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A review and re-analysis of Cosens *et al.* (2006) aerial survey assessment of bowhead whale abundance for the eastern Canadian Arctic

Examen et nouvelle analyse de l'évaluation par Cosens et coll. (2006) des relevés aériens de l'abondance du stock de baleines boréales de l'est de l'Arctique canadien

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ABSTRACT

A review of Cosens *et al.* (2006) single-platform analysis of double-platform aerial surveys of bowhead whale populations in the Eastern Arctic was conducted. A similar single-platform analysis was conducted with revised data, accounting for errors and certain potential biases in the original analysis. Errors and potential sources of bias in the original analysis included use of off-transect sightings, duplicate sightings, sightings in narrow fiords, sightings with uncertain angle readings, distance calculation errors, and poorly fitting detection functions. A reanalysis of the single-platform approach, using a global detection function, resulted in about half the numbers estimated by Cosens *et al*. Supplementary analyses were conducted, including double-platform mark-recapture distance sampling with covariates, to account for perception bias and variables that influence sighting detectability with distance. Recapture rate was low, demonstrating the likelihood that observers missed significant numbers of animals that were available to be seen. Ice was the only covariate to improve the fit of the detection function. The double-platform analysis resulted in an estimate nearly twice that estimated by Cosens *et al.* single platform method. The results of the double-platform approach suggest that there is a sizeable bowhead whale population, but large confidence intervals reflect the uncertainties due to small sample size in sightings, mark-recapture and dive behaviour, and the compounding of these uncertainties when used to correct for detection probability, missed animals, and availability bias. Potential biases in both directions are discussed.

RÉSUMÉ

Un examen de l’analyse par plateforme unique réalisée par Cosens et coll. (2006) des relevés aériens à double plateforme des populations de baleines boréales de l’est de l’Arctique canadien a été effectué. Une analyse à plateforme unique similaire a été réalisée à partir de données révisées, en tenant compte des corrections à apporter aux erreurs et biais de l’analyse originale. Parmi les erreurs et sources potentielles de biais de l’analyse originale figuraient les observations hors transect, les doubles observations, les observations dans les fjords étroits, les observations avec une lecture d’angle incertaine, les erreurs de calcul des distances et les mécanismes de détection peu adaptés. Les résultats de la nouvelle analyse à plateforme unique, s’appuyant sur une capacité de détection globale, se sont chiffrés à la moitié environ des estimations de Cosens et coll. Certaines analyses supplémentaires ont été réalisées, notamment un échantillonnage à double plateforme par marquage-recapture selon la distance avec covariables, de façon à tenir compte des erreurs de perception et des variables susceptibles d’avoir influé sur les observations à certaines distances. Le faible taux de recapture a révélé la possibilité qu’un nombre important d’animaux aient échappé aux observateurs. La glace était la seule covariable pouvant améliorer la capacité de détection. L’évaluation résultant de l’analyse à double plateforme s’est élevée à près du double de celle obtenue par la méthode à plateforme unique de Cosens et coll. Les résultats de l’approche à double plateforme laissent croire à une population appréciable de baleines boréales, mais la largeur des intervalles de confiance témoigne de l’incertitude résultant de la taille limitée des échantillons lors des observations, des activités de marquage-recapture, de l’observation des comportements de plongée, ainsi que l’effet combiné de ces incertitudes lorsqu’elles sont utilisées comme facteurs de correction du calcul de la probabilité de détection et du nombre d’animaux non repérés, ainsi que des biais de disponibilité. Les biais potentiels dans les deux directions sont examinés.

INTRODUCTION

Bowhead whale aerial surveys of the eastern Canadian Arctic were conducted between 2002 and 2004, as part of a major assessment of narwhal (*Monodon monoceros)* and bowhead whale (*Balaena mysticetus*) populations (Cosens *et al.* 2006). The surveys were double-observer, line transect surveys, designed to cover what was considered to be the most significant areas of narwhal and bowhead whale summer distribution during optimal summer viewing conditions. The surveys were also designed based on the presumed stock regions at the time, and were intended to cover the survey area sequentially over three years, with the goal of providing individual stock estimates and total population estimates for narwhal and bowhead.

Subsequent to the design and completion of the surveys, evidence for a single stock of bowhead whales was obtained, limiting the possibilities of pooling individual estimates from different regions surveyed in different years. Cosens *et al.* (2006) reported a partial population abundance estimate for bowhead whales from these surveys of 7309 (95% CI: 3161–16900), based on a single platform analysis of pooled sightings. This was considered a partial estimate of the population since it was based on only a segment of the total area, recognizing that a sizeable proportion of bowhead whales were likely distributed outside the survey area.

The new estimate represented a marked increase from previous estimates of only a few hundred animals in the 1970s (Davis and Koski 1980, Finley and Johnston 1977, McLaren and Davis 1982), and provided support to existing Inuit claims that numbers of bowhead whales have increased noticeably over the past decades (NWMB 2000). Although earlier surveys likely underestimated numbers of bowhead, the magnitude of the reported increase and justifies thorough scrutiny of the new estimates. Given that these latest survey estimates were based on relatively few sightings, did not utilize the mark-recapture data, and that certain aspects of the survey design were problematic for analysis, a review of the data and supplementary analysis was considered necessary to evaluate the accuracy and validity of the conclusions of Cosens *et al.* (2006).

This report describes a review of the survey data and the results of a reanalysis. The review entailed a close examination of the raw data for errors in identification of bowhead whales, proper use of duplicate sightings, and distance estimates. The reanalysis elaborates on and uses a different approach in the application of the detection function, additionally incorporates a mark-recapture approach and re-examines the application of availability bias. It discusses survey design issues, potential sources of uncertainty and the direction of potential bias in abundance estimates.

METHODS

Survey Design and Data Collection

The surveys were multi-species, aerial line transect surveys of the eastern high Arctic, conducted in 2002-2004 and designed to cover the most significant areas of known narwhal and bowhead whale distribution. Due to the extent of the total survey area and on the presumption of discrete stocks, segments of the target survey area were designed to be covered by regional surveys in sequential years (Figures 1 and 2). Some areas in the original survey design were not covered, while segments of some areas received coverage in more than one year. Sample coverage was comparable for most survey regions, with transect spacing in open water areas ranging from 23.5 to 33.0 km, except for surveys of eastern Baffin Island, where transect spacing in open water areas was 55.3 km.

Surveys were designed mainly with transect lines perpendicular to the coast. Exceptions to this were in Eclipse Sound where the two transects in the western portion of this stratum were largely parallel to the coast (Figure 1). There were also numerous fiords that were less than 10 km wide (Figures 1 and 2) which were sampled using transects running along the center and following the major axis of the fiord. Ideally, surveys should be designed to survey such areas with transects perpendicular to fiord axis. Due to budget constraints but also topographic considerations (steep high banks which prevent the aircraft from sampling close to the coast when using transects perpendicular to the fiord axis), such survey design was not feasible.

In 2002, surveys were flown in Eclipse Sound, Prince Regent Inlet, Gulf of Boothia and Committee Bay from 5 to 12 August (Figure 3). In 2003, two simultaneous surveys were done. Whales in the southern Gulf of Boothia, the west side of Foxe Basin and northwestern Hudson Bay, were surveyed from 7 to 15 August 2003 (Figure 4). A survey conducted from August 7-17 covered Admiralty Inlet (Figure 4) and the east coast of Baffin Island (Figure 5). In 2004, surveys were conducted in Eclipse Sound, Admiralty Inlet and Barrow Strait.

