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Abundance estimate of the Eastern Canada – West Greenland bowhead whale population based on the 2013 High Arctic Cetacean Survey

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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.

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ABSTRACT

Bowhead whale hunting is an integral part of Inuit culture. Up-to-date abundance estimates of the entire Eastern-Canada West-Greenland (EC-WG) bowhead population are necessary to support sustainable management of the harvest. A multi-year survey design was chosen in 2002-2003 because two separate populations of eastern Arctic bowhead whales were still recognized at the time. Since then, eastern Arctic bowheads were re-assessed as a single population. No aerial surveys had attempted to cover the full extent of bowhead whale summer distribution in the Eastern Canadian Arctic in a single year.

DFO conducted the High Arctic Cetacean Survey (HACS) in August 2013 to update abundance estimates for known stocks of Baffin Bay narwhal and for the EC-WG bowhead whale population. The survey was designed to cover the largest possible proportion of the summering areas of the EC-WG population while at the same time improving on the precision of past estimates. Three aircraft were used simultaneously to cover the vast survey area within a short time frame. This document presents the results of the survey and new abundance estimates for the EC-WG bowhead population, as well as an updated Potential Biological Removal (PBR) estimate.

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 platforms on each side of the aircraft to correct for the proportion of whales missed by visual observers. Abundance in Isabella Bay was estimated using density spatial modelling to account for its complex shape and uneven coverage. Estimates were corrected for availability bias (whales 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 bowhead whales in the study area in August.

The survey achieved complete coverage of important summer aggregation areas like Prince Regent Inlet, Gulf of Boothia, Admiralty Inlet, Eclipse Sound, Isabella Bay and Cumberland Sound. However, Fury and Hecla Strait, Northern Foxe Basin and Roes Welcome Sound could not be covered. The fully corrected abundance estimate for the EC-WG bowhead whale population was 6,446 (Coefficient of Variation [CV] 26%). Sources of uncertainty arise mainly from the high level of clustering observed at several scales, in particular in Isabella Bay and Cumberland Sound. Based on this abundance estimate and a recovery factor of 0.5 in the PBR calculation, the EC-WG bowhead whale population can support a total human-induced mortality of 52 whales annually.

Estimation de l'abondance de la population de baleines boréales de l'est du Canada et de l'ouest du Groenland selon l'Inventaire des cétacés dans l'Extrême-Arctique de 2013

RÉSUMÉ

La chasse à la baleine boréale fait partie intégrante de la culture inuite. Il est essentiel d'avoir accès aux estimations les plus récentes de l'abondance des populations de baleines boréales de l'est du Canada et de l'ouest du Groenland afin d'assurer la gestion durable de cette chasse. En 2002-2003, puisqu'on croyait toujours qu'il existait deux populations distinctes de baleines boréales de l'est de l'Arctique, le relevé avait été conçu selon une approche pluriannuelle. Depuis, il a été reconnu que les baleines boréales de l'est de l'Arctique constituent une population unique. Aucun relevé aérien n'a couvert la totalité de l'aire de répartition estivale des baleines boréales dans l'est de l'Arctique canadien en une seule année.

Le MPO a procédé à l'Inventaire des cétacés dans l'Extrême-Arctique au mois d'août 2013 afin de mettre à jour les estimations d'abondance des stocks de narvals de la baie de Baffin et de baleines boréales de l'est du Canada et de l'ouest du Groenland. Le relevé visait à couvrir la plus grande proportion possible des zones de regroupement estival des baleines boréales de l'est du Canada et de l'ouest du Groenland, tout en augmentant la précision des estimations antérieures. Trois aéronefs ont été utilisés simultanément pour couvrir la vaste zone de relevé dans un court délai. Le présent document donne les résultats du relevé et les nouvelles estimations d'abondance de la population de baleines boréales de l'est du Canada et de l'ouest du Groenland, de même qu'une estimation du prélèvement biologique potentiel.

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 baleines non-détectés par les observateurs. L'abondance dans la baie Isabella a été estimée au moyen d'une modélisation de la densité spatiale afin de tenir compte de sa forme complexe et de la couverture irrégulière. Les estimations ont été corrigées pour tenir compte des biais de disponibilité (baleines qui ne peuvent être observés parce qu'elles sont sous l'eau lors du passage de l'aéronef) 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 baleines boréales dans la zone du relevé en août.

Le relevé a atteint une couverture complète des principales zones de regroupement estival, comme l'inlet Prince-Régent, le golfe de Boothia, l'inlet de l'Amirauté, le détroit d'Eclipse, la baie Isabella et la baie Cumberland. Cependant, le détroit de Fury and Hecla, le nord du bassin Foxe et le détroit de Roes Welcome n'ont pu être couverts. L'estimation de l'abondance entièrement corrigée était de 6 446 (coefficient de variation [CV] de 26 %) pour la population de baleines boréales de l'est du Canada et de l'ouest du Groenland. Le niveau élevé de regroupement observé dans plusieurs zones, en particulier dans la baie Isabella et la baie Cumberland, a donné lieu à des sources d'incertitude. Selon cette estimation de l'abondance et un facteur de récupération de 0,5 dans le calcul du prélèvement biologique potentiel, la population de baleine boréale de l'est du Canada et de l'ouest du Groenland peut subir une mortalité anthropique totale de 52 individus par année.

INTRODUCTION

Bowhead whales (*Balaena mysticetus*) are ice-associated baleen whales with a nearly circumpolar Arctic distribution. Subsistence hunts for bowhead whales are an important part of Inuit culture (Priest and Usher 2004). Two populations were initially recognized in the eastern Canadian Arctic: one in Hudson Bay-Foxe Basin and the other in Baffin Bay-Davis Strait. However, evidence from genetics and satellite telemetry studies (Postma et al. 2006; Dueck et al. 2006) suggested that bowhead whales from the Eastern Canadian Arctic were part of a single population that is shared with West Greenland.

This single Eastern Canada–West Greenland (EC-WG) population was historically overharvested by commercial whalers (Higdon 2010) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recommended in 2009 that it be listed as a Species of Special Concern under the *Species at Risk Act*. A limited subsistence hunt resumed in the Nunavut Settlement Area in 1996 and in the Nunavik Marine Region in 2008. These hunts are co-managed by the Nunavut Wildlife Management Board, the Nunavik Marine Region Wildlife Board and Fisheries and Oceans Canada (DFO).

Sustainable management of the population relies on up-to-date abundance estimates and the prediction of future trends under various scenarios. In 1981, aerial surveys of EC-WG winter range estimated population abundance at 1,349 (95% Confidence Intervall [CI] 402-4,529, Koski et al. 2006). Aerial surveys were also conducted in 2002, 2003 and 2004, although under a multi-year survey design because two separate populations of eastern Arctic bowhead whales were still recognized at the time. Following the re-assessment as a single population, a series of estimates have resulted from re-analysis of the 2002 aerial surveys using newly developed statistical analysis techniques: 14,400 according to Dueck et al. (2008), 8,187 in Heide-Jørgensen et al. (2008), and 6,344 in Givens et al. (2009). Although relatively imprecise, all of these estimates indicate that the EC-WG population has increased significantly since bowhead whales were first protected from commercial whaling in the first half of the 20th century.

No aerial surveys have covered the full extent of bowhead whale summer distribution in the Eastern Canadian Arctic in a single year. DFO was planning to conduct the High Arctic Cetacean Survey (HACS) in August 2013 to update abundance estimates for known stocks of Baffin Bay narwhal (*Monodon monoceros*). The summer distribution range of narwhals overlaps to great extent with that of EC-WG bowhead whales, and survey methodology (e.g., aircraft altitude) is similar for both species. Therefore, the survey area was expanded to include the summer range of bowhead whales. This document presents the results of the survey and new abundance estimates for the EC-WG bowhead population, as well as an updated Potential Biological Removal (PBR) estimate, which is necessary for management advice.

METHODS

STUDY AREA AND SURVEY TIMING

The objective of HACS was to cover the entire summering range of both Canadian Baffin Bay narwhal stocks and EC-WG bowhead whales. The extent of the study area was based on previous aerial surveys and telemetry tracking studies of both species (Figure 1), reports of traditional knowledge and recent observations by Inuit hunters.

