LRC is the hunting loss rate correction and is equal to 1.28 (SE 0.15, Richard 2008), R_{max} is the maximum rate of increase for the stock (which is unknown, so the default for cetaceans of 0.04 was used, Wade 1998), $\widehat{N}_{min}$ is the 20th percentile of the log-normal distribution of $\widehat{N}$, and F_r is the recovery factor, which is usually set to 0.1 for a critically low stock status, 0.5 for a depleted status and 1.0 for a healthy status. Here, we used F_r = 1.0 for all stocks except Jones Sound and Smith Sound for which we used F_r = 0.5, to account for uncertainty in stock structure and narwhal movements.

RESULTS

SURVEY COVERAGE AND NARWHAL SIGHTINGS

The timing of the ice break-up in the northern parts of the survey range during the summer of 2013 affected the timing and coverage of portions of the survey areas. At the beginning of the survey period, several areas were still completely (Norwegian Bay, Peel Sound) or partially (Jones Sound, Barrow Strait) covered with ice. Contingency days had been planned to allow for poor weather conditions (with a ratio of two bad-weather days for each good day). In the end, the aircraft were able to survey in adequate conditions for about 40% of the time (Table 2). Weather conditions deteriorated substantially towards the end of the survey period. Some areas were characterized by poor weather during the entire month (e.g., strong winds and thick fog in Smith Sound).

The strata believed to constitute the main aggregation areas of the putative Jones Sound and Smith Sound stocks had been given the highest level of priority (Fig. 3). However, heavy ice conditions imposed some delays. Norwegian Bay was flown in good weather, but its northern part and several of its fiords were still frozen. Narwhals were observed in its southern half. Jones Sound and its fiords were flown in excellent conditions in a single day although few narwhals were observed. Grise Fiord community members said that narwhals arrived late in 2013. Consequently, efforts were made to fly Jones Sound again at a later time, despite deteriorating weather. It was flown again on the last day of the survey (Aug. 26), although with stronger wind conditions than desirable. From this second survey, only the fiord strata were used because of more sheltered conditions (i.e., some Jones Sound fiords were surveyed a second time two weeks after the first survey and the data were combined). Fog and strong winds prevented complete coverage of Smith Sound. Several of the eastern Ellesmere fiords could be surveyed, however, and large numbers of narwhals and belugas were observed in Mackinson Inlet in particular (see Doniol-Valcroze et al. 2015).

Strata of the Somerset Island stock were given the second highest priority ranking (Fig. 4). By using all three aircraft simultaneously, both Peel Sound and Prince Regent Inlet were each surveyed in a single day (Table 2). The Gulf of Boothia was covered a week later over a 2-day period. Narwhals and bowhead whales appeared to be aggregated at the southern end of Prince Regent Inlet and in the northern part of the Gulf of Boothia. Despite heavy ice cover, numerous narwhals were observed in the central, high-density area of Peel Sound.

Because some narwhal movements between Admiralty Inlet and Eclipse Sound were previously documented by satellite telemetry, the survey design was to survey these two strata in quick succession. Admiralty Inlet was surveyed in two days, with a 4-day break in between due to bad weather (Table 2, Fig. 5). Eclipse Sound was covered immediately afterwards, in two successive days. Few narwhals were observed in the high intensity areas, but instead were aggregated in the southern ends of both areas, close to shore or within fiords, and with a high degree of clumping.

The eastern coast of Baffin Island was surveyed by one aircraft over a 2-week period (Table 2, Fig. 6). Strong winds made it difficult to survey the offshore portion of the area and numerous attempts were necessary. In the end, about 90% of the planned transect lines were surveyed, and all planned fiords, except one. Narwhals were seen predominantly in the fiords of the north-western half of the stratum. One narwhal was sighted in Cumberland Sound but was not included in any of the stock estimates due to uncertainty about its stock of origin.

Overall, there were 1707 sightings of narwhal groups while on effort (Fig. 7). Of these, 622 were made in fiord strata (Doniol-Valcroze et al. 2015), and 1085 were made in non-fiord strata. After photo-verification of sightings with missing measurements or coded as “uncertain”, five were missing group size information and 28 were missing a perpendicular distance measurement. After applying the methods described in Pike and Doniol-Valcroze (2015), there were 807 unique sightings in non-fiord strata (i.e., sightings seen by either, or both, observers).

DETECTION FUNCTION

Preliminary analyses showed that the distribution of perpendicular distances was different in fiord strata than in the other strata, and thus only non-fiord observations were used to fit the detection function for the non-fiord strata.

Examination of the histogram of the perpendicular distances of unique sightings suggested right-truncating the data at 1000 m (i.e., discarding sightings beyond 1000 m), which left 762 unique observations (515 seen by primary observers, 523 by secondary observers, and 276 by both). The shape of the histogram suggested that some narwhals were missed close to the track line despite the bubble windows. Therefore, there was a risk that hazard-rate and half-normal distributions would overestimate the probability of detection and the resulting effective strip width. However, almost a hundred narwhal sightings were made within 100 m of the track line and therefore it seemed inappropriate to lose a large amount of data by left-truncating (i.e., discarding sightings close to the trackline). The shape of the histogram suggested that a gamma distribution would fit better, except that a gamma distribution takes the value zero at zero distance. Therefore, we fitted a gamma distribution with an offset term, in addition to half-normal and hazard rate keys.

Model selection was performed on the three key functions and all the combinations of environmental covariates (Table 3). The model with the lowest AIC was one with a truncated gamma key function (Fig. 8). Covariates “sighting rate”, “Beaufort” and “glare” were selected and had the effect of reducing detection distance at higher levels (Beaufort >3, Glare=intense, Sighting rate>10 in the last 30 seconds, Fig. 9). This resulted in an average probability of detection g(x) = 0.48 (CV 2.8%) and an ESHW of 481 m (not including perception bias).

MARK RECAPTURE MODEL

Selection among MR models was performed on all the combinations of environmental covariates as well as covariates “observer” and “group size” (Table 3). The lowest AIC was a model with covariates “distance” and “sighting rate” (Fig. 10). It resulted in a p(0) for observers 1 and 2 of 0.58 (CV 7%), and a combined p(0) of 0.82 (CV 3.4%). Therefore, the overall probability of detecting a narwhal cluster between the track line and a distance of 1000 m was g(x) · p(0) = 0.40 (CV 4.2%).

When the analysis was performed separately for each plane, the combined p(0) for both platforms was relatively homogeneous: p(0)=0.82 for KBG (426 sightings), p(0)=0.91 for KBO (46 sightings), and p(0)=0.83 for CKB (290 sightings).

ENCOUNTER RATES AND GROUP SIZE

Encounter rates per stratum were highly variable (Table 4), reflecting strong differences among areas and the highly aggregated nature of narwhal groups across their summer range. Group sizes followed a heavily skewed distribution, with a long right tail (Fig. 11). Overall, there was no significant relationship between the probability of detection g(x) and the natural log of cluster size Ln(s). The global average group size was 2.76 (CV 3.8%), and stratum-wide mean group sizes ranged from 1.00 to 3.08.

TIME IN VIEW AND AVAILABILITY CORRECTION

An instantaneous correction factor of 3.18 is recommended for survey strata occurring in clear waters where it is assumed narwhals can be seen and identified from a depth of 2 m, and a factor of 4.90 is recommended in fiords with murky waters that presumably limit the detection of narwhals to a depth of 1 m (Watt et al. 2015). There were 527 narwhal sightings for which both a spot time and a beam time were available. Time in view ranged from 0 to 19 seconds, with an average time of 4.3 seconds (Fig. 12). With these data, the resulting weighted availability correction factor C_a was equal to 2.94 (CV 3.4%) for the 0-2 m bin and 4.53 (CV 3.8%) for the 0–1 m bin. Based on comments made by observers and examination of photographs, the 0–1 m correction was applied to East Baffin Island fiords (Doniol-Valcroze et al. 2015). All other strata used the 0–2 m bin.

ABUNDANCE ESTIMATE PER STRATUM AND PER STOCK

Estimates of surface abundance for each stratum are given in Table 4. Surface abundance estimates in fiord strata were taken from Doniol-Valcroze et al. (2015). Note that because the coverage of the SS stratum was incomplete, we reduced the area over which density was calculated and abundance was extrapolated to coincide with the surveyed portion of the stratum (Fig. 3).

In the sensitivity analysis, the entire abundance estimation process was run multiple times with different values for the thresholds used in duplicate identification, including fitting a new detection curve, estimating group size and encounter rates for every run. The resulting surface abundance estimates showed little variation, with CV ranging from 0% (Smith Sound) to 3% (Jones Sound, Admiralty Inlet). Therefore, for the final abundance estimates we used the threshold values identified in Pike and Doniol-Valcroze (time difference of 5 seconds, declination angle difference of 10°), and we applied a multiplier factor of 1 with a CV corresponding to the variation from the sensitivity analysis (CV_{dup}).

Surface abundance estimates from fiord and non-fiord strata were corrected for availability bias using correction factors from Watt et al. (2015) and added for each summer stock (Table 4). With these corrected estimates and recovery factors of F_r=1, the TALC is estimated to be 658 for the Somerset Island stock, 389 for the Admiralty Inlet stock, 134 for the Eclipse Sound stock and 206 for the East Baffin Island stock (Table 5). Using F_r=0.5, the TALC is estimated to be 76 for the Jones Sound stock and 77 for the Smith Sound stock.

DISCUSSION

This analysis provides updated, fully corrected abundance estimates of the six narwhal stocks in the Canadian High Arctic on their summer ranges. It is the first time these stocks have been surveyed in the same summer, and also the first time that abundance estimates are available for the putative Jones Sound and Smith Sound stocks. These estimates result from the combination of a large-scale survey effort that mobilized resources from multiple DFO regions and Nunavut co-management partners, as well as information from concurrent projects such as satellite tracking studies operating in the same area and at the same time of year.