The aerial surveys were flown using two de Havilland Twin Otter aircraft, from a target altitude of 1100 feet and target flight speed of 120 knots (215 kph). The two aircraft operated in different survey regions. In 2002 and 2003, measures of location and speed (GPS) and altitude (GPS or radar altimeter) were recorded every 1-2 seconds on a data-logging system (Midwest Avionics, Winnipeg) operated by the recorder. In 2004, the altitude was recorded using a GPS linked to an SDGPS for improved 3D precision.

The survey crew consisted of a survey flight recorder with two observers on each side of the aircraft. Standard flat windows with the inner covers removed limited visibility to 70° below horizontal and beyond. Observers were paired (front and rear observers) on each side of the airplane and maintained their seat positions in flight. Observers were acoustically isolated by headphones. Front and back observers were visually isolated by a curtain so rear observers could not be cued by reactions of the front observers when sighting an animal or vice-versa. A Roland multi-channel digital recording system, with a single channel for each observer was used in all three years. Observers recorded when a whale group was first seen, noting the species and number of individuals in the group. The declination angle was recorded using a Suunto clinometer when the group was perpendicular to the aircraft. Front observers, which were the most experienced, made observations on the ice cover (tenths), sea state (Beaufort scale), fog (%), or glare (%) in the front half of their viewing area.

<u>Original Data Analysis and Data Review</u>

Cosens *et al.* defined five survey blocks for analysis, based on the selective pooling of data from seven separate surveys, in an attempt to partially accommodate the low sighting rate. For 2002, the survey blocks consisted of Eclipse Sound, Pond Inlet bays and fiords, and Prince Regent Inlet/Gulf of Boothia. For 2003 the survey blocks were Gulf of

Boothia/Foxe Basin/Hudson Bay and Admiralty Inlet/eastern Baffin Island (see Tables 1 and 2 of Cosens *et al.* 2006).

The surveys were analyzed using distance sampling methods, which employ perpendicular distance measures of animals along a transect line. The analyses were originally run in the software program Distance 4.1 (Research Unit for Wildlife Population Assessment, University of St. Andrews). Distances to sightings in these surveys were derived from aircraft altitude and angle measurements when the target was directly abeam of the aircraft. Numbers of sightings and cluster size are other key components of the analysis. A frequency histogram of distance measures are used to estimate a detection function (describing the tendency to detect fewer animals with increasing distance), which provides an estimate of the proportion of surface animals seen over an effective strip width. Curves to model the detection function are fitted to the frequency distribution of the distances and the model curve with the best fit is selected based primarily on Akaike Information Criteria (AIC). Some further details on the distance analysis approach used in the original analysis are provided by Cosens *et al.* (2006), while general distance methods are described by Buckland *et al.* (2001).

Prior to reanalysis of the data, a review of the raw data and original analyses was conducted. The raw data was reviewed in terms of certainty of sighting/species identification, location of sightings (on or off-transect, in narrow fiords, etc.), and errors in the distance calculations. Some errors and potential sources of bias were found in the original analysis, with regard to certainty of sighting/species identification, use of duplicate sightings, use of off-transect sightings in density estimation, use of sightings in narrow fiords and sightings with uncertain angle measurements in detection function estimation. There were also some errors in distance measurements. The errors and potential biases are described in more detail below. The dataset was corrected prior to reanalysis, by recalculating distance measures and excluding inappropriate data.

In the original analysis, Cosens *et al.* (2006) pooled the sightings of primary and secondary observers on each side of the aircraft and proceeded with a single-platform analysis. The dataset included 54 sightings (not reported), excluding 2 sightings made through the camera hatch in the belly of the aircraft. A total of 45 bowhead whale sightings were ultimately used for analyses of all surveys conducted between 2002 and 2003. The reduction in numbers of sightings was due to application of data truncation criteria during analysis. A single sighting in 2004 surveys of Eclipse Sound was not used for analysis.

Cosens *et al.* pooled sightings for two survey blocks in 2002 to calculate a detection function (n=17 sightings), and post-stratified to calculate estimates for each survey block. The data were left and right truncated at 200 and 1000 m respectively and manual distance intervals were specified at 200 m intervals (not reported). Cosens *et al.* indicated that a hazard rate model was selected to fit the sighting data for the ES/PRI/GoB surveys (see Table 2 of Cosens *et al.* 2006), but a half-normal model was actually employed. The fit of the detection function was not provided in the original paper, but is illustrated in Figure 6-a. An error in the reported cv for effective strip width for 2002 surveys in Table 2 of Cosens *et al.* was also detected (should have read 30%, not 77%).

Separate detection functions were used for each of the 2003 surveys, based on 10 sightings for Gulf of Boothia/Foxe Basin/Hudson Bay (GoB/HB) and 18 sightings for Admiralty Inlet/east Baffin Island (AI/eBI) pooled strata (Table 2 in Cosens *et al.* 2006).

For the AI/eBI, the data were left and right truncated at 200 and 1000 m respectively and manual distance intervals were specified at 200 m intervals (not reported). For the GoB/HB dataset, the data were left and right truncated at 300 and 900 m respectively and manual distance intervals at 300 m intervals were used (not reported). A uniform detection function was applied in both cases and the fit to the data is illustrated in Figure 6-b and 2-c.

Errors or sources of bias were identified involving 16 of the 54 sightings (30% of the original dataset). A few minor and some potentially significant sources of errors and/or bias were found in the original analysis, with regard to sighting identity, use of duplicate sightings, and use of off-transect sightings. These are summarized in Table 2.

Four sightings were made in fiords that were less than 4 km wide. These sightings could bias the detection function with shorter sighting distances since the narrow fiords limit the maximum sighting distance on either side of the aircraft. A bias toward shorter distances would provide a positive bias to density estimates. Therefore these sightings should not be used in the detection function determination. Sightings in fiords greater than 4 km in width were used to estimate the detection function.

Some sighting distances in the original analysis appeared to have been calculated using sighting angle and target aircraft altitude instead of actual altitude for some surveys. New distances were calculated using actual altitude. There were also some minor errors in transect length and area calculations. Table 1 provides a summary of survey area and effort for comparison to Cosens *et al.* (2006). Figure 3-5 illustrate the geographic distribution of corrected sightings.

Due to the problematic nature of the survey design in fiords, and relatively low sighting rates in other survey blocks, estimates of bowhead abundance were restricted to the block with the highest sighting rate Prince Regent Inlet/ Gulf of Boothia and Eclipse Sound.

<u>Data Re-Analysis – Single Platform Approach</u>

Analyses in this review were conducted with Distance 5.0, Release 2.

A single platform survey typically uses sightings from a single “primary” platform (i.e. the primary observers). However, due to the scarcity of sightings in these surveys, the primary and secondary platforms do not appear to provide a reasonable approximation of detection probability with distance when examined individually, whereas the pooled data does (Figure 7). Pooling of data for primary and secondary observers for a single platform analysis approach was thus considered appropriate, given that there was no evidence for an inherent difference in platforms (KS, $p = 0.077$).

Similarly, resolution of detection functions for individual survey blocks was poor (Figure 8). A global detection function based on available non-duplicate sightings from all surveys, was thus considered necessary for reasonable approximation of a detection probability. Sightings with uncertain angle readings and sightings in narrow fiords were excluded from analysis of the detection function.