The priority areas for bowhead whales were identified as Prince Regent Inlet, Gulf of Boothia, Northern Foxe Basin, Admiralty Inlet, the eastern coast of Baffin Island (including fiords) and

Cumberland Sound. Additional coverage was desirable in Roes Welcome Sound, Barrow Strait, Lancaster Sound and Eclipse Sound.

Dates for the survey were established based on the short window of relatively ice-free waters in the Arctic Archipelago and the timing of narwhals and bowhead whales aggregating on their summering grounds. The best time was determined to be August, when telemetry studies have shown that whales make limited movements within their main summering aggregation areas and the weather is also most favorable. Using three aircraft allowed the entire survey area to be covered in a relatively short period of time, which should have limited the risk of bias due to potential directed movements of animals within and between survey areas.

SURVEY DESIGN

The survey was designed to cover the largest possible proportion of the population’s summering range (Figure 2) while at the same time improving on the precision of past surveys, which required coverage at a higher intensity. The resulting design reflects constraints imposed by the dual objectives of estimating narwhal and bowhead abundance. In order to minimize the sampling variance, we stratified the study area based on geographic boundaries as well as presumed densities of narwhals and bowhead whales (Figure 2). For instance, a high-density area was identified in the central portion of Cumberland Sound based on telemetry data and Inuit traditional knowledge.

Transect design was performed in Distance (version 6.1, Thomas et al. 2010), using precise coastline shapefiles. Projection for each stratum was selected to minimize distortions of area using Young’s rule (Maling 1992). 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 bowhead whales and narwhals were covered with equally spaced zigzag transects (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, especially between long ones). 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 areas in order of priority for narwhal stocks, which placed some bowhead strata among the first to be surveyed (e.g., Prince Regent Inlet, Gulf of Boothia), while other areas were planned for the end of the survey period (e.g., Cumberland Sound, Roes Welcome Sound). In an effort to avoid the effect of potential directed movements of whales within areas, attempts were made to survey 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 Prince Regent Inlet in the first few days of the survey. When the Prince Regent Inlet, Peel Sound and the northern strata around Ellesmere Island were completed, each plane then deployed north, east and west of Baffin Island, respectively.

Bowhead whales and narwhals are often encountered in fiords during the summer. It is difficult to obtain correct density estimates in fiords 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 (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. A large belly window was used for a pair of high-resolution digital SLR cameras (see below). An observer was stationed at each of the rear and front 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 Program 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 whales (“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) if time permitted. Position and altitude of the aircraft were recorded every 2 seconds using a GPS connected to a laptop running a 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 (four 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 widthwise (long side perpendicular to the track line), at an angle of 27 degrees. 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. Whale 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. If a visual sighting could be identified without ambiguity on the corresponding photo, then the perpendicular distance was retrieved from the pixel position of the sighting on the 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 mean group size).

DATA ANALYSIS

Statistical Framework

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

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

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:

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

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

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

and

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

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):

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

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 do not detect some of the whales visible at the surface. 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 each 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). 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. (2010) 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 (Laake et al. 2014) in R (R Core Team, 2014). 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 used to estimate density and abundance in all non-fiord strata. Detection distance in fiords is often truncated by the shoreline, and therefore should not be pooled with sightings from open areas. Preliminary data examination confirmed that detection distances were lower on average in fiords, and thus the data were dealt with separately.

The analyses were performed on the perpendicular distances of all 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 left and right truncations. 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 ice cover, cloud cover, sea state and glare (Marques et al. 2007).

Because observers were instructed to give priority to group size estimation, some observations were lacking a perpendicular distance measurement (usually when high densities of whales 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 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.

Encounter Rates

The number of unique sightings of bowhead groups 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). Briefly, 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.

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.

DSMs are typically fitted with thin-plate regression splines (Wood 2003). However, previous work has highlighted that in some cases, the fitted surface tends to increase unrealistically as predictions are made further away from the locations of survey effort (Miller et al. 2013a). This problem can be alleviated using a generalization of thin plate regression splines called Duchon splines (Miller and Wood 2014). Problems can also occur when smoothing over areas with complicated boundaries (Wood 2008). If two parts of the study area are linked by the model without taking into account obstacles, then some boundaries (e.g., peninsula, island) can be "smoothed across". Therefore, we also fitted a "soap film" smoother (Wood 2008), which usually performs better for complex study regions by reducing smoothing of density contours across land boundaries and minimizes edge effects. The soap film is a bivariate smooth of spatial coordinates only and cannot include covariates such as distance to mouth and to shore.

We fitted models with and without covariates, for each of the three types of spatial smoothers, in the package *dsm* (Miller et al. 2013b), available within the R software (R Core Team 2014). There were two levels of model selection. Within each model, flexibility (estimated degrees of freedom) and removal of model terms were based on functions from the *mgcv* package (Wood 2001), which uses restricted maximum likelihood to choose a statistically defensible degree of smoothing, with penalties for unnecessary flexibility. Then, the best model (choice of smoother and covariates) was selected based on AIC.

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. Previous research on narwhals has suggested that they can be seen and identified to species at a depth of ~2 m at an altitude of 990 m in clear water (Richard et al. 1994). However, there is no experimental evidence to suggest how deep a bowhead whale can be detected from an aircraft. This makes it difficult to determine which depth bins to use to calculate an instantaneous availability bias correction factor. In previous studies, it was assumed that bowhead whales could be seen and identified down to 4 m below the sea surface. Here, to account for this uncertainty, we have combined multiple depth bins (0-2, 0-4 and 0-6 m bins), giving equal weight to each possibility.

The correction factor for availability bias when sightings are instantaneous is given by $C_I = 1/P_a$, where P_a is the proportion of time spent by whales in the combined 0-2, 0-4 and 0-6 m bins. Watt et al. (2015) have analyzed data from, 22 bowhead whales fitted with satellite-linked time depth recorders near the communities of Igloolik and Pangnirtung, for which data were available at the time of HACS, i.e., during August 2013. These instrumented whales were assumed representative of the population surveyed and of their behaviour during the survey period, and therefore we used correction factors that were specific to the geographic location of each stratum and to the period during which it was surveyed.

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

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

Total Abundance Estimate And Recommended Total Allowable Landed Catch

Total abundance was calculated by summing the estimated corrected abundances of all strata, including any fiord stratum. Variance for the population-wide abundance estimate was calculated by adding the variances of each stratum.

When there is insufficient information for a full stock assessment, a conservative mathematical approach is used to recommend sustainable harvest levels for marine mammals (Hammill and Stenson 2007). The Potential Biological Removal (PBR, Wade 1998) determines the maximum level of human-caused mortality (e.g., hunting mortality, hunting loss, ship strikes, net entanglements) from a population. As long as total human-caused mortality is less than the PBR value, population abundance is expected to remain stable or to increase. The PBR is calculated as:

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

Where 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 *Fr* is the recovery factor, which is usually set to 0.1 for stocks listed as endangered, 0.5 for those that are threatened or depleted and 1.0 for healthy stocks (Wade 1998). In previous science advice, DFO has cautioned that, given the high level of uncertainty with the current and historical population estimates, a high level of risk avoidance (i.e., $F_r = 0.1$) should be considered for the management of this population until it could be demonstrated that a higher recovery factor was warranted. Currently, there is accumulating evidence that makes it possible to use a higher recovery factor in the PBR calculation for the EC-WG bowhead whale population. Given that our knowledge of current population size is still only based on few surveys over a 34 year period, and that we are uncertain about the size of the EC-WG bowhead whale population prior to commercial whaling, we used a recovery factor of 0.5 in the PBR calculation.

RESULTS

SURVEY COVERAGE AND BOWHEAD 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 or partially covered with ice (e.g., Lancaster Sound, Barrow Strait). 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 d for about 40% of the time (Table 1). Weather conditions deteriorated substantially towards the end of the survey period and not all planned areas could be covered.