There are several advantages to simultaneous coverage of all stocks vs spreading survey effort over multiple years. This partially addresses concerns of potential movements among neighbouring stocks during summer, and may yield insights into the possibility of inter-annual exchanges between areas such as Eclipse Sound and Admiralty Inlet. At the analysis stage, this also provides a higher sample size of observations, which decreases uncertainty in estimating detection function and the impact of environmental covariates.

Accurate abundance estimates require that all individuals have a possibility of being sampled (Buckland et al., 2001), which implies that their entire distribution range be surveyed. Using traditional knowledge and telemetry studies, we have tried to sample the entire areas known to be used by Admiralty Inlet, Eclipse Sound and East Baffin Island narwhals. However, complete coverage could not be achieved for the Somerset Island stock, which is believed to range further west and south than it was possible to survey (although presumably at lower densities), and for the Smith Sound and Jones Sound stocks, which exact distribution ranges are unknown. Instead we have focused on intense coverage of the known core areas of these summer stocks.

For instance, the survey design for the Somerset Island summering area focused on increasing effort in the central Peel Sound and Prince Regent Inlet strata, while ensuring that other important areas such as the Gulf of Boothia were covered. It is the first time that these substrata were surveyed simultaneously. The corrected abundance estimate of ca. 50,000 is higher than the most recent previous estimate of 35,000 (based on surveys done in separate years), but similar to the estimate of 52,000 that was obtained when using the larger but less precise 1996 estimates for Prince Regent Inlet from Innes et al. (2002). Taken stratum-by-stratum as well as overall, our 2013 estimate is more precise (CV 20%), which is due to increasing coverage intensity in PS and PRI, and based on more complete coverage than any previous survey of this stock.

Our 2013 results for Admiralty Inlet (~35,000 narwhal) and Eclipse Sound (~10,000 narwhal) differ substantially from previous survey estimates of the same stocks (18,000 for Admiralty Inlet in 2010 and 20,000 for Eclipse Sound in 2004). However, given the imprecise nature of the estimates and uncertainty about population structure, it is not clear if these changes reflect true changes in abundance. Other factors can explain variation in abundance estimates. For instance, the 2010 Admiralty Inlet result was obtained by averaging two complete surveys that yielded different abundance estimates (24,398 and 13,729), which could be due to movement in and out of the surveyed area, but could also illustrate how aggregation rates influence abundance estimates. We note that during HACS, narwhal sightings in Admiralty Inlet and Eclipse Sound were characterized by extremely high clustering and were encountered almost entirely in the low-intensity strata, while very few sightings were made in the high intensity strata of both regions. This likely resulted in a less precise estimate. However, a relatively high number of lines and coverage were maintained in the low coverage area that reduced the effect of the unexpected location of the observed high densities on the precision of abundance in these two strata.

The combined estimate for Admiralty Inlet and Eclipse Sound (~45,000) is similar to the total of previous abundance estimates, although previous surveys were never conducted in the same year. Documented movements of individual narwhals between Eclipse Sound and Admiralty Inlet raise the possibility of some degree of exchange between the two summering areas. The precautionary approach of managing at the smallest discernable units to avoid local depletion favours the use of the discrete stock estimates. However, given the possibility of exchange between the two stocks, we calculated a pooled TALC of 542 for AI and ES at the request of co-management partners (Table 5).

The surface estimate of ca. 3,800 narwhals for East Baffin Island fiords (Doniol-Valcroze et al. 2015) is close to the 2003 estimate of 3,487 (Richard et al. 2010), despite different statistical approaches. The HACS results confirm that a large number of narwhals use the East Baffin fiords during summer, especially in the northern part. Once corrected for availability bias, the 2013 estimate of ca. 17,500 is larger from the corrected estimate of 2003 (10,000) due to the use of a different correction factor than in previous studies, one that is based on the 0–1 m bin to account for reduced visibility in fiords with murky or opaque waters.

The Jones Sound and Smith Sound estimates are new and cannot be compared to previous surveys. The HACS results confirm that relatively large numbers of narwhals were found in Jones Sound and the adjacent Norwegian Bay, all of which are presumed to be available to hunters from the Grise Fiord community. However, few narwhals were seen in the Jones Sound stratum itself, with Norwegian Bay making up most of the estimate. We note that numerous sightings were made in Jones Sound fiords during the 2012 reconnaissance survey, whereas there were very few sightings in fiords in 2013 for this area. Off-line sightings were made in eastern Jones Sound in 2013 and were not included in the analysis, but confirmed the presence of additional narwhal groups in Jones Sound. Future tagging projects will likely increase our knowledge of narwhal movements and stock structure in this area. Until further information becomes available, however, we use a recovery factor of 0.5 in the calculation of the PBR to account for the uncertainty in stock structure and movement patterns. A recovery factor of 1.0 was used for all the other stocks, as is usually suggested for large populations with additional stock assessment information.

Despite being one of the priority areas, Smith Sound could not be surveyed completely because of unfavourable weather conditions persisting throughout the month. Therefore, we suggest it is difficult to justify extrapolating the density estimate based on relatively few lines in the northern part (lines that are short and close to shore) to the entire stratum, which is large and extends far offshore. Instead, it seems preferable to reduce the area over which survey results are extrapolated to a subset more representative of the realized effort. The resulting estimate should be considered a minimum estimate.

The Barrow Strait and Lancaster Sound strata could not be surveyed as planned (Somerset Island stock). However, groups of narwhals were sighted during training flights in early August in Barrow Strait, and one narwhal was seen during an aborted attempt to complete transects in Lancaster Sound in mid-August. These sightings were not included in the abundance estimates. Unfortunately, there was no information from satellite tracking on narwhal movements in that area during the 2013 survey. Based on previous studies, we expected the vast majority of Somerset Island narwhals to be distributed farther south in Prince Regent Inlet and Peel Sound at that time of year. However, we cannot exclude the possibility that significant numbers of narwhals were in Barrow Strait or Lancaster Sound during the survey, which would result in a negative bias in the abundance estimate for that stock. One narwhal was sighted in Cumberland Sound but was not included in any of the stock estimates due to uncertainty about its stock of origin. Overall, we have no information on movements between fiords and open-water strata that may have occurred during the survey, for any of the stocks. Most fiords, however, were surveyed in the same day as the neighbouring open-water areas, and we have no reason to believe that directional movements into or away from fiords may have biased our estimates.

Despite the use of data-driven methods and less reliance on arbitrary thresholds, a potential bias in the HACS lies in the identification of duplicate sightings between primary and secondary observers(Pike and Doniol-Valcroze 2015). The MRDS analysis estimated that the probability of detection of narwhals by both observers combined was low $p(0)=0.82$, which is relatively low yet within the range of previous narwhal surveys, e.g., 0.90 and 0.77 in Asselin and Richard (2011), 0.84 to 0.92 in Richard et al.(2010). A low value for $p(0)$ results in higher abundance estimates than when $p(0)$ is estimated close to 1. While it is important to adjust for perception bias in surveys, there is a risk that if the identification of duplicate sightings is underestimated, the resulting estimates will not be conservative. Closer examination of the data, as well as model selection, showed that high levels of aggregation and consequently high sighting rates were responsible for the low $p(0)$. This reflects two distinct phenomena: first, observers are indeed more likely to miss narwhals in high aggregations, and thus the $p(0)$ adequately corrects for this true perception bias. Second, our ability to identify duplicate sightings breaks down at high encounter rates, and this may result in a positive bias in the estimates (i.e., non-conservative correction factors).

We tried to quantify the uncertainty due to duplicate identification by using a sensitivity analysis in which the entire abundance estimation process (except for fiord strata) was repeated multiple times with different threshold values for duplicate assignment. The results show that our method to assign duplicates was robust to reasonable variations in the threshold values (difference in beam time and in declination angle), and that the effect on the abundance estimates of each stratum (and this, N_{min} and PBR) was small (an additional CV component of 1–3%). We included this additional uncertainty in our final estimates.

Overall, our objectives of updating abundance estimates of narwhal stocks in the Canadian High Arctic and improving their precision and accuracy were met. Concurrent, long-term telemetry studies of diving behaviour were critical to obtaining estimates of availability bias. Abundance estimates also were improved by implementing new analysis techniques to address specific challenges associated with narwhal use of fiords. The success of HACS was also due in no small part to involvement of the Inuit communities and co-management partners, including their participation in a 2012 reconnaissance survey of previously unsurveyed areas.

ACKNOWLEDGEMENTS

We thank the communities and Hunters' and Trappers' Organizations of Arctic Bay, Clyde River, Grise Fiord, Hall Beach, Kugaaruk, Pangnirtung, Pond Inlet, Qikiqtarjuaq, Resolute Bay and Taloyoak. We also thank Inuit observers Leo Ihakik, Robert Karetak, Ivan Koonoo, Karlene Napayok and Bonnie Tapati. We thank Mike Kristjanson (Chief Infrastructure and Logistics) and Jodi MacGregor (Arctic Logistics Operations Manager) from the Polar Continental Shelf Program, Earth Sciences Sector, as well as Ken Borek pilots and engineers. This project benefitted considerably from previous DFO satellite tracking projects, and we thank in particular Jack Orr and Bernard LeBlanc for their efforts and input. Funding came from the DFO Ecosystem Science Directorate, the Nunavut Implementation Fund, the Nunavut Wildlife Management Board, the Polar Continental Shelf Program, the Government of Nunavut Fisheries and Sealing, and CEMAM.