Left truncation was used to compensate for the lack of visibility beneath the aircraft. Several iterations of trying different values of left truncation suggested that 250 m was the most appropriate value, trimming 5.9% of sightings. Right truncation was also employed to improve the fit of the detection function. Right truncation was set at 1500 m; this trimmed 5.9% of sightings at the far right of the distribution. The model used to fit the data was a half-normal key, with no adjustments (Figure 9), providing a global detection function probability of 0.35 (se = 0.06, df = 33) and an effective strip width (ESW) = 528.1 (se = 89.9).

The global detection function was applied to an analysis of the survey blocks independently to estimate abundance of animals for the survey block and for the survey strata within the survey blocks. The procedure involved sequential filtering of data for the areas of interest and using a multiplier (representing the detection probability and error term for the global detection function) in combination with a uniform detection function model and the same specifications for left and right truncation distances were used (Buckland *et al.* 2001).

<u>Data Re-Analysis – Double-Platform Mark-Recapture Approach</u>

A double platform analysis was conducted using the MRDS engine of Distance 5.1 (Release 2). A background to mark-recapture analysis in distance sampling is provided in Buckland *et al.* (2004). As in the single platform analysis, sightings with uncertain angle readings, off-transect sightings and sightings in narrow fiords were excluded. Duplicate sightings were identified using the following criterion:

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

Sightings were pooled to obtain a global detection function for all surveys and truncation of the distance data was specified as in the single platform analysis. Due to limitations of the MRDS engine, left truncation was performed on the data prior to analysis by subtracting 250 from all distance values. Right truncation was then specified at 1250 m (1500 minus 250).

A multi-covariate approach to mark-recapture analysis was conducted, in which the effect of platform side, observer name, sea state, ice concentration, fog and glare on detection probability was examined and used as appropriate. Each of the covariates was tested individually to examine the effect in comparison to no covariates. The model best describing the observed mark-recapture (MR) data was a logit model with no covariates. None of the covariates lowered the AIC for the MR model.

The shape of the detection function with distance (DS model) was also examined with and without covariates. The shape of the sighting data was best fit by a half-normal model. Observer name, side of aircraft, sea state and ice concentration each individually improved the fit of the DS model, with ice concentration being the most important covariate. The model failed to converge when additional covariates were added as main effects, so the global detection function with a single covariate (ice) in the DS model was used. Figure 10 illustrates the fit of the detection function to the data.

RESULTS

Single Platform Analysis

Encounter rates were highest in the Eclipse Sound and Prince Regent Inlet/Gulf of Boothia survey block with a total of 16 sightings and densities ranging from 0.01 to 0.04 whales/km^2 (Table 1). A summary of the results of the single platform analysis are provided in Table 3. The estimated number of surface animals for Eclipse Sound and Prince Regent Inlet/Gulf of Boothia based on this method was 902 (cv=0.34; 95% CI: 455-1789).

Double Observer (Mark-Recapture) Analysis

A total of 34 sightings were available for mark recapture analysis. The number of sightings seen only by the primary platform was 23, and the number seen only by the secondary platform was 16. Just 5 sightings were seen by both platforms. The probability of detection by a single platform was 0.19 (cv =0.31) and that for both platforms combined was 0.34 (cv=0.28). Plots depicting the sightings by individual and pooled observers are given in Figure 11.

The results of the double-platform mark-recapture analysis are summarized in Table 4. The estimated number of surface animals for Eclipse Sound and Prince Regent Inlet/Gulf of Boothia based on this double platform approach was 3744 (cv=0.46) with 95% CI of 1518-9231.

Availability Bias

The overall weighted mean PTS for the entire active tag period for all four whales was 0.27 (cv = 0.48). When examined on a weekly basis, the weighted mean PTS varied from 0.22 (cv = 0.36, n = 3), to 0.32 (cv = 0.62, n = 3). The maximum value was observed in early July, during the period before breakup. The minimum PTS was observed in late July during the period of peak migration. The average for the week ending 9 August 2003 (the week most representative of the aerial surveys) was 0.26 (cv = 0.39, n = 3). This is only a slight difference relative to the original estimate of instantaneous sightability of 0.25 (cv=0.31).

Correcting for availability bias using the instantaneous correction factor and using the method of Innes *et al.* (2002), the single platform approach provides a partial estimate for the eastern Arctic of 3469 (cv=0.52; 95% CI 1336-9012), based on the results for survey block 1, which included Eclipse Sound and Prince Regent Inlet/Gulf of Boothia. Similarly, the double platform approach provides a partial estimate for the population of 14400 (cv=0.61; 95% CI 4811-43105). A summary of estimates for all survey blocks and strata, corrected for availability bias, are provided for both of the single and double platform analyses in Table 5.

DISCUSSION

Survey Design and Objectives

Assumptions about bowhead stock structure were called into question by new information after the surveys were complete. Thus, the original objectives to obtain separate stock estimates in sequential years and to pool abundance estimates for different survey areas for different years and to obtain a total population estimate could not be fulfilled. The objective to obtain abundance estimates for two stocks was replaced by the objective of obtaining a partial population estimate of the single population bowhead whales, based on the results of surveys in a single year. The highest whale encounter rate occurred in 2002, during a survey of Prince Regent Inlet. Supporting evidence for central Prince Regent Inlet as a significant summering area is provided by the results of tagging work. Dueck *et al.* (2006) documented movement into Prince Regent Inlet by a majority of whales tagged in both Foxe Basin and Cumberland Sound. Thus it is reasonable to take the results of the surveys in this region as those best representing a partial estimate of the population.

However, despite considerable effort, these surveys resulted in a relatively low encounter rate of bowhead whales. In distance sampling, line transect survey design should include 10-20 transects per survey region for reliable estimation of encounter rate, while a minimum of 60-80 observations or sightings are recommended as a guideline for reliable estimation of a detection function. The actual number of sightings required for a reliable estimation of the detection function may be less stringent, depending on the study objectives, the shape of the detection function, or the scale of interest (Buckland *et al.* 2001). In this case, survey effort and design were influenced primarily by extent of the survey area and the budget available. No preliminary estimate of sighting density for bowhead whales was available to aid in survey design.

Surveys of narrow inlets and fiords are problematic in terms of design and analysis. The surveys reported here used transects centrally placed along the main axis of fiords and bays. Ideal survey design would dictate that inlets and fiords be surveyed using shorter transects running perpendicularly to the water body. This provides two advantages over centrally positioned transects running parallel to the water body. It avoids clipping of the observation distance (i.e. when the shoreline is within the detection distance), which can lead to a bias in the estimated detection function (a bias toward shorter sighting distances would lead to positive bias in abundance). It also avoids the possibility of distributional bias of animals within narrow water bodies. Since we chose to use a global detection function, we excluded from this estimation all sightings of animals on fiord transects were the fiord width was less than 4 km. This compensates for the potential bias due to clipping but does not account for potential distributional bias of whales in wider fiords.

Global Detection Function and Mark Recapture

Bias may exist as a result of pooling of sightings to estimate a global detection function and mark-recapture rates. Since detection probability can potentially vary with environmental factors such as sea state or the presence of ice, sightings made in one survey area where environmental factors are different than another region might bias the global detection function when applied to individual survey blocks (Buckland *et al.* 2001). In comparing the histograms of sighting distance for the different survey blocks, it is apparent that the distances in block one are on average shorter than those in block 2, and about the same as those in block 3 (Figure 8). Thus, in terms of the potential effect on block 1 (on which abundance estimates representative of the population are based), the global detection function is biased toward larger sighting distances. This bias in the global detection function is thus likely negative with regard to density and abundance estimates for block 1, given that larger sighting distances would translate to a larger effective strip.