By using all three aircraft simultaneously, Prince Regent Inlet was surveyed in a single day. The Gulf of Boothia was covered a week later over a 2-day period (Figure 3). Numerous bowhead sightings were made in these strata. However, Fury and Hecla Strait, Northern Foxe Basin and Roes Welcome Sound could not be covered. Admiralty Inlet was surveyed in two days, with a 4-day break in between due to bad weather (Figure 4). Bowhead whales were sighted in the southern part of the inlet. Eclipse Sound was covered immediately afterwards, in two successive days. The eastern coast of Baffin Island was surveyed by one aircraft over a 2-week period (Figure 5). Strong winds made it difficult to survey the offshore portion of the area and numerous attempts were necessary. In the end, all planned fiords except one and about 90% of the planned transect lines were surveyed. Large numbers of bowhead whales were sighted in Isabella Bay.

Overall, there were 242 sightings of bowhead groups (Figure 6), of which 56 were made in fiord strata and 186 outside fiords. Of these, only one was missing group size information altogether, but 44 sightings were coded as “uncertain” for group size. Also, 10 sightings were coded as “uncertain” for perpendicular distance. After applying the methods described in Pike and Doniol-Valcroze (2015) to identify duplicate sightings between observers 1 and 2, there were 128 unique sightings in non-fiord strata.

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 2400 m, which left 117 observations. The shape of the histogram suggested that there was no need for left-truncation. Model selection was performed on the three key functions and all the combinations of environmental covariates. The model with the lowest AIC was one with a half-normal key function with no adjustment series and covariate “cloud cover” (Figure 7). This resulted in an average probability of detection g(x) = 0.52 and an ESHW of 1,256 m (CV 7.8%).

MARK RECAPTURE MODEL

Selection among MR models was performed on all the combinations of environmental covariates as well as covariates “observer” and “side of plane”. The lowest AIC was a model with covariate “cloud cover” in the DS model and no covariates in the MR model (Figure 8). It resulted in a p(0) for both observers 1 and 2 of 0.83, and a combined p(0) of 0.97 (CV 1.6%).

The overall probability of detecting a bowhead cluster between the track line and a distance of 2400 m was $g(x) \cdot p(0) = 0.51$ (CV 7.9%).

ENCOUNTER RATES AND GROUP SIZE

Encounter rates per stratum were variable among strata (Table 2), with the highest rate observed in the high-density stratum of Cumberland Sound. The majority of bowhead whales sighted were single (79%), with 19% of pairs and only 2% of groups of three or four individuals (Figure 9). Overall, there was no significant relationship between the probability of detection g(x) and the natural log of cluster size Ln(s) and mean group size was used in producing abundance estimates (Table 2). The global average group size of sightings within truncation distances was 1.22 (CV 3.7%).

FIORD ANALYSIS (ISABELLA BAY)

Sampling coverage and sightings

As scheduled, all fiords in Admiralty Inlet and Eclipse Sound were surveyed. In the East Baffin Island fiord stratum, we selected 10 fiords out of 54, and were able to survey 9 of these. Among all fiord strata, 39 bowhead groups were sighted in Isabella Bay (i.e., East Baffin PSU 14), resulting in 24 unique sightings for a total of 38 individuals. No sightings were made in any of the other fiords.

Detection function model

Right-truncation at 1400 m removed one distant sighting and left 23 unique sightings. Left truncation was not used. We fitted MCDS models to the data with different key functions, with and without covariates. The model that best fitted the data was a hazard-rate key function with no covariates (Figure 10a); p(x) was estimated at 0.62 and the effective strip half-width was 864 m (CV 18.5%). Mean group size in Isabella Bay was 1.61 (CV 22%), with a larger proportion of pairs and trios than in non-fiord strata (Figure 10b), and a gathering of 9 whales that were apparently feeding in close proximity to one another.

Spatial model

Spatial models were fitted for Isabella Bay, the only fiord in which bowhead observations were made. Model selection showed that a soap filter with no covariate and a negative binomial distribution provided the best fit to the counts-per-segment. The resulting density surface (Figure 11) shows how the soap filter prevented “leakage” of density gradients across islands and land boundaries, thus handling well the complex shape of this fiord.

The surface density was integrated to yield a surface abundance estimate of 128 bowhead whales within Isabella Bay (CV 57.7%, of which 10% originate from the variance in the detection function and 90% are due to the variance in the GAM). When extrapolated to unsurveyed fiords along East Baffin Island, the stratum estimate was 284 (CV 69.4%).

AVAILABILITY CORRECTION

Based on the results of Watt et al. (2015) and on the timing of bowhead sightings in each stratum, we used correction factors of 4.05 (± 0.838) in Prince Regent Inlet, 3.44 (± 0.838) in the Gulf of Boothia, 4.12 (± 0.766) in East Baffin Island fiords, 3.98 (± 0.840) in Admiralty Inlet, Eclipse Sound and the offshore area of East Baffin Island, and 5.68 (± 0.533) in Cumberland Sound.

ABUNDANCE ESTIMATES

Estimates of abundance (surface and corrected) for each stratum are given in Table 2. Total corrected abundance for the EC-WG population was estimated at 6,446 bowhead whales (CV 26.4%). This yields a $\widehat{N}_{min}$ of 5,182 and a PBR of 52 with a recovery factor of F_r = 0.5.

DISCUSSION

One of the objectives of the 2013 High Arctic Cetacean Survey was to provide an updated abundance estimate for the EC-WG bowhead whale population, based on complete coverage of its summering range. Due to unfavorable weather conditions, it was not possible to survey all of the planned areas. However, the survey achieved complete coverage of important summer aggregation areas like Prince Regent Inlet, Gulf of Boothia, Admiralty Inlet, Eclipse Sound, Isabella Bay and Cumberland Sound. It was the first time that all of these areas were surveyed in a single year, which resulted in a fully corrected estimate of 6,446 bowhead whales (95% CI 3,722–11,200). This was made possible by 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.

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. We have attempted to sample the entire area known to be used by EC-WG bowhead whales in summer based on traditional knowledge and telemetry studies. The lack of coverage of Northern Foxe Basin and Fury and Hecla Straits, which are considered important aggregation areas for bowheads in August, and to a lesser extent Repulse Bay and Lancaster Sound, is likely the most significant source of negative bias in our final estimate. However, information from concurrent satellite tracking of 11 individuals suggests that most bowhead whales were within the survey area during August 2013 (particularly in the Gulf of Boothia and Cumberland Sound), and only a small proportion of them were in Northern Foxe Basin, and Fury and Hecla Strait. Despite its incomplete coverage, this population estimate is similar to most previous estimates based on the 2002, 2003 and 2004 partial surveys of the population's range, and in particular with the latest accepted (incomplete) estimate of 6,344 (Givens et al. 2009). With a CV of 26%, the HACS survey is the most precise of the time series of estimates, which is due to a higher number of bowhead sightings and higher coverage intensity (i.e., line spacing).

One of the main difference between the HACS bowhead data and previous surveys is the high combined probability of detection p(0) of 0.97, whereas previous estimated values were much lower (e.g., 0.34 in Dueck et al. 2008). Our results benefit from a large number of sightings available for MR analysis (223 vs 34 in Dueck et al. 2008), and the probability of detection is consistent across aircraft.

Another source of bias in our estimate comes from the availability correction factor. We have used updated information on diving behaviour from bowhead whales instrumented in areas and at time periods that are representative of the survey coverage. This increases our confidence in the estimated proportion of time that bowhead whales are presumed available to detection by visual observers, P_a. However, there is no experimental evidence to suggest how deep a bowhead whale can be detected from an aircraft. This makes it difficult to determine which depth bins to use to calculate an instantaneous availability bias correction factor. To account for this uncertainty, we have combined multiple depth bins (0-2, 0-4 and 0-6 m bins), giving equal weight to each possibility.

Moreover, $C_I = 1/P_a$ is an appropriate correction factor when sightings are instantaneous (e.g., for photographic surveys. During HACS, visual sightings were not instantaneous and thus the correction factor does not account for the search time available to observers to detect animals, and can positively bias the estimate (McLaren 1961). Ideally, data on the dive cycle of bowhead whales in August in the study area should be used to adjust the availability correction factor for the time in view of bowhead sightings.