Project lead: Kevin Hedges[1]. Project management: Christine Abraham[2], Steve Ferguson[1] and Mike Hammill[3], who all proved invaluable in getting the project funded and off the ground (pun intended). Survey design: Thomas Doniol-Valcroze[3], Jean-François Gosselin[3], Jack Lawson[4] and Pierre Richard[1]. Logistics: Blair Dunn[1], Jason Hamilton[1] and Bernard LeBlanc[1]. Team leaders and equipment operators: Natalie Asselin[1], Jean-François Gosselin[3], Jack Lawson[4] and Daniel Pike. DFO observers: Catherine Bajzak[3], Alejandro Buren[4], Pierre Carter[3], Thomas Doniol-Valcroze[3], Blair Dunn[1], Patt Hall[1], Lee Sheppard[4], Samuel Turgeon[3] and Brent Young[1]. DFO readers of photographic data: Pierre Rivard[3] and Jean-François Lussier[3].

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TABLES

Table 1. Estimated numbers of narwhal in recognized Baffin Bay summer stocks. For all stocks, or sub-regions within a stock (i.e., Somerset Island), the most recent estimate is presented. All estimates were fully corrected for perception and availability bias in the original studies. Alternative estimates are noted in the comments where appropriate. Adapted from DFO (2012) and Higdon and Ferguson (unpubl. rep.).

Summer stock	Survey year	Population estimate	CV	95% CI	Source	Survey method	Comments
Admiralty Inlet	2010	18,049	0.23	11,613-28,053	Asselin and Richard 2011	Line transect survey with distance methodology and double-observer counts, photographic survey of aggregations	Two complete surveys (mean estimates 24,398, 13,729), averaged using effort-weighted mean.
Somerset Island							
Barrow Strait	2004	2,925	0.46	1,140-6,270	Richard et al. 2010	Line transect survey with distance methodology and double-observer counts	Higher estimate in 1996 survey (Innes et al. 2002), mean = 5,898, but less precise (CV = 0.75)
Prince Regent Inlet	2002	20,871	0.71	4,805-59,157	Richard et al. 2010	Line transect survey with distance methodology and double-observer counts	Estimate from 1996 survey (Innes et al. 2002) larger and more precise (mean = 34,159; CV = 0.35)
Peel Sound	1996	5,240	0.6		Innes et al. 2002	Line transect survey with distance methodology and double-observer counts	Similar to 1984 estimate of 1701 on surface (CV 0.25) (Richard et al. 1994) when corrected by 3.1 (Asselin and Richard 2010) (5,273)
Gulf of Boothia	2002	6,770	0.3	3,638-11,862	Richard et al. 2010	Line transect survey with distance methodology and double-observer counts	First time surveyed
Sum		35,806					Total = 52,057 if higher estimates from 1996 (Innes et al. 2002) used for Barrow Strait and Prince Regent Inlet
Eclipse Sound	2004	20,225	0.36	9,471-37,096	Richard et al. 2010	Line transect survey with distance methodology and double-observer counts	
East Baffin Island	2003	10,073	0.31	5,333-17,474	Richard et al. 2010	Line transect survey with distance methodology and double-observer counts	
Total		84,153					Total estimate of 100,404 narwhals if 1996 results for Somerset Island stock are used with the 2002 Gulf of Boothia estimate

Table 2. Sequence of survey completion. Blue cells indicate a day during which a stratum was flown, while red cells indicate that poor weather conditions prevented the plane from surveying that day(with the name of the community where the plane was based given in brackets).

Date	Aircraft 1	Aircraft 2	Aircraft 3
2013-08-01	preparation (Resolute)	preparation (Resolute)	preparation (Resolute)
2013-08-02	preparation (Resolute)	preparation (Resolute)	preparation (Resolute)
2013-08-03	weather (Resolute)	weather (Resolute)	weather (Resolute)
2013-08-04	Smith Sound	Smith Sound	Smith Sound
2013-08-05	Peel Sound	Peel Sound	Peel Sound
2013-08-06	weather (Resolute)	weather (Resolute)	weather (Resolute)
2013-08-07	weather (Resolute)	weather (Resolute)	weather (Resolute)
2013-08-08	Norwegian Bay	Norwegian Bay	Norwegian Bay
2013-08-09	Prince Regent Inlet	Prince Regent Inlet	Prince Regent Inlet
2013-08-10	Jones Sound	Jones Sound	transfer to Clyde River
2013-08-11	weather (Resolute)	weather (Arctic Bay)	East Baffin
2013-08-12	weather (Resolute)	Admiralty Inlet	East Baffin
2013-08-13	weather (Resolute)	weather (Arctic Bay)	weather (Clyde River)
2013-08-14	weather (Resolute)	weather (Arctic Bay)	transfer to Pangnirtung
2013-08-15	Gulf of Boothia	weather (Arctic Bay)	East Baffin
2013-08-16	Gulf of Boothia	weather (Arctic Bay)	weather (Pangnirtung)
2013-08-17	weather (Kugaruk)	Admiralty Inlet	East Baffin
2013-08-18	weather (Kugaruk)	Eclipse Sound	East Baffin
2013-08-19	weather (Kugaruk)	Eclipse Sound	weather (Pangnirtung)
2013-08-20	weather (Kugaruk)	weather (Arctic Bay)	Cumberland Sound
2013-08-21	weather (Hall Beach)	weather (Arctic Bay)	weather (Pangnirtung)
2013-08-22	weather (Hall Beach)	weather (Resolute)	weather (Pangnirtung)
2013-08-23	weather (Hall Beach)	weather (Resolute)	Cumberland Sound
2013-08-24	weather (Hall Beach)	weather (Resolute)	weather (Pangnirtung)
2013-08-25	weather (Resolute)	weather (Resolute)	East Baffin
2013-08-26	Jones Sound	Jones Sound	weather (Pangnirtung)

Table 3. Mark-recapture distance sampling model selection based on AIC. The table shows the 30 best models in order of increasing AIC. sr: sighting rate; Beaufort: sea state conditions on the Beaufort scale; glare: extent and intensity of sun glare; ice: ice cover.

Detection	DS model	AIC_{DS}	MR model	AIC_{MR}	AIC_{total}	ΔAIC
gamma	~sr+beaufort+glare	10105.3	~distance+sr+beaufort	1657.51	11762.81	0
gamma	~sr+beaufort+glare	10105.3	~distance+sr+beaufort+ice	1657.64	11762.94	0.13
gamma	~sr+glare	10106.3	~distance+sr+beaufort	1657.51	11763.81	1
gamma	~sr+glare	10106.3	~distance+sr+beaufort+ice	1657.64	11763.94	1.13
hazard-rate	~sr+beaufort+glare	10108.8	~distance+sr+beaufort	1657.51	11766.31	3.5
hazard-rate	~sr+beaufort+glare	10108.8	~distance+sr+beaufort+ice	1657.64	11766.44	3.63
hazard-rate	~sr+glare	10110	~distance+sr+beaufort	1657.51	11767.51	4.7
hazard-rate	~sr+glare	10110	~distance+sr+beaufort+ice	1657.64	11767.64	4.83
gamma	~sr+beaufort	10111	~distance+sr+beaufort	1657.51	11768.51	5.7
gamma	~sr+glare	10105.3	~distance+sr+ice	1663.24	11768.54	5.73
gamma	~sr	10111.1	~distance+sr+beaufort	1657.51	11768.61	5.8
gamma	~sr+beaufort	10111	~distance+sr+beaufort+ice	1657.64	11768.64	5.83
gamma	~sr	10111.1	~distance+sr+beaufort+ice	1657.64	11768.74	5.93
hazard-rate	~sr+beaufort	10111.7	~distance+sr+beaufort	1657.51	11769.21	6.4
hazard-rate	~sr+beaufort	10111.7	~distance+sr+beaufort+ice	1657.64	11769.34	6.53
gamma	~sr+beaufort+glare	10106.3	~distance+sr+ice	1663.24	11769.54	6.73
gamma	~sr+glare	10105.3	~distance+sr	1664.99	11770.29	7.48
gamma	~sr+beaufort+glare	10106.3	~distance+sr	1664.99	11771.29	8.48
hazard-rate	~sr+beaufort+glare	10108.8	~distance+sr+ice	1663.24	11772.04	9.23
hazard-rate	~sr	10114.7	~distance+sr+beaufort	1657.51	11772.21	9.4
hazard-rate	~sr	10114.7	~distance+sr+beaufort+ice	1657.64	11772.34	9.53
hazard-rate	~sr+glare	10110	~distance+sr+ice	1663.24	11773.24	10.43
half-normal	~sr+glare	10116	~distance+sr+beaufort	1657.51	11773.51	10.7
half-normal	~sr+glare	10116	~distance+sr+beaufort+ice	1657.64	11773.64	10.83
hazard-rate	~sr+beaufort+glare	10108.8	~distance+sr	1664.99	11773.79	10.98
half-normal	~sr+beaufort+glare	10116.5	~distance+sr+beaufort	1657.51	11774.01	11.2
half-normal	~sr+beaufort+glare	10116.5	~distance+sr+beaufort+ice	1657.64	11774.14	11.33
gamma	~sr+beaufort	10111	~distance+sr+ice	1663.24	11774.24	11.43
gamma	~sr	10111.1	~distance+sr+ice	1663.24	11774.34	11.53
hazard-rate	~sr+beaufort	10111.7	~distance+sr+ice	1663.24	11774.94	12.13

Table 4. Survey coverage, sightings, and abundance estimates by stratum and by summer stock. Fiord surface estimates were calculated in Doniol-Valcroze et al (2015). CV_{ER}: CV of encounter rates. CV_{GS}: CV of group size. CV_{DP}: CV of detection function (including perception bias). C_a: Correction factor for availability bias (from Watts et al 2015). CV_{dup}: CV of duplicate identification.