In terms of potential bias on density and abundance as a result of pooling mark-recapture data, the direction of bias is similar to that for the global detection function. The observed recapture rate varied from 0.125 for survey blocks 1 and 2 (2 of 16 and 1 of 8 sightings respectively) to 0.20 for survey block 3 (2 of 10 sightings). The influence of block 3 in the global mark-recapture value results in a higher rate of recaptures and thus a negative bias for density and population estimates with regard to block 1.

Small sample size may be a source of bias. Although the observed distance frequency histogram used in the analysis provides a reasonable fit to a detection function, changes in the number of sightings could significantly alter the shape of the detection function. Similarly, a change in the observed number of recaptures would affect the overall probability of detection significantly. For instance a change in the number of recaptures by one would change the observed recapture rate by about 18%. The direction of these potential biases is unknown.

<u>Availability Bias</u>

Cosens *et al.* (2006) used an estimate of availability bias for these surveys based on data collected by Dueck *et al.* (2005) for four whales instrumented with dive recording tags in 2003. The proportion of time at the surface (PTS) was reported by the tags as the proportion of time spent above 4 m depth during four sequential six-hour periods per day. Data from 269 sample periods were available, spanning the period from early July to mid-August.

Dueck *et al.* (2005) reported the mean and error for PTS summarized by individual, location and time period. In calculating sightability for aerial surveys, Dueck *et al.* (2005) provided estimates of PTS partitioned by weekly periods, by calculating an unweighted mean and error of the average individual PTS for each whale for the given period (Table 3 in Dueck *et al.* 2006). The result for the week of August 9 was used by Cosens *et al.* (2006) as a correction factor for availability bias. Use of an unweighted mean and error assumes that the contribution of each individual during the given period accurately reflects the gender/reproductive class they represent, regardless of sample size. A weighted mean is more appropriate, since sample size is critical in accurately describing the mean.

The PTS value used for availability bias correction in this study was based on a sample of 50 (6 h) time periods from three individuals. The estimate represented the mid-summer residency period and fell between the observed values for pre-breakup and peak summer migration. The value appears to reflect behaviour consistent with resident summer activity (e.g. less directed movement/social activity, interspersed with feeding bouts at depth). Results from visual studies in other regions indicate that proportion of time-at-surface is typically lowest during migration, followed by feeding and local travel, and finally socializing (Würsig *et al.* 1984, Carroll *et al.* 1987, Richardson *et al.* 1995).

The three individuals on which the correction factor was based in this study consisted of a juvenile (est. 12 m) female (n=7), a young adult (est. 13 m) male (n=22), and an adult (est.

13 m) female with a calf (n=21). The male contributed the lowest PTS value. If animals in PRI/GoB and Eclipse Sound consist mainly of juveniles and females with calves, then the actual mean PTS may be somewhat higher than that used here. The magnitude of this bias may be as high as 16%, based on a comparison of PTS values determined for all three animals (0.26) versus only the two females (0.31).

A negative source of bias in the availability bias correction factor may exist. The depth threshold (4 m) for recording surface activity is deeper than the depth to which bowhead whales are likely to be detected by observers in the survey aircraft. Evidence suggests that dark animals in clear water may be correctly identified to a maximum depth of 2 m when observed on the trackline (Richard *et al.* 1994, Heide-Jørgensen 2004). Visibility to depth drops off rapidly with increases in sea state and with increasing distance of the target animal from the trackline. Given the constraints of the flat windows used in these surveys, which forces observers to view at shallower angles to the water surface, observers are likely to detect whales less frequently than would be predicted on the basis of PTS. The extent of this bias is unknown.

Few estimates of the proportion of time that bowhead are visible at the surface exist for eastern Arctic bowhead whales. Heide-Jorgensen *et al.* (2003) reported values ranging from 13% to 34% for one (adult male) bowhead, based on satellite-linked telemetry during movements between Greenland and Baffin Island waters. Heide-Jørgensen (unpubl. data in Heide-Jørgensen and Aquarone 2002) also reported values of 17-21% based on visual observations (41 to 90 minutes of observation) of two bowhead whales in west Greenland waters and one in Tremblay Sound, Baffin Island.

Considerable data on dive behaviour are available for bowhead in the western Arctic. Values for percentage time visible from the air range from 7.0-35.8% for visual observations (unweighted mean = 16.2%, S.D=9.0%; see review in Krutzikowsky and Mate 2000). It is uncertain to what extent these may be biased toward shorter dive cycles and thus longer proportion of time at the surface. Estimates based on telemetry results for eight bowhead whales in the Western Arctic range from 8.5-16.4% (unweighted mean = 11.1%, SD=2.4%, n=8), although this is an indirect calculation rather then a direct measure of PTS as available for this study.

Compared to results of other studies, the PTS value used in this study appears to be a reasonable estimate of the instantaneous sightability of whales. However, a known source of bias when correcting for the instantaneous sightability may be referred to as the “time-window” effect. This refers to the effect of the time available to observers to detect animals at the surface. The longer the time available, the greater the probability of detection. To account for this effect, researchers have used the formula of McLaren (1961) which uses dive interval information and available observation time (t) to estimate the inverse of the probability that animals will be at the surface during the period of observation (Frost et al., 1985; Barlow et al., 1988; Laake et al., 1997).

This time-window effect could not be directly accounted for in this study, as the available dive data did not include direct measures of surface time or dive time. However, the magnitude of this bias can be approximated, based on approximations for the time window and dive intervals. One reasonable approximation of the time window is the maximum time between initial sighting and time abeam (when observers began searching for new sightings). This was 12 seconds (n=29, mean=5.3, SD=2.6). This may be a slight underestimate of the true time window, since whales may have been beneath the surface at the beginning of the time window. Davis *et al.* (1982) estimated a time window for similar surveys of 18 seconds, based on a detection distance ahead of the aircraft of 1 km and the time required to travel 1 km at a survey flight speed of 200 kph. However their surveys were flown slightly slower (200 kph vs 215 kph) and included uncertainties in distance estimation ahead of the aircraft. Thus 12 seconds is likely a reasonable approximation of the time window for our surveys.

Depending on behaviour, bowhead whale mean surface time typically ranges from 1 min to 4.7 min while mean dive time ranges from 1.5 min to 15.8 min (Koski *et al.* 2004, Richardson *et al.* 1995, Krutzikowsky and Mate 2000). However, visual observations, on which most estimations of dive intervals are based, are inherently biased toward shorter dive cycles. On the basis of a time window of 12 sec, an overall PTS of 0.26, and assuming relatively short surface and dive times (e.g. surface time = 2 min), the magnitude of this bias would be about 9%[1]. The bias is inversely proportional to the surface time.

<u>Conclusion</u>

A reanalysis of Cosens *et al.* (2006) survey data was conducted and revealed errors as well as opportunities for further analytical treatment. Cosens *et al.* (2006) used only a single platform approach to the analysis of these surveys. The partitioning of sightings by respective survey strata in the original analysis provides relatively weak approximations of distance sighting frequencies upon which to estimate detection functions. The new approaches taken in the reanalysis allow for comparison of model fit between the global and single strata, between single and double-platform approaches, as well as an examination of the potential biases in the representative population estimates. Pooling of data for determination of detection function and mark-recapture rate allowed for more robust estimation of survey parameters, while potential bias as a result of pooling in terms of density and abundance appeared to be negative.