Twenty-four bowhead groups (38 individuals) were detected in Isabella Bay, an area known for its large concentration of bowhead whales during the summer. This was the only fiord, and the only area along the eastern coast of Baffin Island, where bowhead whales were observed, which corresponds closely to satellite tracking information. Isabella Bay was treated as a primary sampling unit (PSU) like any other fiord within the design of the survey to estimate narwhal abundance. However, it could be argued that for the specific purpose of estimating bowhead abundance, this area should have been a separate stratum, since few bowhead whales were expected in other East Baffin fiords. Such a stratification scheme would have resulted in a lower CV around the estimate for East Baffin Island, and would have prevented extrapolation of sightings made in Isabella Bay to the rest of the stratum. Such stratification is strongly encouraged for future survey efforts.

Overall, our objective of updating and improving the abundance estimates of the EC-WG bowhead whale population was met, with the 2013 aerial survey abundance estimate indicating that the population can support a maximum human-induced mortality of 52 whales annually across its range from all sources (e.g., Greenland and Canadian harvest, struck and loss, net entanglements, ship collisions). Our analysis benefited from the use of concurrent, long-term tagging projects to improve adjustments for availability bias, and from the use of photographs (to retrieve missing data and provide comparisons to the visual surveys), and was improved as well by implementing new analysis techniques to address specific challenges in the data (e.g., for fiord strata). 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 the survey as observers and in satellite tagging efforts.

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Project lead: Kevin Hedges[1]. Project management: Christine Abraham[2], Steve Ferguson[1] and Mike Hammill[3] 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].

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TABLES

Table 1. 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 2. Survey coverage, sightings, and abundance estimates of bowhead whales by stratum. 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. CV_{Ca}: CV of availability correction factor.

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}	Abundance (corrected)	CV
AIL	4,526	387	18	5	0.0129	0.86	6	1.20	0.17	0.51	0.08	21	0.94	3.98	0.21	82	0.97
CSH	9,100	640	8	70	0.1093	0.46	84	1.20	0.05	0.51	0.08	439	0.48	5.68	0.09	2,495	0.49
CSL	15,029	231	6	1	0.0043	0.52	1	1.00	0.00	0.51	0.08	35	0.53	5.68	0.09	201	0.54
EBO	43,419	1,140	28	11	0.0096	0.65	13	1.18	0.10	0.51	0.08	231	0.68	3.98	0.21	920	0.72
ESL	4,334	335	29	2	0.0060	0.70	2	1.00	0.00	0.51	0.08	8	0.71	3.98	0.21	32	0.74
GB	63,178	1,627	11	8	0.0049	0.40	10	1.25	0.13	0.51	0.08	192	0.51	3.44	0.24	660	0.56
PRI	29,178	1,888	18	20	0.0106	0.21	26	1.30	0.08	0.51	0.08	219	0.29	4.05	0.21	886	0.36
EBF	10,091		9	24								284	0.69	4.12	0.19	1,170	0.72
Total	178,855											**1,429**				**6,446**	**0.26**

FIGURES

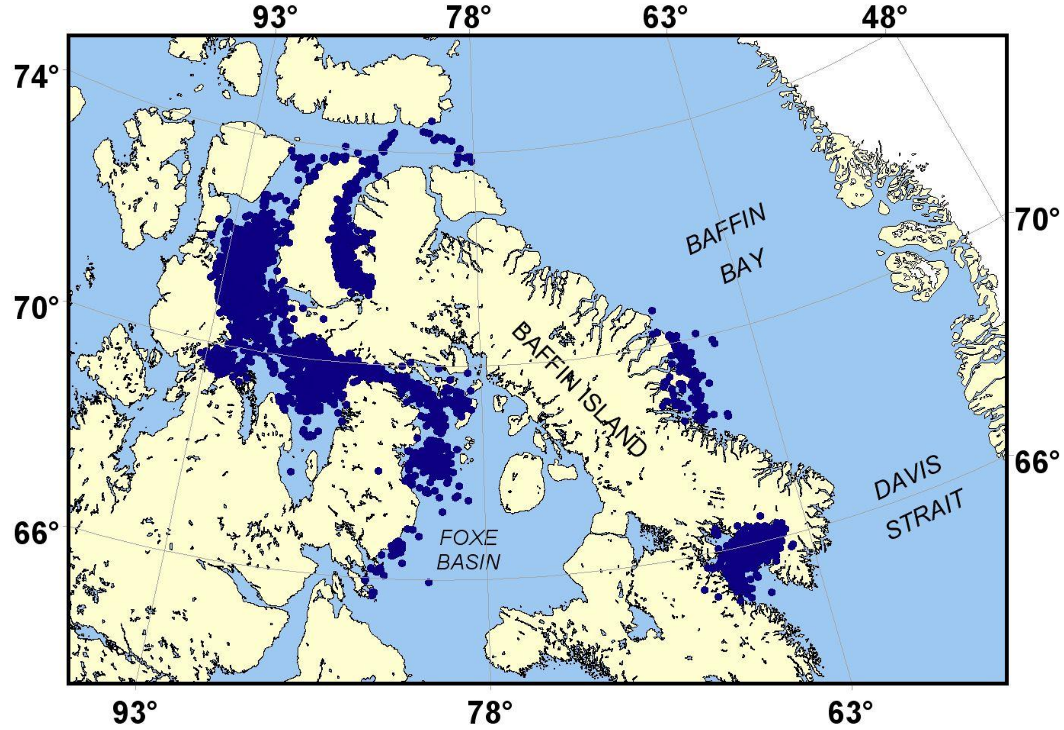


Figure 1. Map showing the locations for the month of August of bowhead whales equipped with satellite transmitters (DFO, unpubl. data). This information was used to define the study area for the 2013 High Arctic Cetacean Survey.