Stock / Stratum	Area (km²)	Effort (km)	Number of Transects/PSU	Number of unique sightings	Encounter rate (km⁻¹)	CV_{ER}	Number of individuals	Mean group size	CV_{GS}	Prob. detection	CV_{DF}	Surface abundance	CV	C_a	CV_{Ca}	CV_{dup}	Abundance (corrected)	CV
Jones Sound																		
JS	19,231	930	13	16	0.017	1.08	38	2.38	0.15	0.32	0.04	940	1.08					
NB	13,713	635	9	41	0.065	0.30	113	2.76	0.14	0.32	0.04	3,331	0.29					
total (offshore)			22	57	0.036	0.51	151	2.65	0.11	0.32	0.04	4,271	0.33					
JSF	2,413	888	6	24								45	0.94					
Total	35,357											**4,316**	**0.32**	2.94	0.03	0.03	**12,694**	**0.33**
Smith Sound																		
SS	10,861	546	11	76	0.139	0.98	171	2.24	0.07	0.39	0.04	3,647	0.97					
SSF	4,237	413	4	165								1,916	0.45					
Total	15,098											**5,563**	**0.65**	2.94	0.03	0.00	**16,360**	**0.65**
Somerset Island																		
GB	63,178	1,627	11	81	0.050	0.26	158	1.95	0.09	0.35	0.04	7,335	0.28					
PRI	29,178	1,888	18	88	0.047	0.58	208	2.36	0.08	0.35	0.04	3,627	0.63					
PSHI	5,454	527	13	165	0.313	0.18	456	2.76	0.08	0.35	0.04	5,781	0.21					
PSLO	17,499	860	16	4	0.005	0.39	8	2.00	0.20	0.35	0.04	179	0.38					
Total	115,309		58	338	0.069	0.17	829	2.45	0.05	0.35	0.04	**16,921**	**0.20**	2.94	0.03	0.01	**49,768**	**0.20**
Admiralty Inlet																		
AIH	3,981	500	16	26	0.052	0.64	61	2.35	0.18	0.30	0.04	535	0.64					
AIL	4,526	387	18	220	0.568	0.34	678	3.08	0.09	0.30	0.04	11,237	0.45					
total (offshore)			34	246	0.277	0.31	739	3.00	0.08	0.30	0.04	11,772	0.43					
AIF	912	456	7	132								143	0.85					
Total	9,419											**11,915**	**0.42**	2.94	0.03	0.02	**35,043**	**0.42**

Stock / Stratum	Area (km^2)	Effort (km)	Number of Transects/PSU	Number of unique sightings	Encounter rate (km^{-1})	CV$_{ER}$	Number of individuals	Mean group size	CV$_{GS}$	Prob. detection	CV$_{DF}$	Surface abundance	CV	C$_a$	CV$_{Ca}$	CV$_{dup}$	Abundance (corrected)	CV
Eclipse Sound																		
ESH	2,839	460	14	2	0.004	0.77	2	1.00	0.00	0.34	0.04	16	0.77					
ESL	4,334	310	29	68	0.220	0.33	142	2.09	0.11	0.34	0.04	2,415	0.34					
total (offshore)			43	70	0.091	0.32	144	2.06	0.11	0.34	0.04	2,431	0.34					
ESF	1,286	447	7	673								1,135	0.19					
Total	8,459											**3,566**	**0.24**	2.94	0.03	0.03	**10,489**	**0.24**
East Baffin Island																		
EBO	43,419	1,140	28	3	0.003	0.63	3	1.00	0.00	0.39	0.04	**122**	**0.63**	2.94	0.03	0.00	357	0.63
EBF	10,091	1358	9	773								**3,799**	**0.35**	4.53	0.04	0.01	17,198	0.35
Total	53,510																**17,555**	**0.35**

Table 5. Calculation of Potential Biological Removal (PBR) and Total Allowable Landed Catch (TALC) for each Canadian Baffin Bay narwhal stock, based on the 2013 High Arctic Cetacean Survey. Abundance estimates are corrected for perception and availability biases. $\widehat{N}_{min}$ is the 20th percentile of the log-normal distribution of the abundance estimate. F_r is the Recovery factor. Given the possibility of some degree of exchange between the Admiralty Inlet and Eclipse Sound stocks, a pooled TALC was calculated at the request of co-management partners in addition to separate estimates (bottom row).

Stock	**Abundance (corrected)**	**CV**	$\widehat{N}_{\text{min}}$	F_r	**PBR**	**TALC**
Jones Sound	**12,694**	**0.33**	9,714	0.5	**97**	**76**
Smith Sound	**16,360**	**0.65**	9,897	0.5	**99**	**77**
Somerset Island	**49,768**	**0.20**	42,081	1	**842**	**658**
Admiralty Inlet	**35,043**	**0.42**	24,895	1	**498**	**389**
Eclipse Sound	**10,489**	**0.24**	8,564	1	**171**	**134**
East Baffin Island	**17,555**	**0.35**	13,214	1	**264**	**206**
Admiralty Inlet	35,043	0.42				
Eclipse Sound	10,489	0.24				
Total AI+ES	**45,532**	**0.33**	34,716	1	**694**	**542**

FIGURES

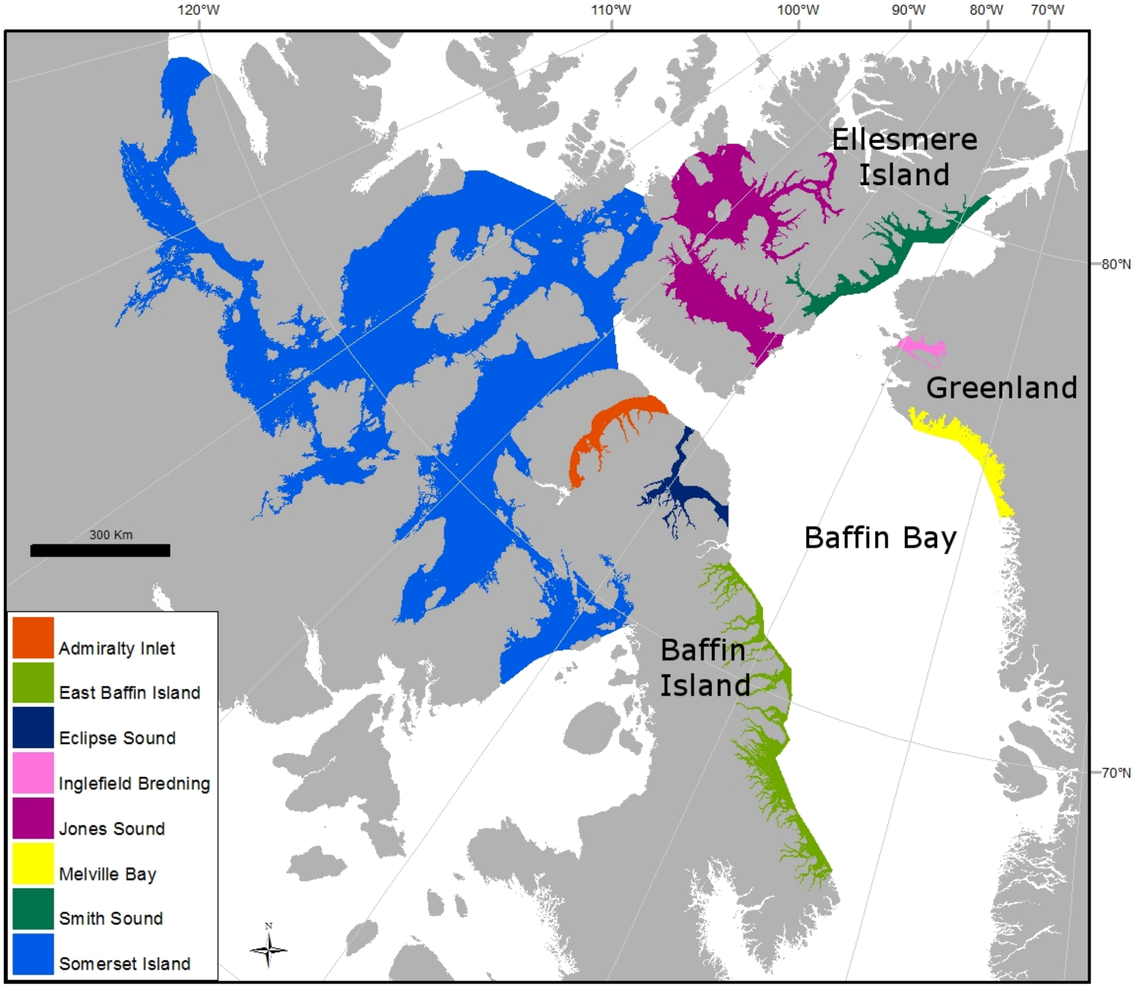

Figure 1. Map of High Arctic narwhal summer aggregations (source: NAMMCO/SC/21-JCNB/SWG/14-05). Melville Bay and Inglefield Bredning are summering aggregations in Greenland recognized as part of the Baffin Bay population by the Canada-Greenland Joint Commission on Conservation and Management of Narwhal and Beluga, and were not considered in this study.