The single platform approach represents the most conservative estimate of bowhead whale abundance, which does not account for the numbers of visible whales that were missed by observers. Extending the analysis to a double-platform mark-recapture covariate approach demonstrates the likelihood that observers missed significant numbers of animals at the surface that were available to be seen. Small sample size in the mark/recapture is a significant source of uncertainty in the extrapolated estimates.

Data on availability bias indicates that animals spend significantly more time beneath the surface than at the surface. The true availability bias correction factor may be somewhat smaller than that used here, due to the effect of the time available for observers to detect whales. Abundance estimates may be positively biased by this effect by about 9%.

Although the results suggest the possibility of a sizeable bowhead whale population, the large confidence limits in the abundance estimate reflect the extent of the uncertainties in the various components of the estimate. Potential biases exist in both directions. Due to

[1] The magnitude of bias is equivalent to the difference between the instantaneous correction factor (0.26) as determined in this study, and that approximated by the McLaren formula, $P = [t / (s+u)] + [s / (s+u)]$, where P = the probability of detection; t = time window available = 12 sec; s = surface time, estimated to be 120 sec; and u = dive time, estimated to be 360 sec.

the large uncertainties, caution should be used in interpreting the abundance of eastern Arctic bowhead whales.

Greater precision in the estimates of abundance for this population is required. Given the range of the population and the sighting rates encountered in these surveys, a complete population estimate may not be feasible. However, even a partial estimate will require greater survey effort to increase sample size of sightings, in order to improve detection probability and mark-recapture estimation. More dive tag information, particularly dive interval data, is needed to assess dive behaviour to account more accurately and precisely for availability bias.

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Table 1. Summary of revised survey area and effort statistics and revised numbers of bowhead whale sightings.
* single transect per bay; ** single transect every two bays

Year	Survey block	Survey region	Area (sq km)	Number of transects	Transect spacing (km)	Effort (km)	Sightings n	Encounter rate n/L	%cv (n/L)
2002	1	Eclipse Sound	5914	6	28.4	234	5	0.02	57
		Eclipse Sound bays and fiords	1810	6	*	342	0	-	-
		Prince Regent Inlet and Gulf of Boothia	87195	21	28.4	2463	11	0.005	31
2003	2	Southern Gulf of Boothia	29763	4	33.0	1108	1	0.001	95
		Foxe Basin	38537	16	33.0	1599	5	0.003	75
		Fury and Hecla Strait	294	1	-	133	2	0.02	0
		NW Hudson Bay	33436	15	33.0	1071	0	-	-
	3	Admiralty Inlet	9464	9	23.5	571	3	0.009	58
		Admiralty Inlet bays and fiords	868	6	*	236	0	-	-
		East Baffin Island coast	51387	14	55.3	2208	1	0.001	110
		East Baffin Island fiords 1	11204	17	**	1193	6	0.005	61
		East Baffin Island fiords 2	4109	7	**	155	0	-	-

Table 2. Summary of review of survey data, indicating the number of sightings in the original analysis and potential sources of error and bias. The numbers in parentheses refer to the sightings used and reported by Cosens *et al.* (2006) after data filtering through specifications of truncation distances. Additional reporting errors in the original text of Cosens *et al.* are provided in the third column.

Survey region	Original analysis (number of sightings)	Summary of review of data and actual number of sightings available for re-analysis. Additional errors described.
2002 Eclipse Sound	6 (5)	6 sightings available. A hazard rate reportedly used in the analysis for 2002 surveys; actual model used was a half-normal. The reported cv for effective strip width should have read 30%, not 77%.
2002 Prince Regent Inlet & Gulf of Boothia	13 (12)	One sighting of ambiguous certainty used in the original analysis, leaving 12 sightings available, of which one of these was excluded in the original analysis during truncation of the data. Also note error described above.
2003 Admiralty Inlet & east Baffin Island coast	25 (18)	Of the 25 sightings, 4 were considered too ambiguous, 2 were duplicate sightings, 4 sightings were in narrow fiords (fiord width < 4 km), 1 sighting was off transect and had an uncertain angle reading, and 2 sightings had uncertain angle readings; 12 on-transect sightings remaining. Errors in the distance measurements were also found for all sightings in this survey block (they appear to have been based on calculations using a single (possibly target) altitude, rather than the actual altitude at the time of the sighting).
2003 Gulf of Boothia/Foxe Basin/Hudson Bay	10 (10)	10 sightings, but 2 were off-transect, leaving 8 on-transect sightings.
2004 Eclipse Sound/Admiralty Inlet/Barrow Strait	No data used, but reference to one sighting of three whales	The reported sighting was made in Milne Inlet where the fiord width was less than 4 km, thus not useful for detection function calculation in any case.
Total	54 (45)	38 sightings, excluding 2 sightings with uncertain angle readings, 2 off-transect sightings and 4 sightings in narrow fiords; does not account for sightings excluded in subsequent analyses during truncation or filtering

Table 3. Results of single platform analysis, summarizing expected cluster size, density and surface estimates for bowhead whales by survey block and survey strata. The results were based on a global detection function fitted to pooled sightings truncated at 250 and 1500 m (ESW = 1250 m). Survey strata with no whale sightings were removed prior to analysis. The single platform method does not account for whales that were available to be seen but were missed by observers.

Year	Survey block	Survey region	Expected cluster size E(s)	CV of E(s)	Density (D_hat)	N_hat	CV of N_hat	95% CI of N_hat
2002	1	Eclipse Sound	1.8	0.32	0.04	259	0.68	64 - 1049
		Prince Regent Inlet and Gulf of Boothia	1.5	0.11	0.01	644	0.37	313 - 1322
		Total for block 1			0.01	902	0.34	455 - 1789
2003	2	Southern Gulf of Boothia	1.0	-	0.001	31	0.97	3 - 372
		Foxe Basin	1.5	0.33	0.004	149	0.77	35 - 633
		Fury and Hecla Strait	1.0	-	0.03	8	0.37	1 - 57
		Total for block 2			0.003	187	0.64	54 - 649
	3	Admiralty Inlet	1.3	0.25	0.01	117	0.66	31 - 433
		East Baffin Island coast	1.0	-	0.001	68	1.12	10 - 469
		East Baffin Island fiords 1	1.2	0.14	0.01	75	0.65	22 - 255
		Total for block 3			0.003	259	0.48	103 - 651

Table 4. Results of double platform mark-recapture analysis, summarizing expected cluster size, density and surface estimates for bowhead whales by survey block and survey strata. The results were based on a global detection function fitted to pooled sightings truncated at 250 and 1500 m (ESW = 1250 m). Survey strata with no whale sightings were removed prior to analysis. The double platform method accounts for whales that were available to be seen but were missed by observers.