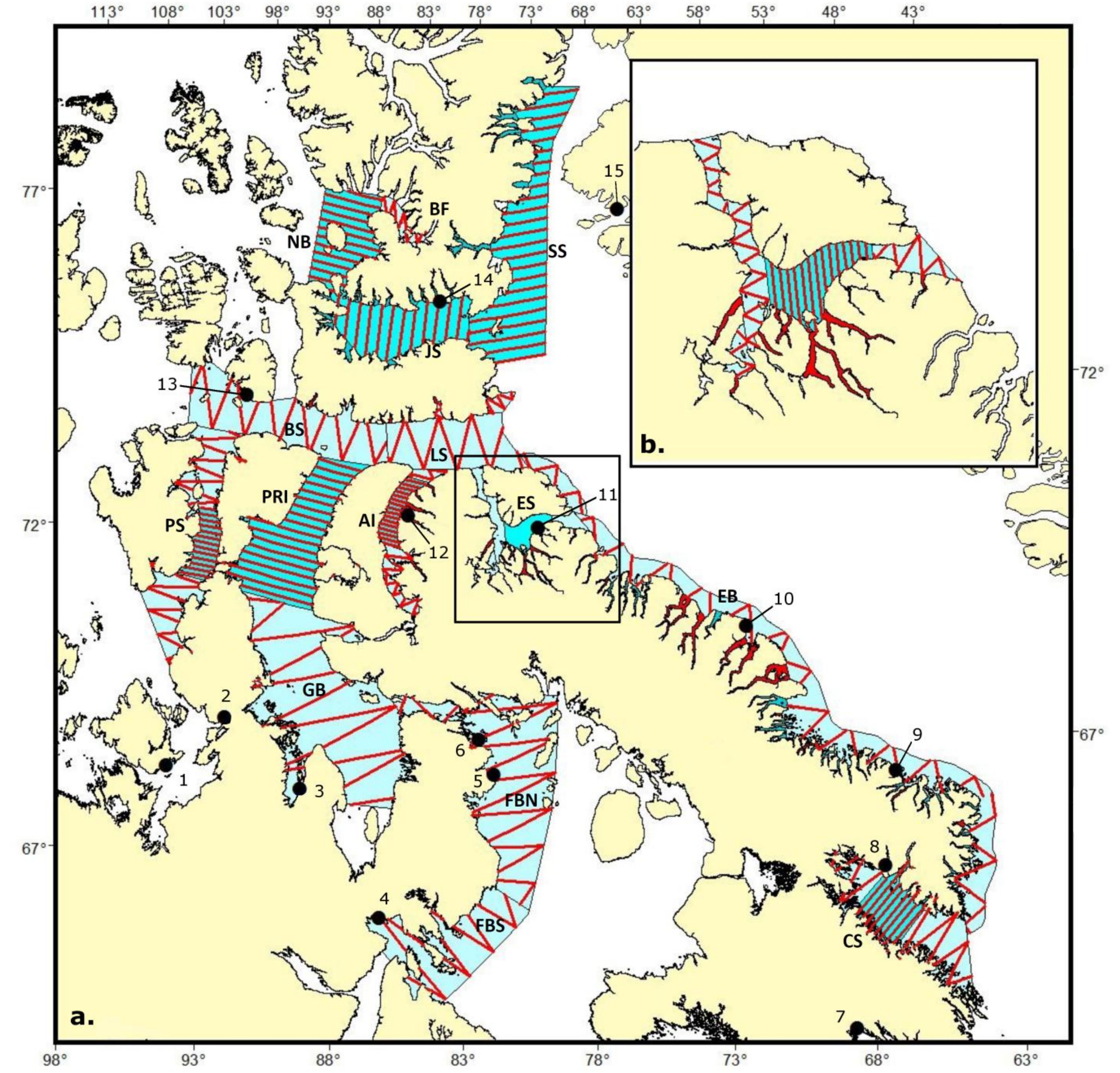


Figure 2. a.) Map of planned survey strata (blue polygons), transect lines (red lines), and fiord strata (red areas). AI: Admiralty Inlet. BF: Baumann Fiord. BS: Barrow Strait. CS: Cumberland Sound. EB: East Baffin. ES: Eclipse Sound. FBN: Foxe Basin North. FBS: Foxe Basin South. GB: Gulf of Boothia. 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).

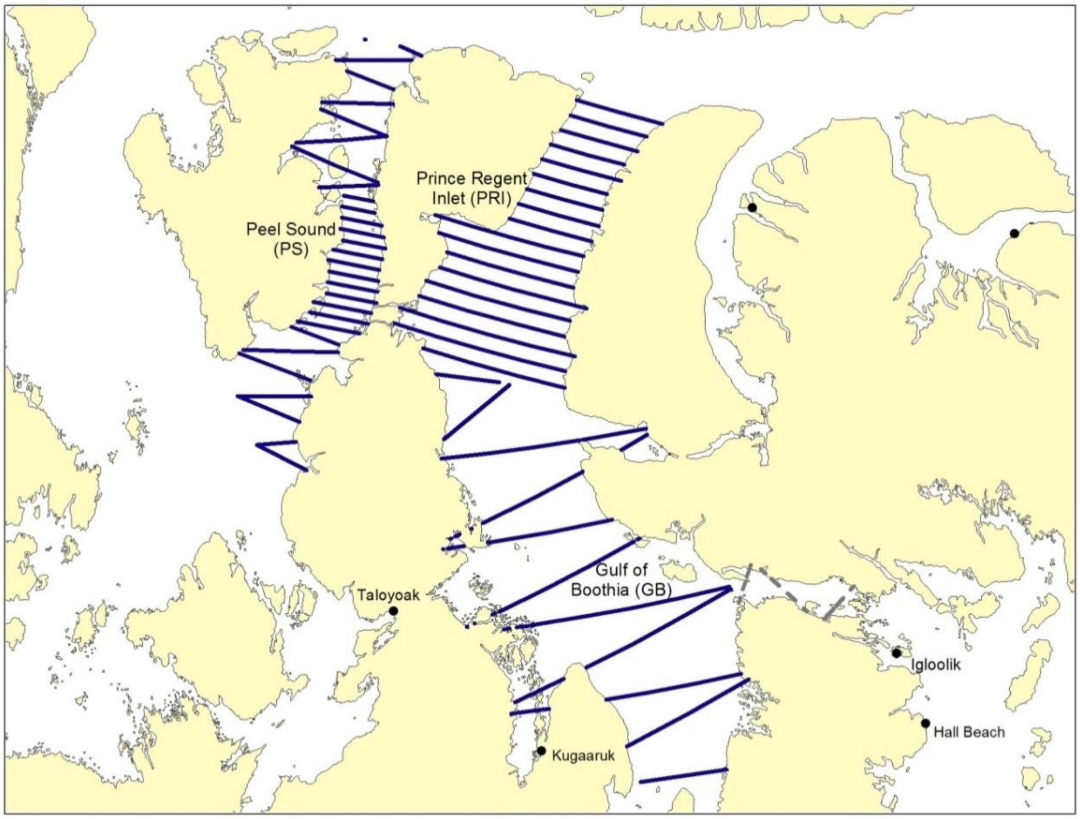


Figure 3. Somerset Island survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

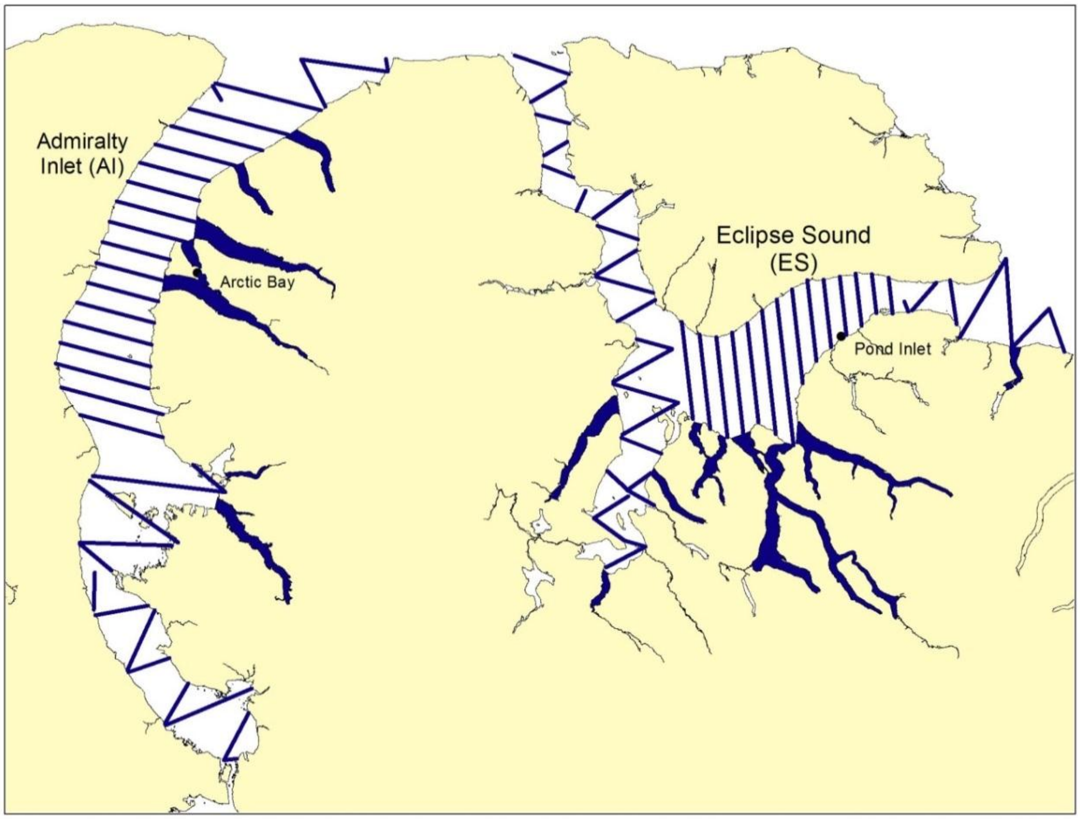


Figure 4. Admiralty Inlet and Eclipse Sound survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