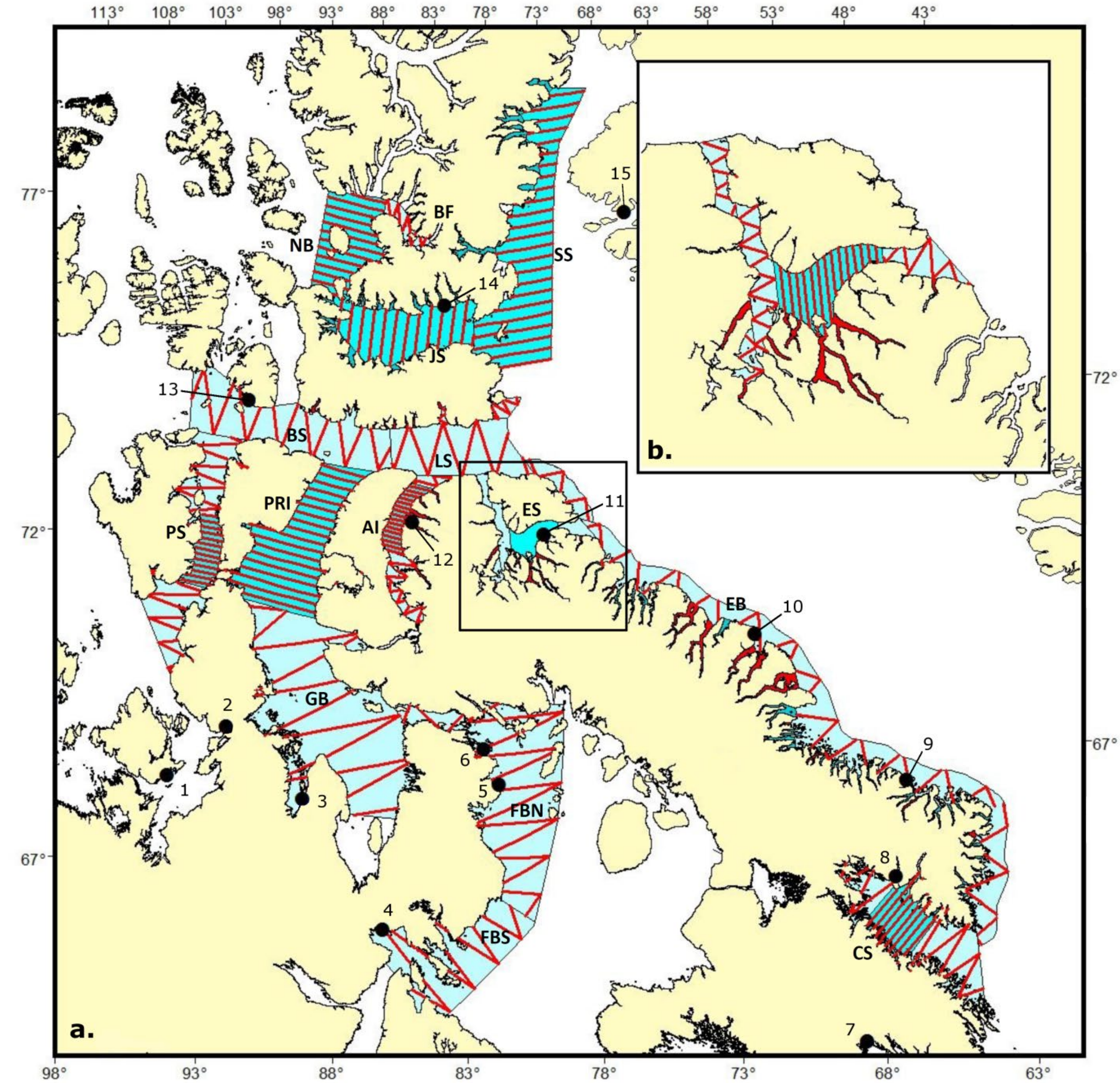

Figure 2. a.) Map of planned survey strata (blue polygons), transect lines (red lines), and fiord strata (red areas). AI: Admiralty Inlet. BF: Baumann Fiord. BS: Barrow Strait. CS: Cumberland Sound. EB: East Baffin Island. ES: Eclipse Sound. FBN: Foxe Basin North. FBS: Foxe Basin South. GB: Gulf of Boothia. JS: Jones Sound. LS: Lancaster Sound. NB: Norwegian Bay. PRI: Prince Regent Inlet. PS: Peel Sound. SS: Smith Sound. Communities (black dots): 1. Gjoa Haven; 2.Taloyoak; 3. Kugaaruk; 4. Repulse Bay; 5. Hall Beach; 6. Igloolik; 7. Iqaluit; 8. Pangnirtung; 9. Qikiqtarjuaq; 10. Clyde River; 11. Pond Inlet; 12. Arctic Bay; 13. Resolute; 14. Grise Fiord; 15. Qaanaaq (Greenland). b.) inset : zoom of the Eclipse Sound stratum (boxed area).

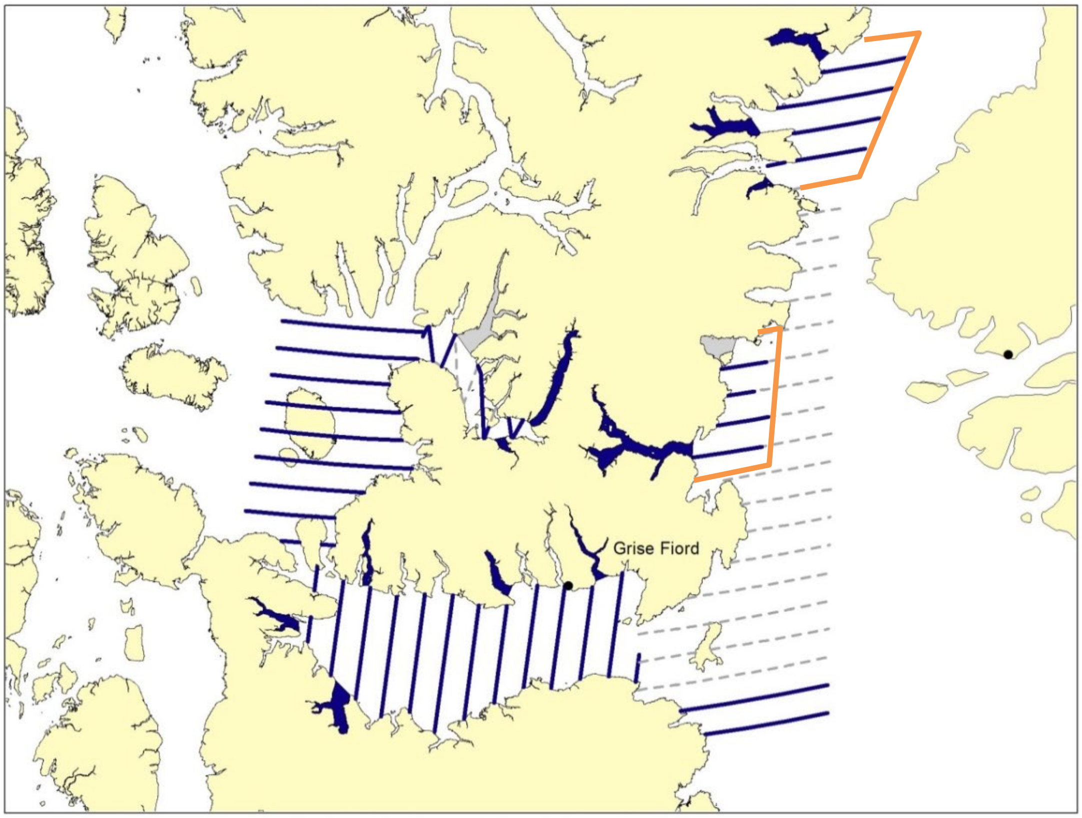

Figure 3. Norwegian Bay, Jones Sound and Smith Sound survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords. Orange box: resized stratum for Smith Sound, over which sightings were extrapolated (because of missing effort in the southern part).

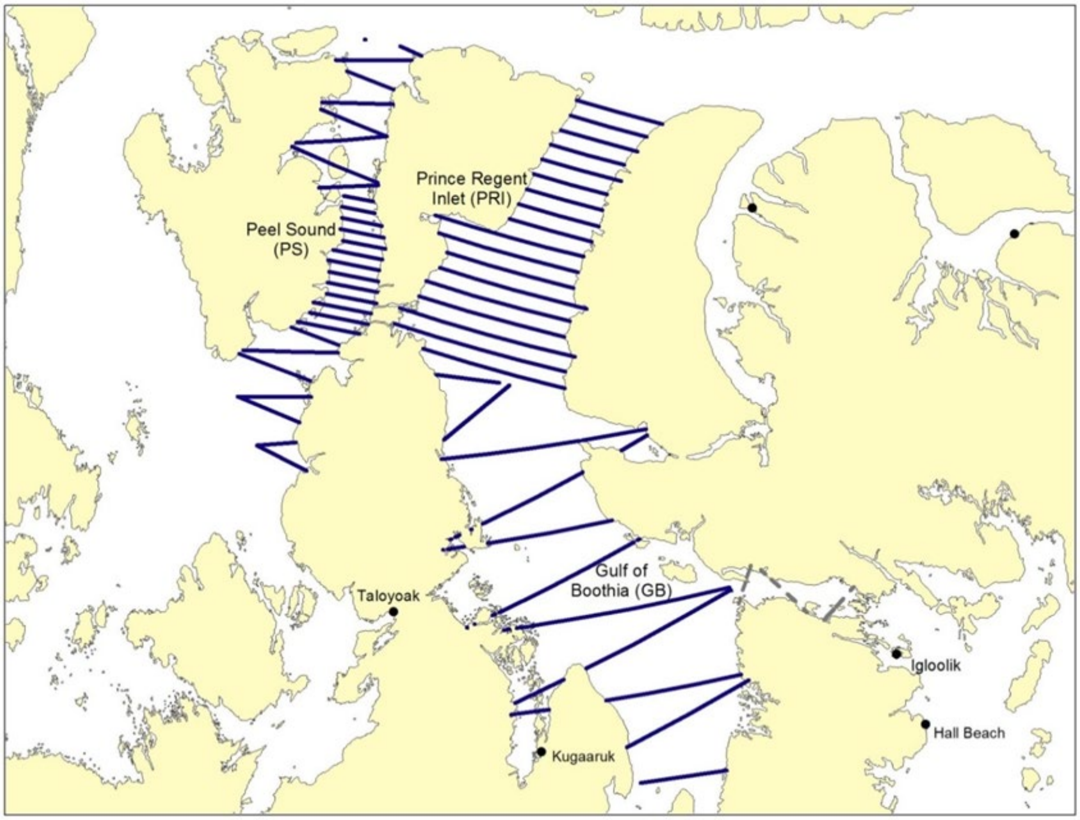

Figure 4. Somerset Island survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