Year	Survey block	Survey region	Expected cluster size E(s)	CV of E(s)	Density (D_hat)	Abundance N_hat	CV of N_hat	95% CI of N_hat
2002	1	Eclipse Sound	2.1	0.03	0.09	532	0.66	134 - 2101
		Prince Regent Inlet and Gulf of Boothia	1.6	0.07	0.04	3212	0.50	1220 - 8455
		Total for block 1	1.6	0.10	0.04	3744	0.46	1518 - 9231
2003	2	Southern Gulf of Boothia	1.0	0.00	0.004	127	1.01	12 - 1388
		Foxe Basin	1.0	0.00	0.008	325	0.89	65 - 1633
		Fury and Hecla Strait	1.5	-	0.04	12	0.55	2 - 87
		Total for block 2	1.0	-	0.007	464	0.71	122 - 1762
	3	Admiralty Inlet	1.5	0.11	0.03	301	0.72	72 - 1244
		East Baffin Island coast	1.0	0.00	0.002	101	1.15	14 - 713
		East Baffin Island fiords 1	1.2	0.03	0.010	111	0.70	29 - 413
		Total for block 3	*1.3*	0.12	0.007	513	0.56	174 - 1508

Table 5. Summary of abundance estimates of bowhead whales based on surface estimates and corrected for availability bias. Corrections applied to both the single platform analysis (A) and the double platform mark recapture analysis (B).

A. Single platform analysis.

Year	Survey block	Survey region	Surface estimate (N)	CV (N)	N adjusted for availability bias (N_a)	CV (N_a)	95% confidence limits of N_a	
2002	1	Eclipse Sound	259.0	0.01	996	39%	476	2083
		Prince Regent Inlet and Gulf of Boothia	644.0	0.00	2477	39%	1185	5179
		Total for block 1	902.0	0.00	3469	39%	1659	7253
2003	2	Southern Gulf of Boothia	31.0	0.01	119	39%	57	249
		Foxe Basin	149.0	0.01	573	39%	274	1198
		Fury and Hecla Strait	8.0	0.00	31	39%	15	64
		Total for block 2	187.0	0.01	719	39%	344	1504
	3	Admiralty Inlet	117.0	0.01	450	39%	215	941
		East Baffin Island coast	68.0	0.01	262	39%	125	547
		East Baffin Island fiords 1	75.0	0.01	288	39%	138	603
		Total for block 3	259.0	0.00	996	39%	476	2083

B. Double platform analysis.

Year	Survey block	Survey region	Surface estimate (N)	CV (N)	N adjusted for availability bias (N_a)	CV (N_a)	95% confidence limits of N_a	
2002	1	Eclipse Sound	531.9	0.66	2046	77%	541	7742
		Prince Regent Inlet and Gulf of Boothia	3212.1	0.50	12354	64%	3945	38688
		Total for block 1	3744.0	0.46	14400	61%	4811	43105
2003	2	Southern Gulf of Boothia	126.5	1.01	487	108%	87	2731
		Foxe Basin	325.0	0.89	1250	97%	252	6204
		Fury and Hecla Strait	12.3	0.55	47	68%	14	157
		Total for block 2	463.9	0.71	1784	81%	441	7211
	3	Admiralty Inlet	300.8	0.72	1157	82%	283	4721
		East Baffin Island coast	101.0	1.15	388	121%	60	2510
		East Baffin Island fiords 1	111.0	0.70	427	80%	107	1701
		Total for block 3	512.7	0.56	1972	68%	589	6598

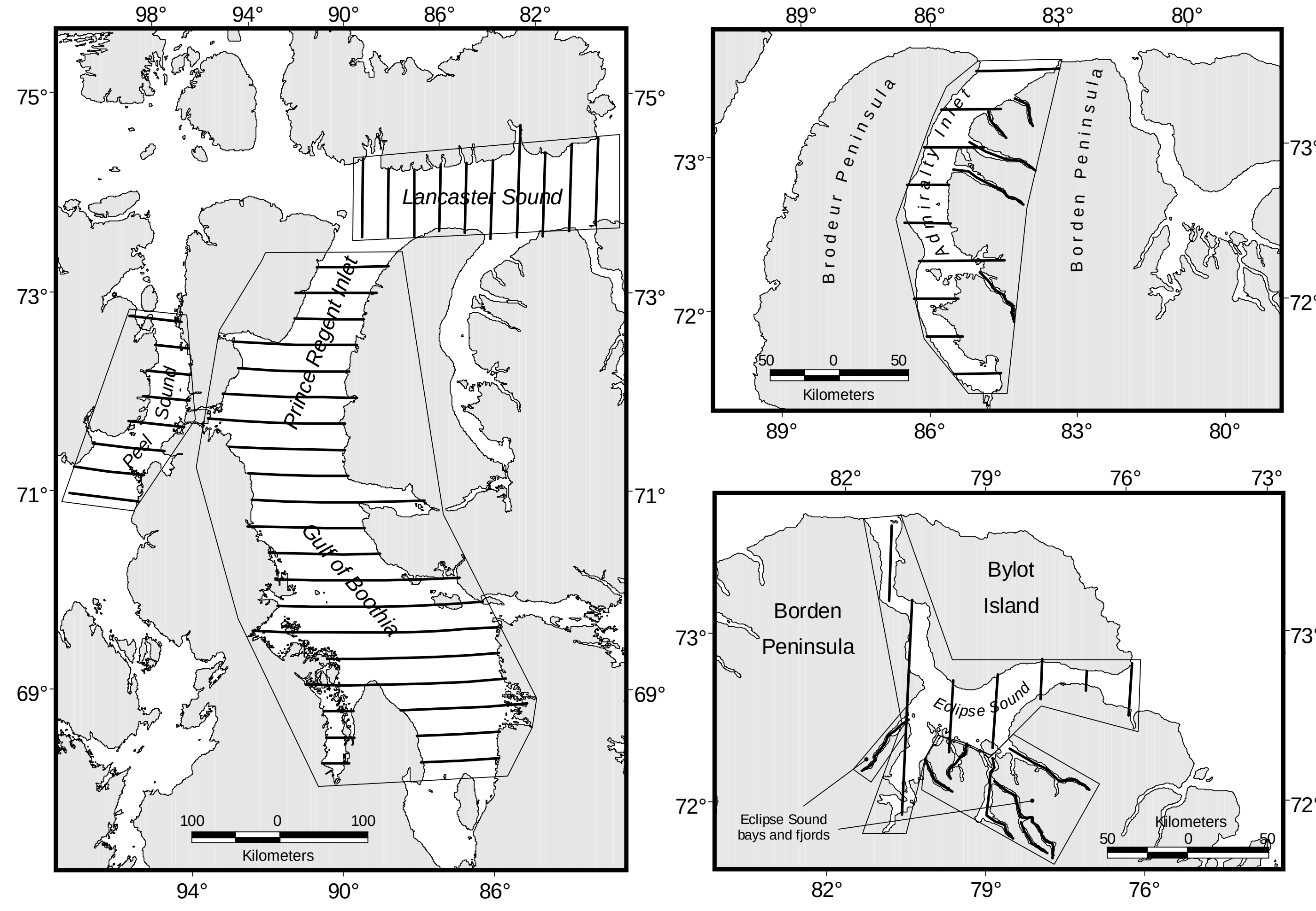


Figure 1. Maps depicting the survey strata and transect design for aerial surveys planned for 2002.