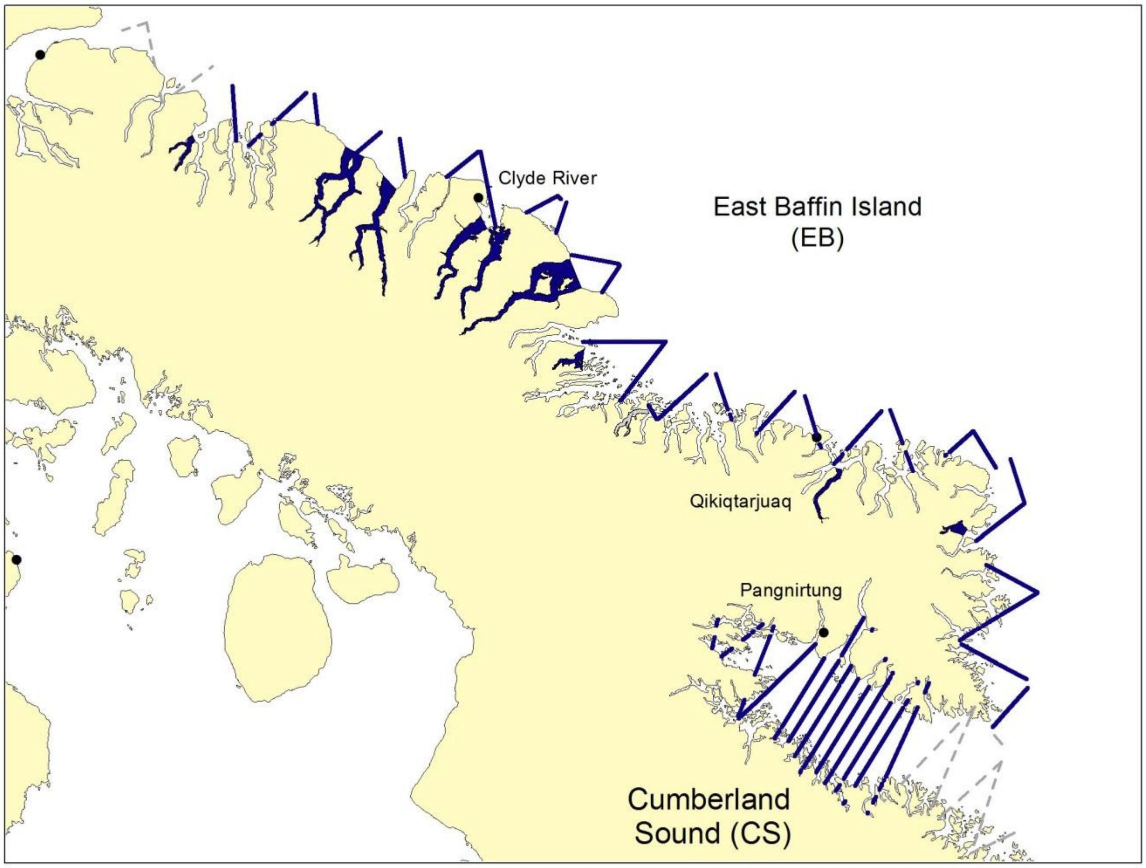


Figure 5. East Baffin Island and Cumberland Sound survey completion. Grey dashed lines: planned transects. Blue lines: surveyed transects. Grey areas: planned fiords. Blue areas: surveyed fiords.

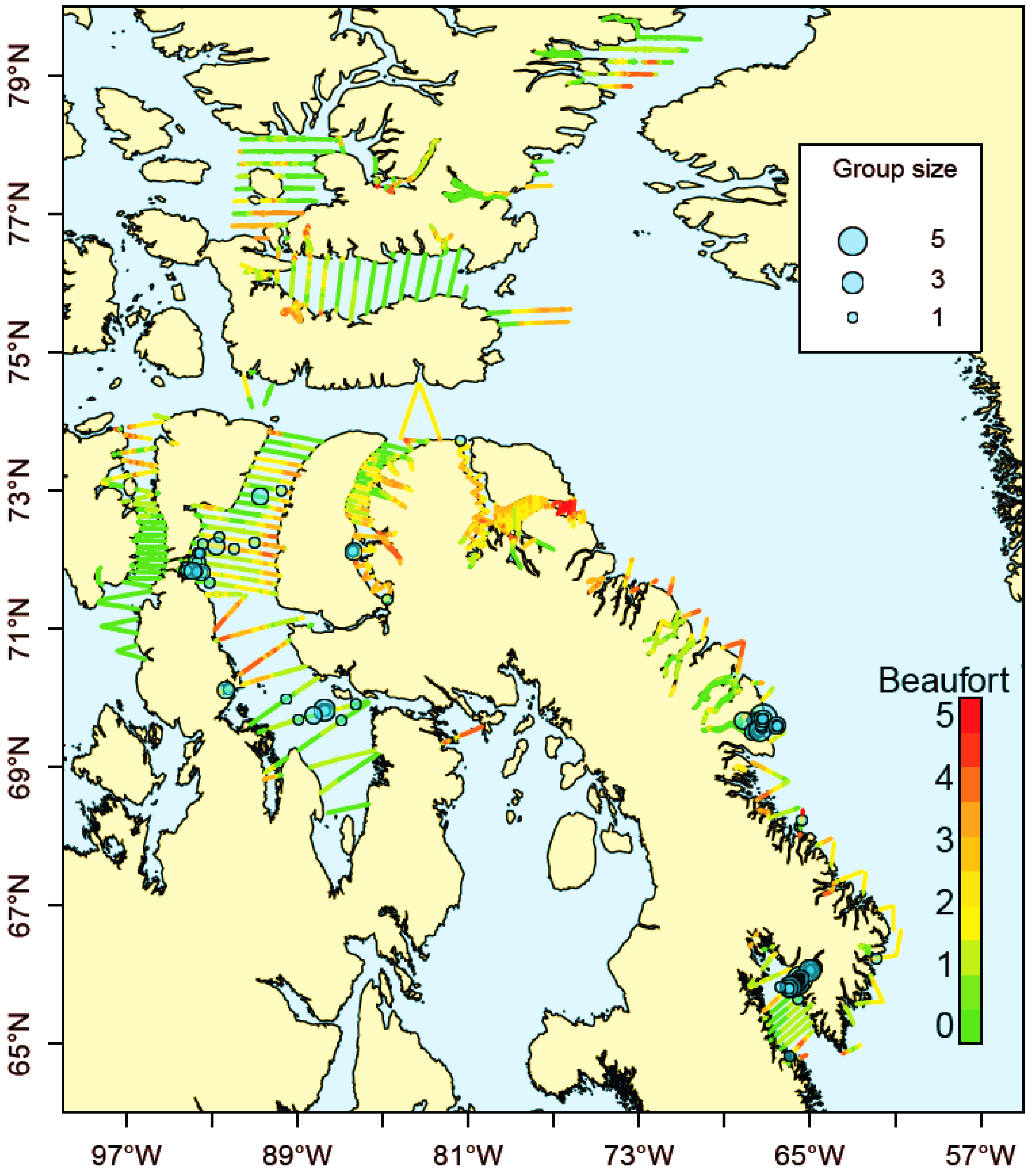


Figure 6. Map of realized survey effort (lines) and bowhead whale groups (blue circles). Color of lines corresponds to Beaufort conditions during survey.