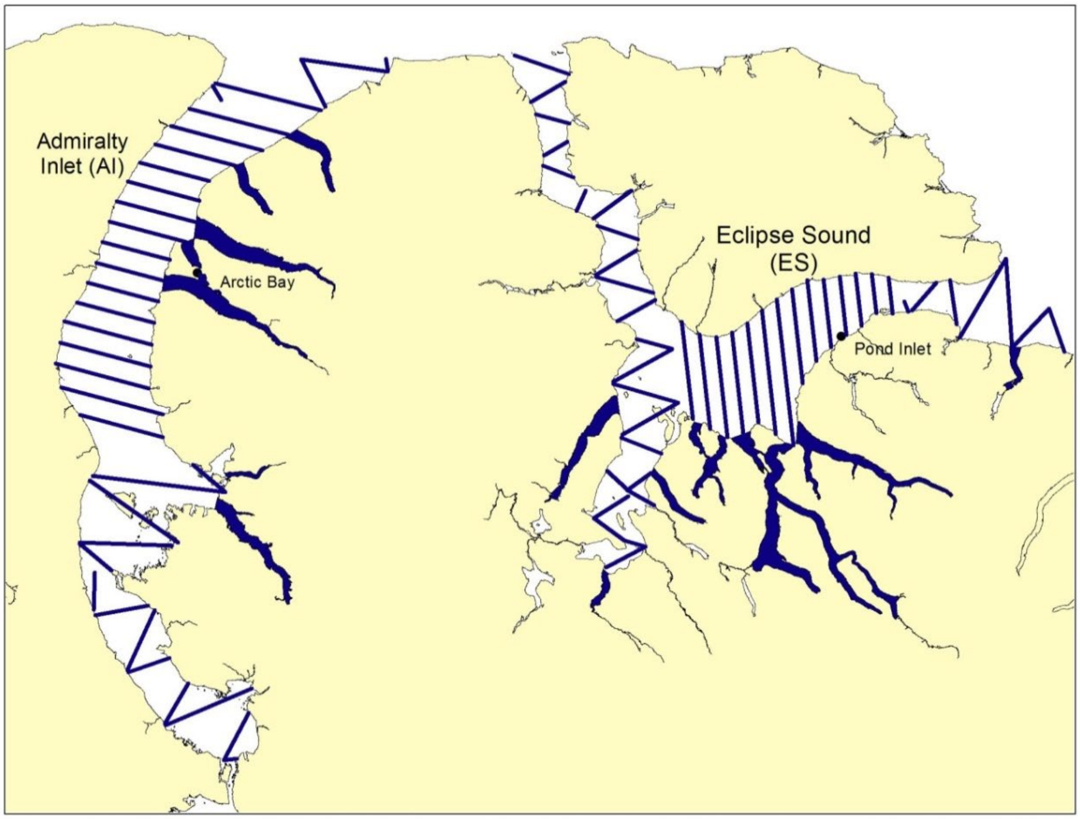

Figure 5. Admiralty Inlet and Eclipse Sound survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

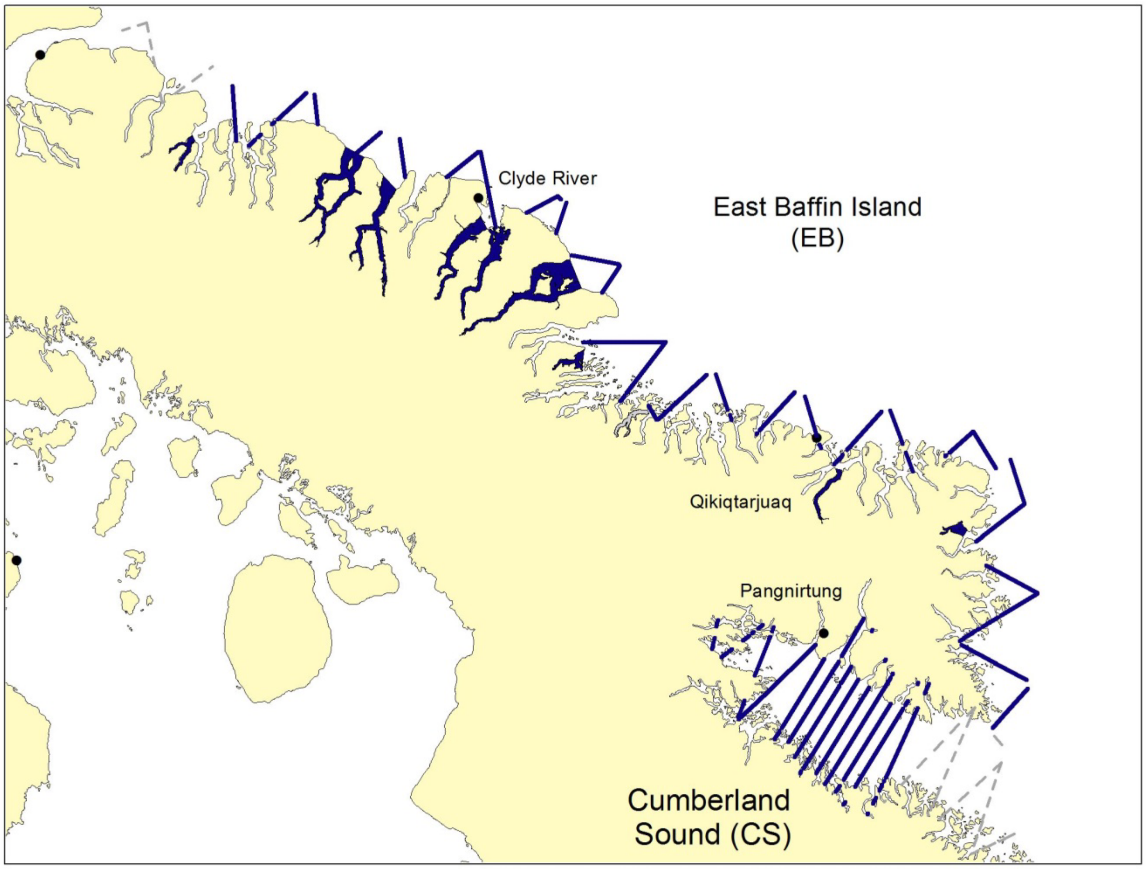

Figure 6. East Baffin stock and Cumberland Sound survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

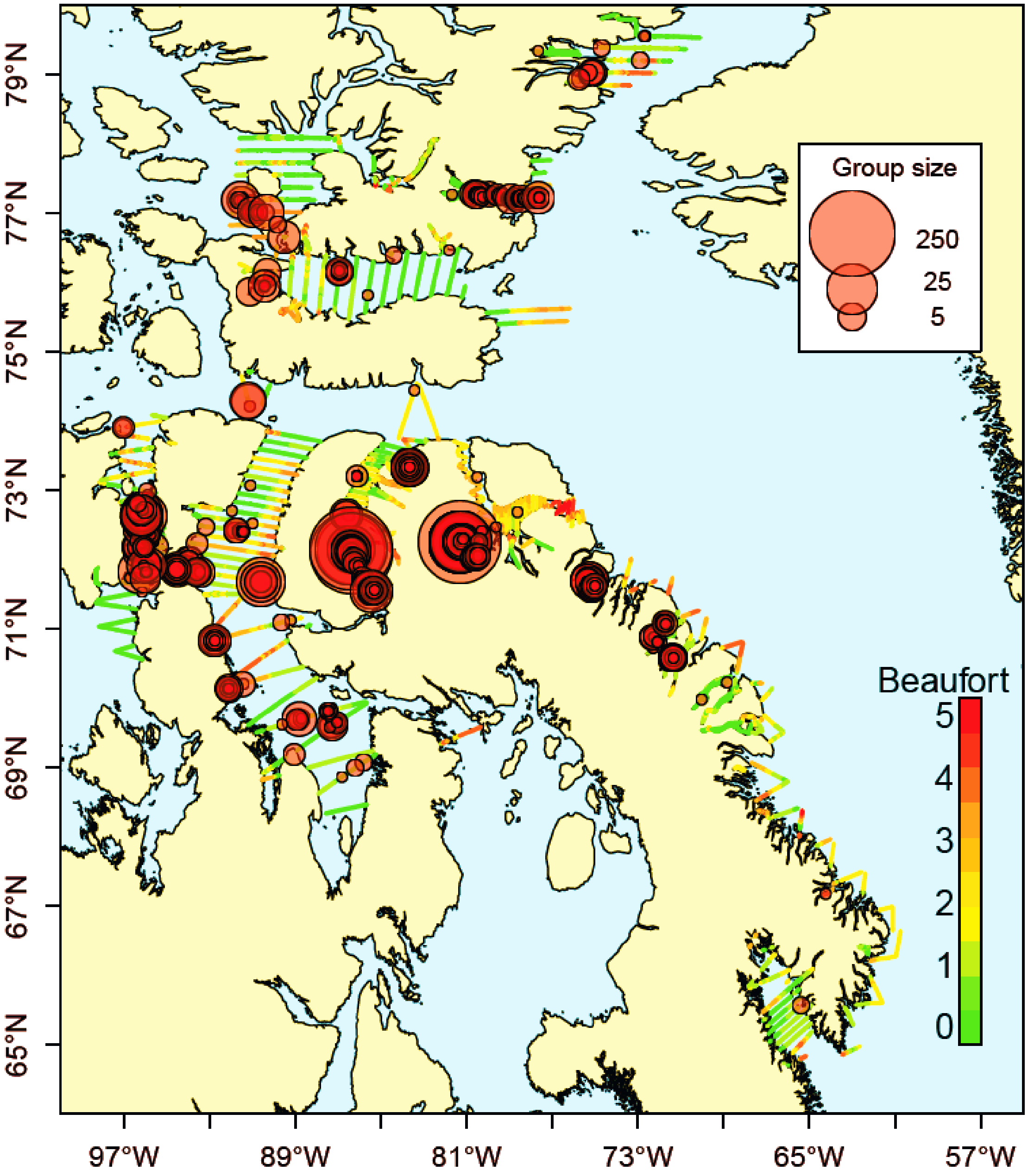

Figure 7. Unique sightings of narwhal groups made during the 2013 High Arctic Cetacean Survey (red circles). Lines represent realized effort with color scale showing Beaufort conditions.