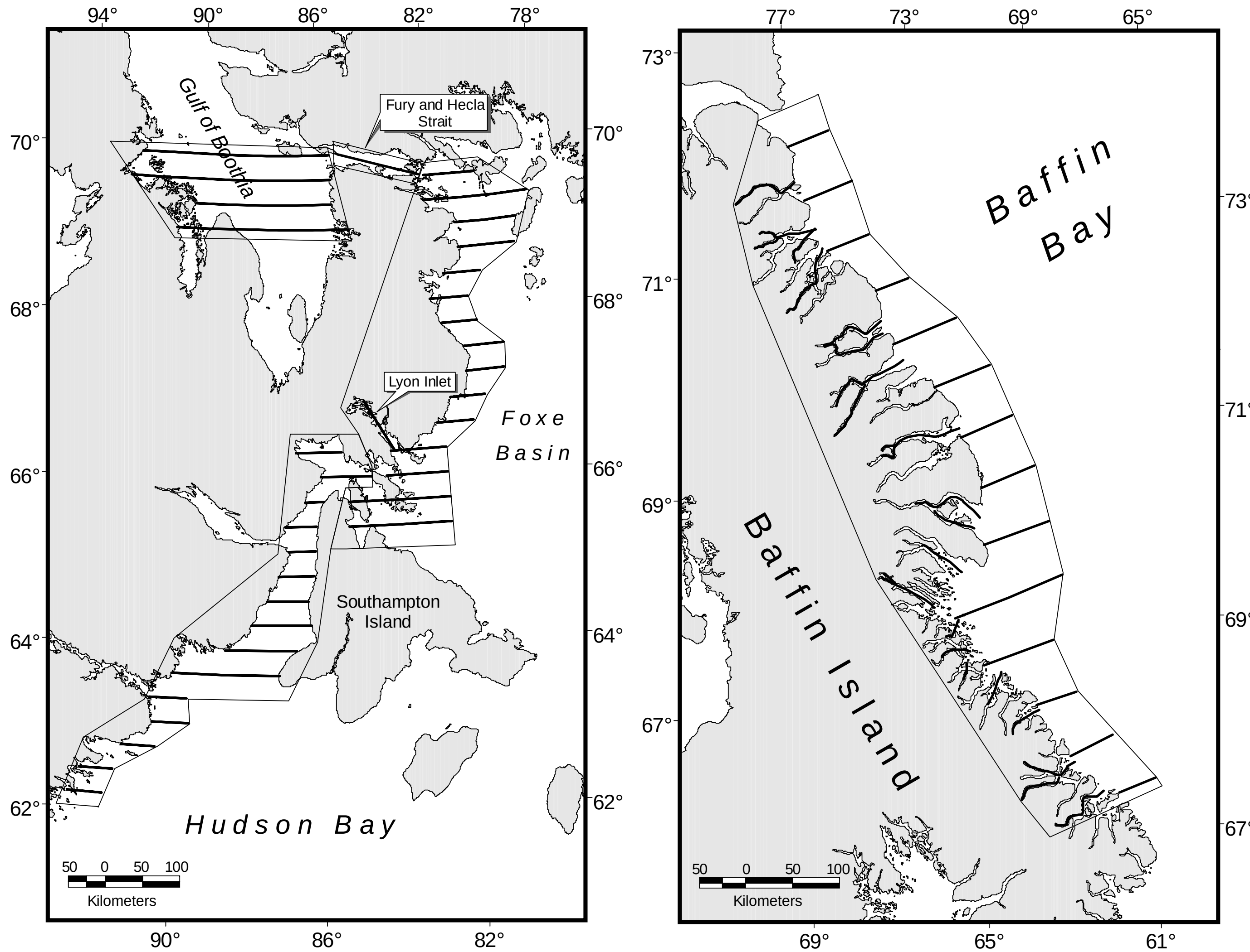


Figure 2. Maps depicting the survey strata and transect design for surveys planned for 2003

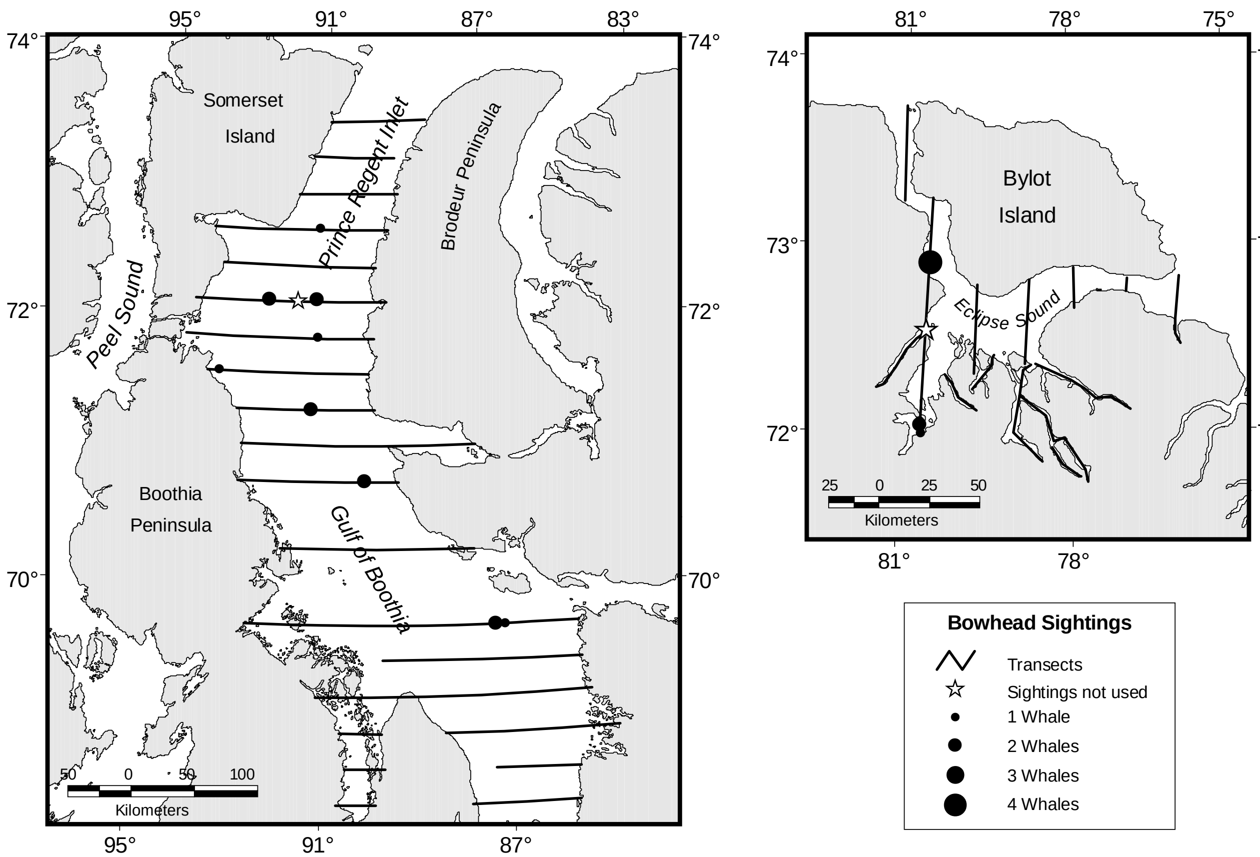


Figure 3. Distribution of on-transect bowhead whale sightings for aerial surveys conducted in 2002.