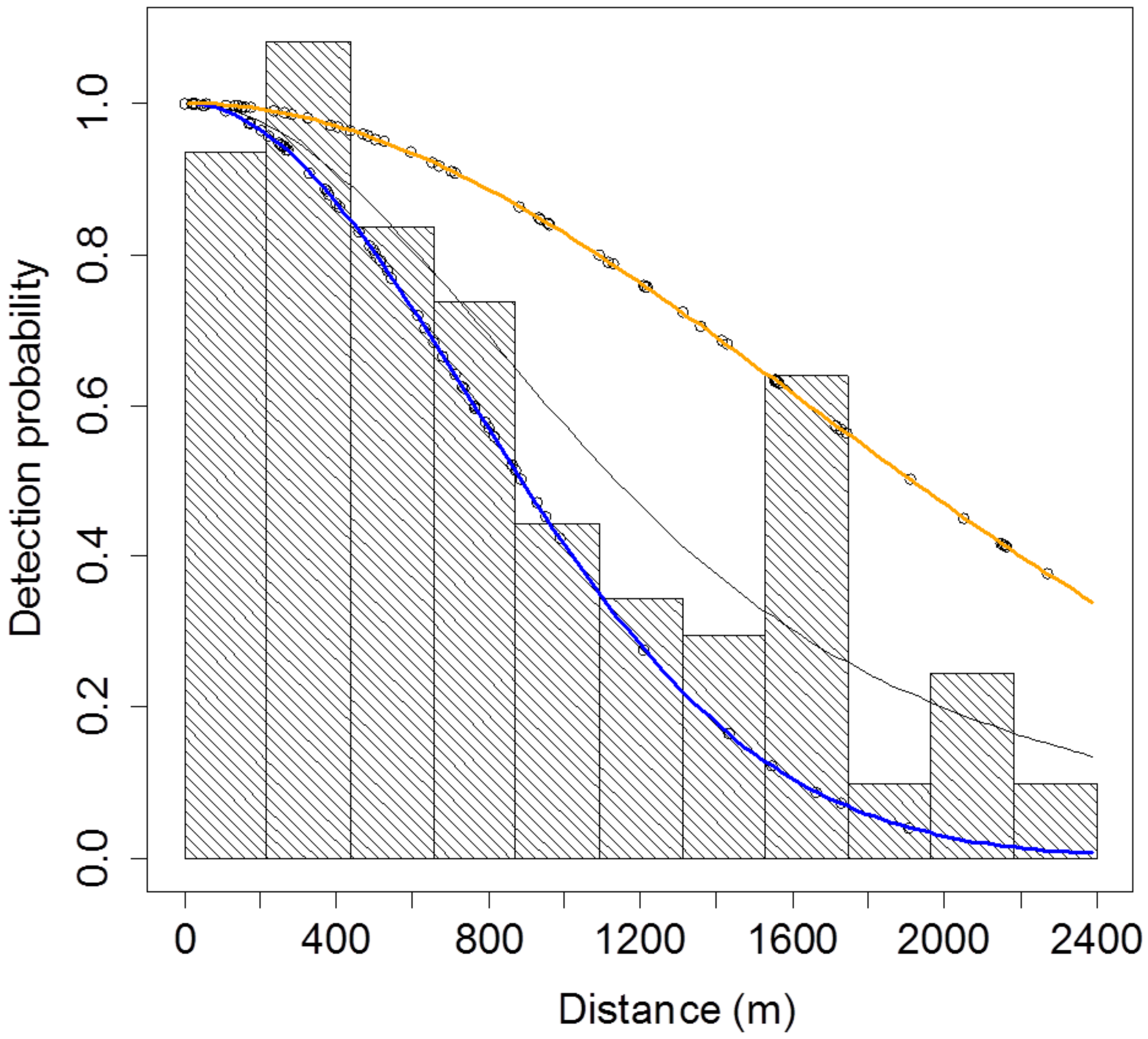
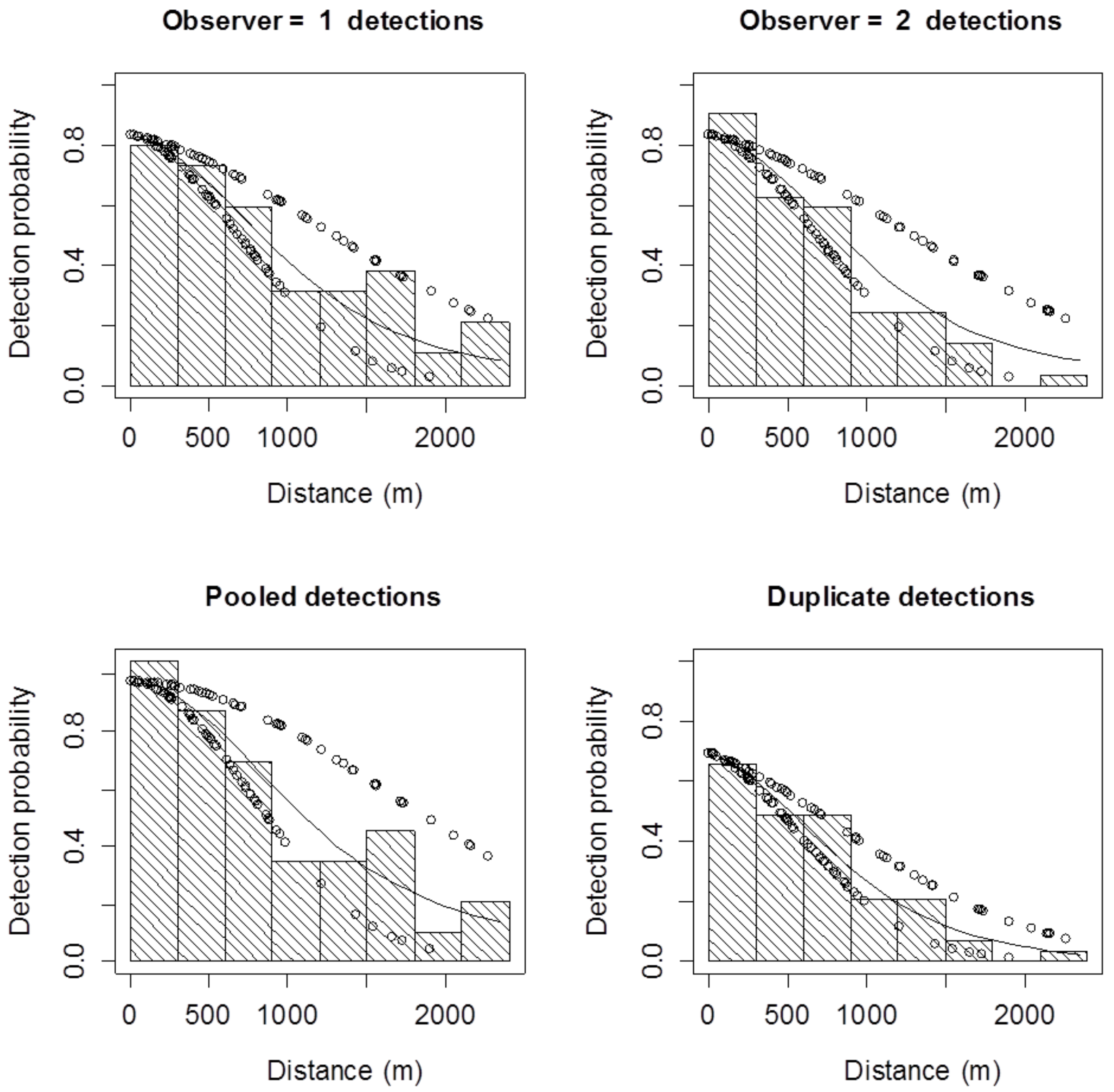


Figure 7. Histogram of perpendicular distances of bowhead whale sightings in all non-fiord strata, with fitted half-normal function after right-truncation at 2400 m. Circles are the probability of detection for each sighting given its perpendicular distance and covariate value "cloud cover". Lines are the fitted model for the average (black), low level of the covariate (blue) and high level of the covariate (orange, cloud cover > 50%).


Observer = 1 detections

Observer = 2 detections

Pooled detections

Duplicate detections

Figure 8. Detection function plots of MRDS analysis assuming point independence between observers. Circles are the probability of detection for each sighting given its perpendicular distance and covariate value “cloud cover”. Lines are the fitted models.