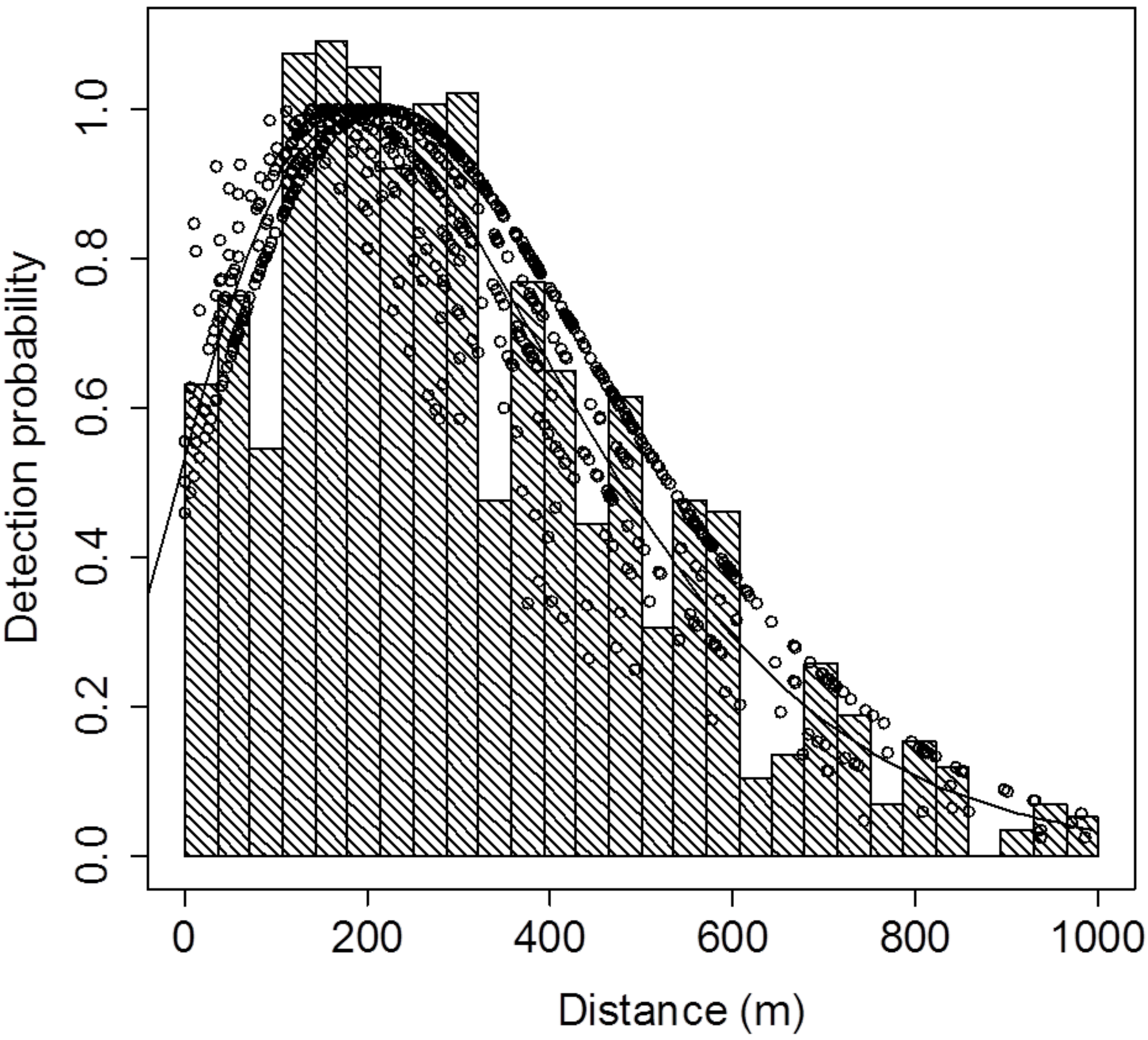

Figure 8. Histogram of perpendicular distances of narwhal sightings in all non-fiord strata, with fitted gamma detection function, after right-truncation at 1000 m (no left truncation). Circles are the probability of detection for each sighting given its perpendicular distance and other covariate values. Line is the fitted model.

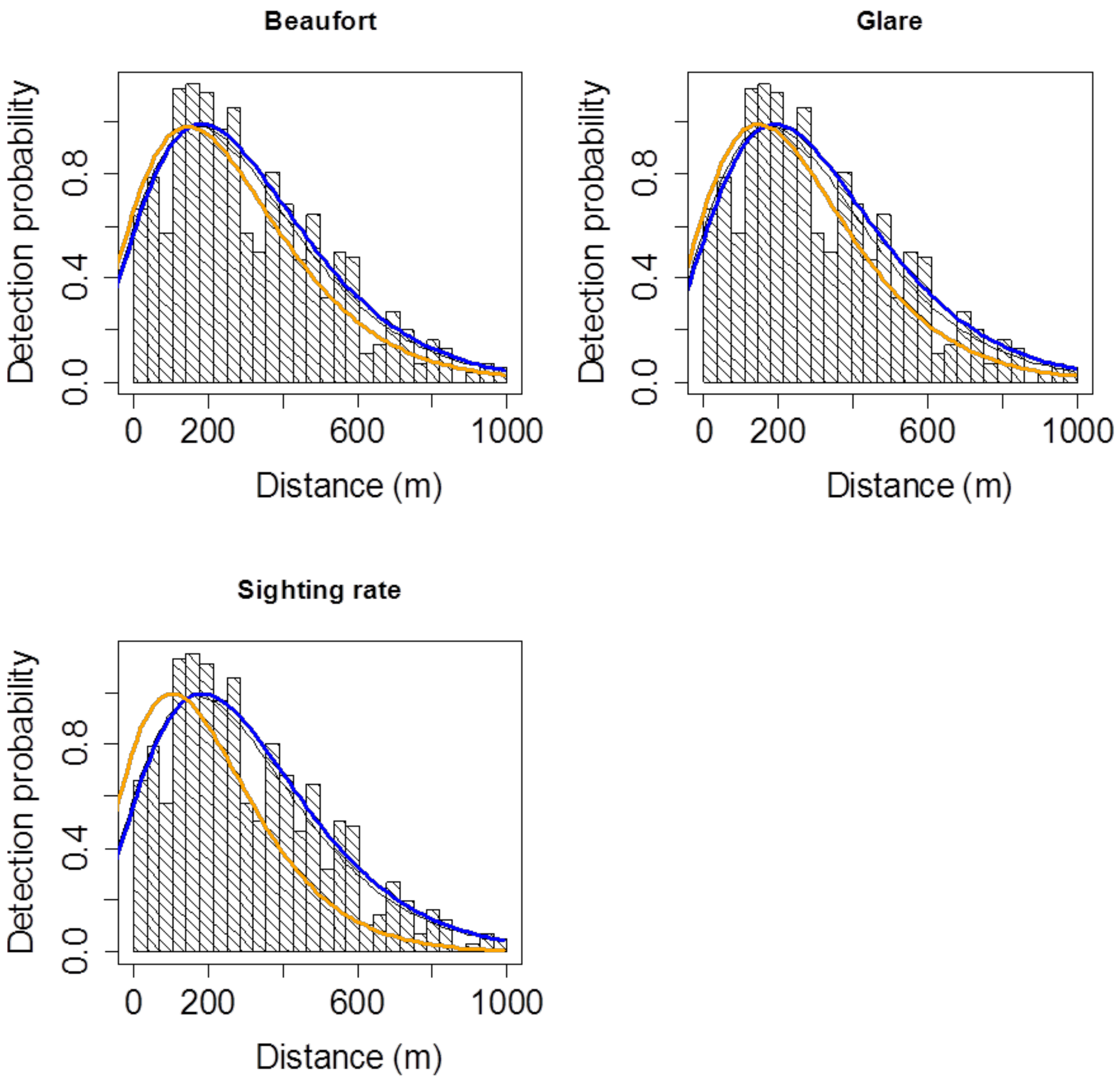

Figure 9. Predicted detection probabilities as a function of 3 environmental covariates in the detection function. Blue: "low" level of the covariate. Orange: "high" level of the covariate (Beaufort >3, Glare=intense, Sighting rate>10 in the last 30 seconds).