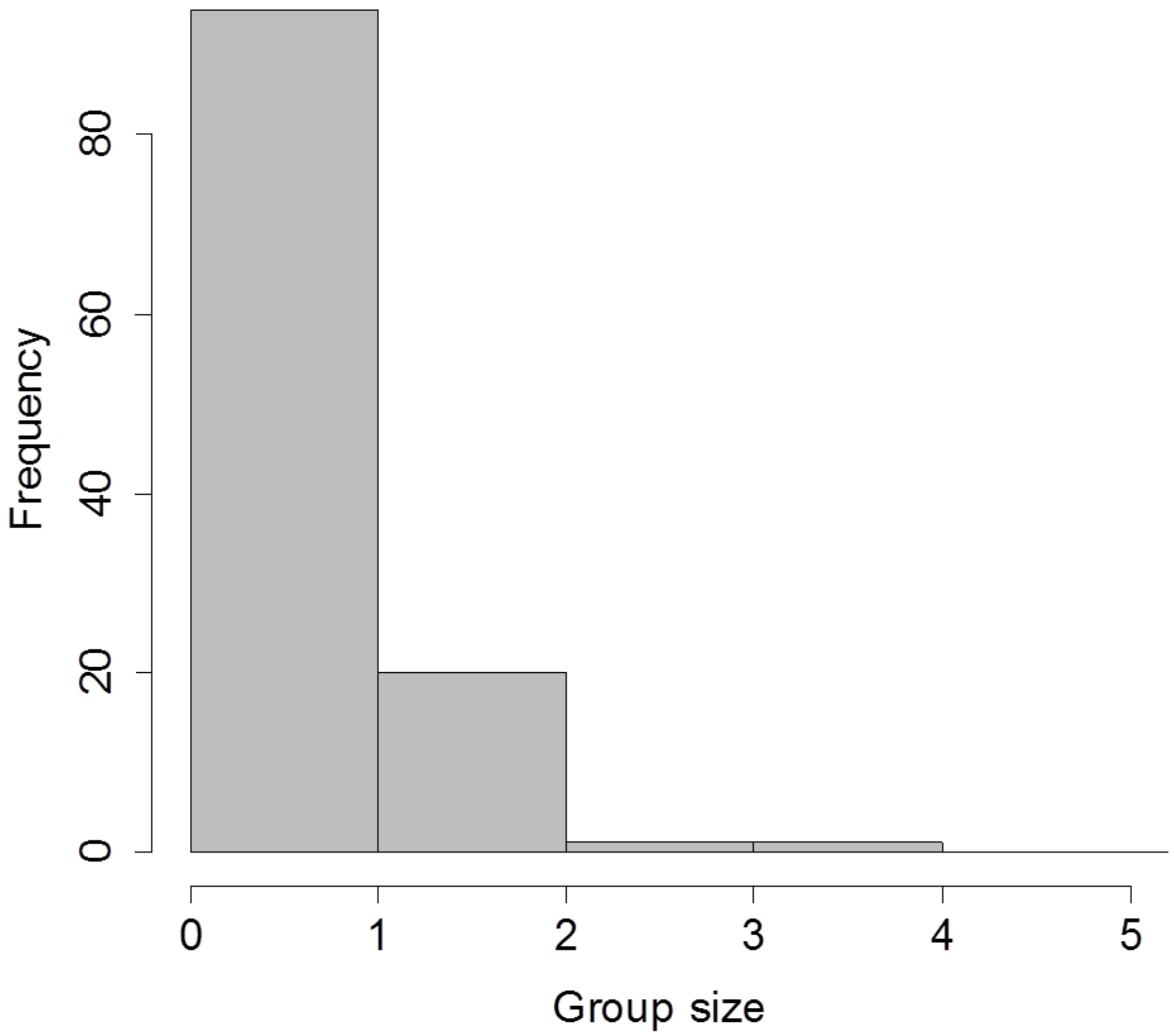


Figure 9. Histogram of group size of 117 unique sightings of bowhead whales within truncation distance (2400 m) in non-fiord strata.

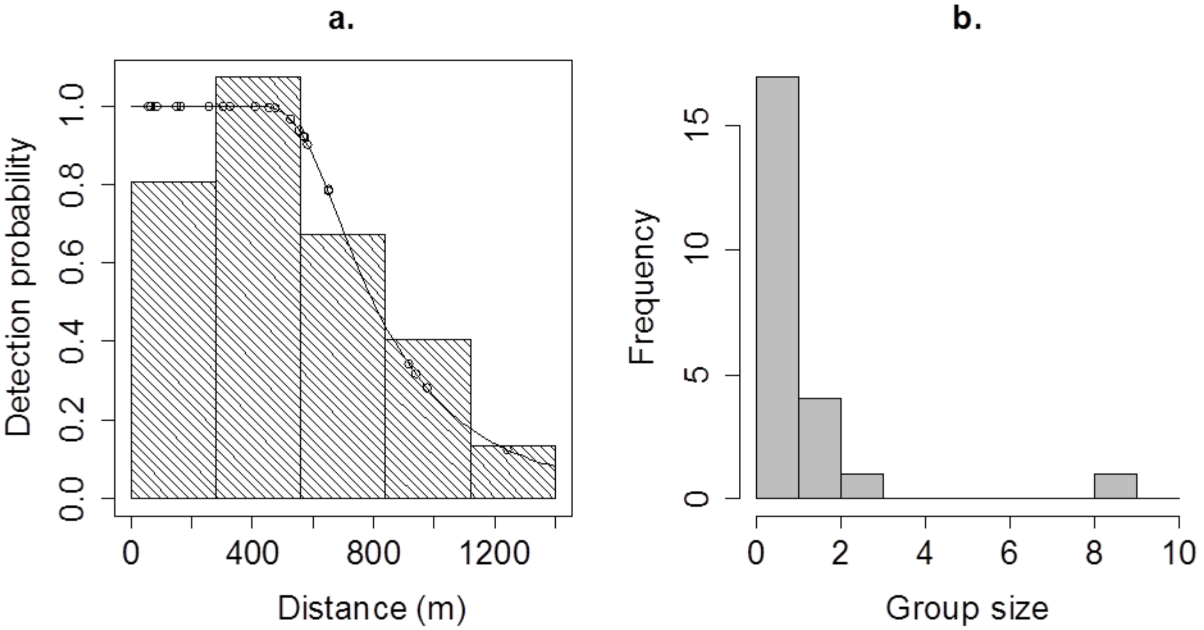


Figure 10. a. Histogram of perpendicular distances of 27 unique sightings of bowhead whales in Isabella Bay, with fitted hazard-rate function after right-truncation at 1400 m (omits a single detection made beyond 1400 m). b. Histogram of group size of 27 unique sightings of bowhead whales within truncation distance in Isabella Bay.

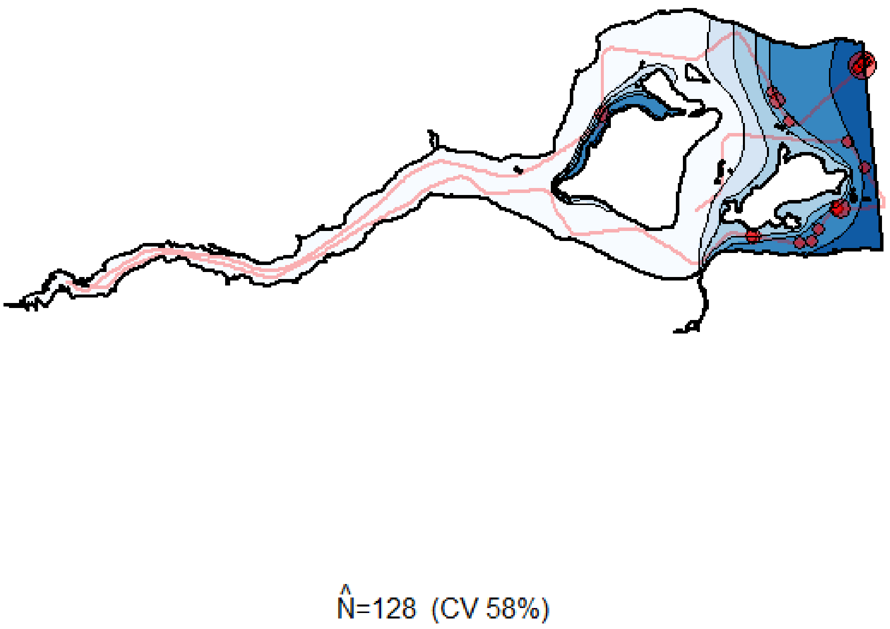


Figure 11. Spatial density surfaces of bowhead abundance in Isabella Bay (PSU14 in the East Baffin Island fiord stratum), using a soap filter. Red line: track of aircraft. Red circles: sightings of bowhead whale groups. Darker shading indicates higher predicted density. $\hat{N}$ *= estimated surface abundance.*