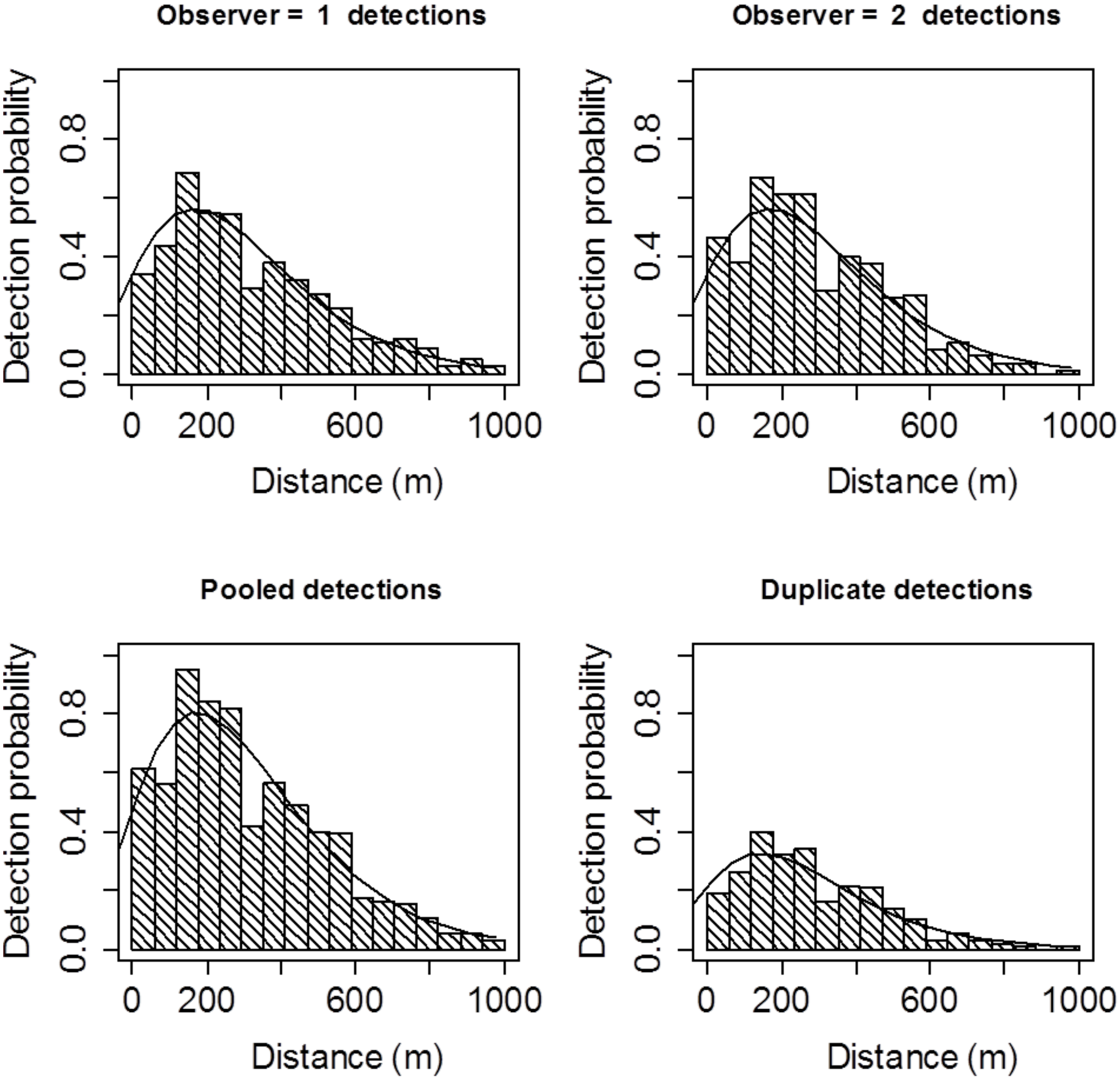

Figure 10. Detection function plots of MRDS analysis assuming point independence between observers. Lines are the fitted models.

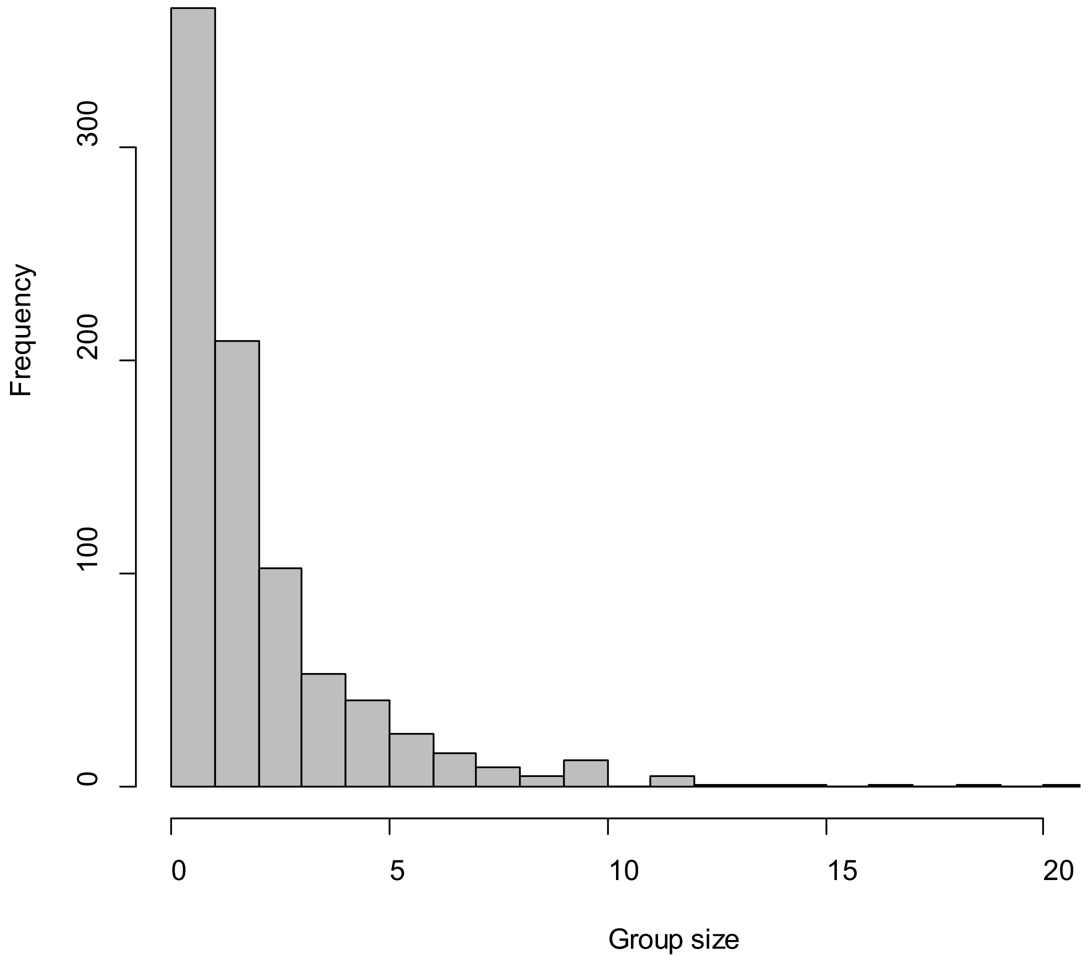

Figure 11. Histogram of group size of 846 unique narwhal sightings. For clarity, one group of 32 and two groups of 75 not shown on figure.

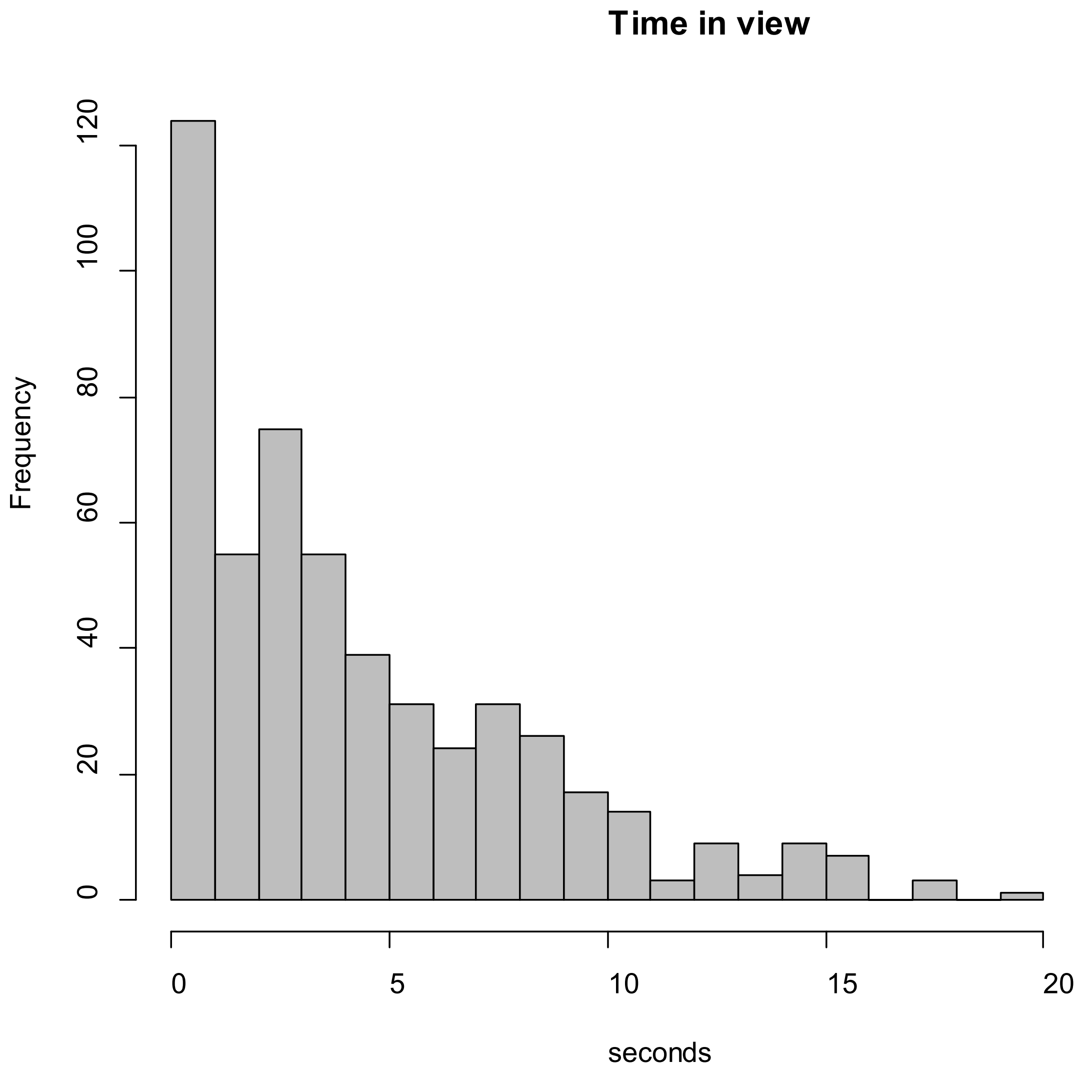

Figure 12. Histogram of time in view (i.e., difference between “spot time” and “beam time”) for 527 narwhal sightings.