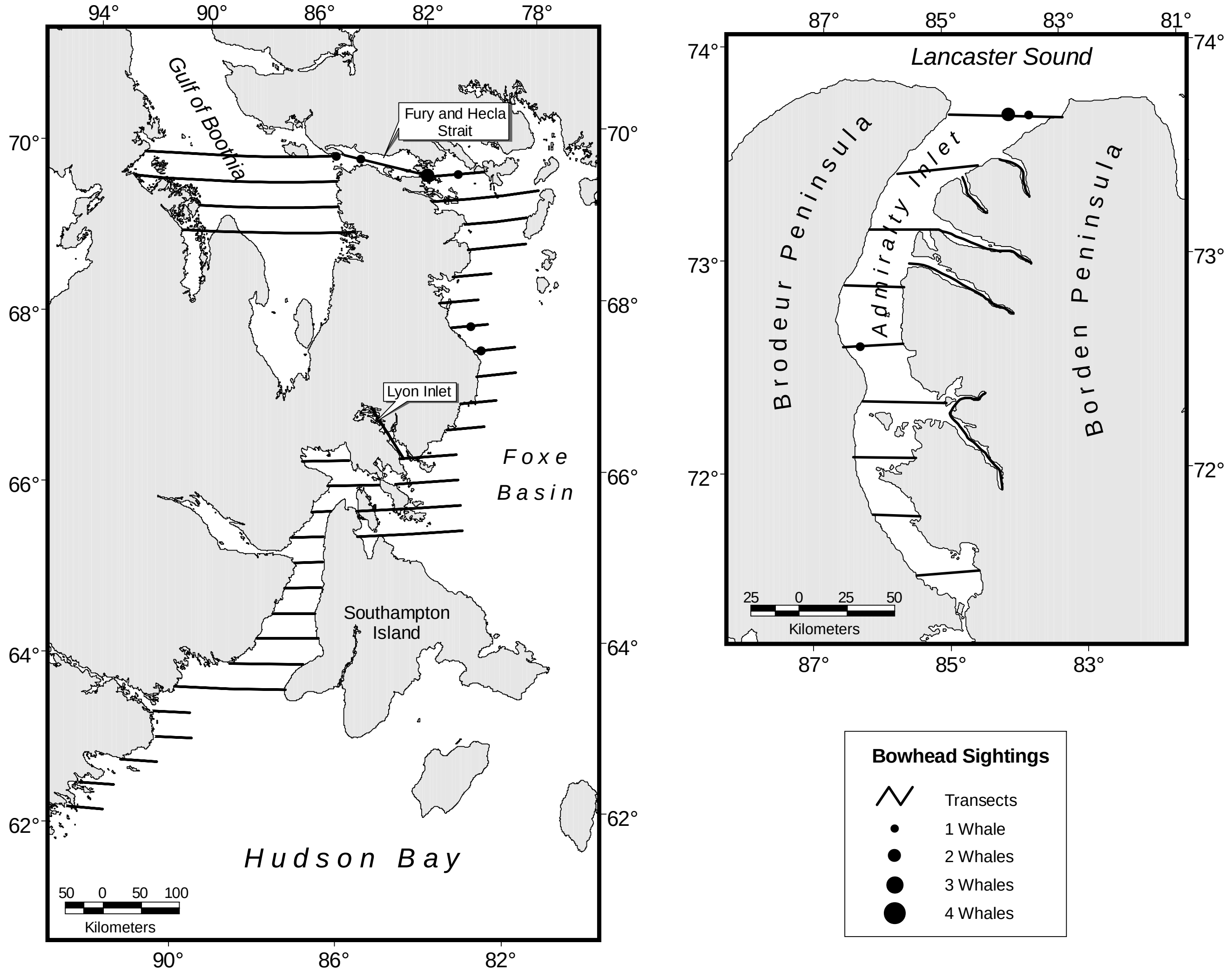


Figure 4. Distribution of on-transect bowhead whale sightings for aerial surveys conducted in 2003 in Gulf of Boothia, Foxe Basin, northwest Hudson Bay, and Admiralty Inlet.

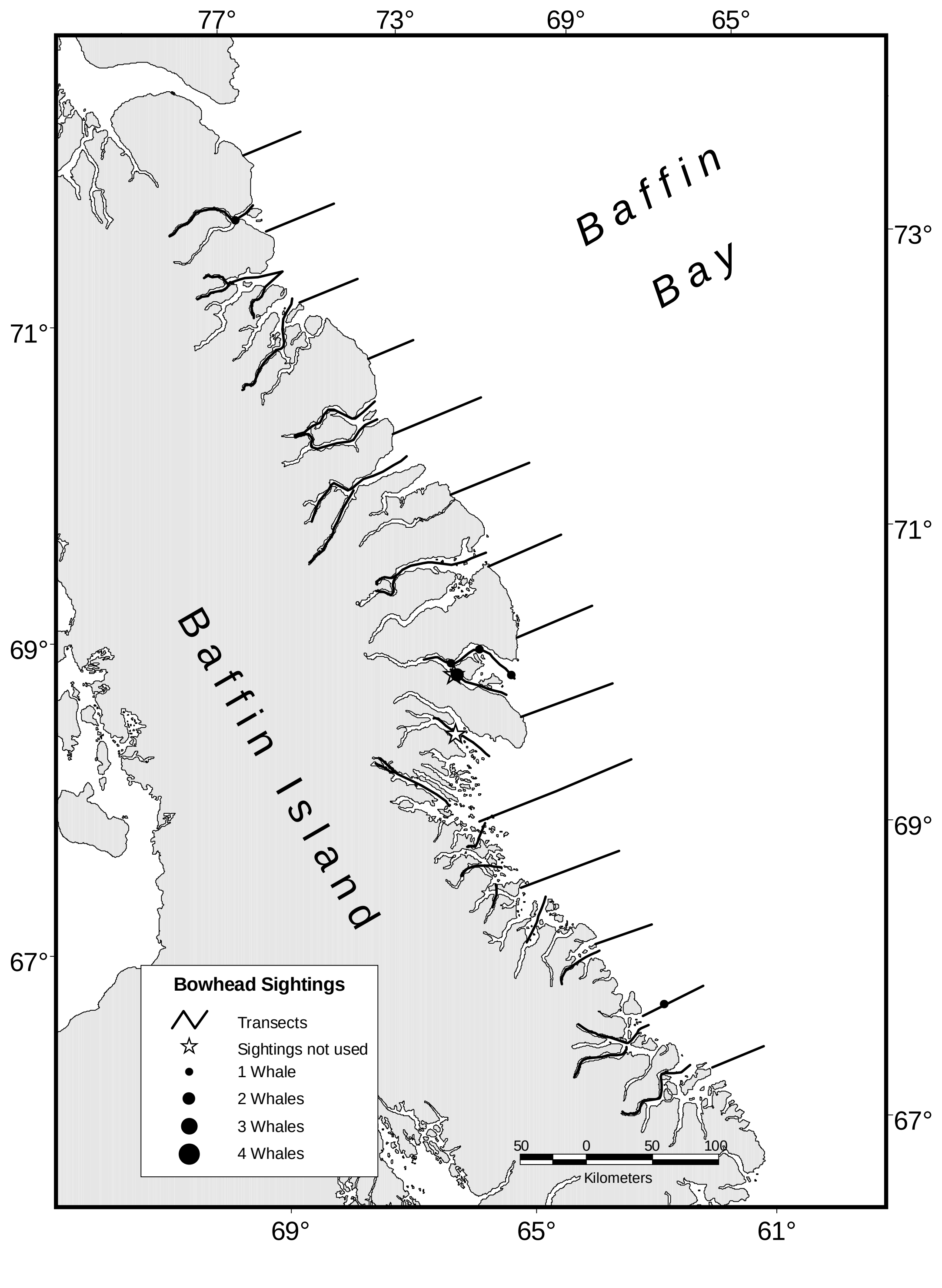
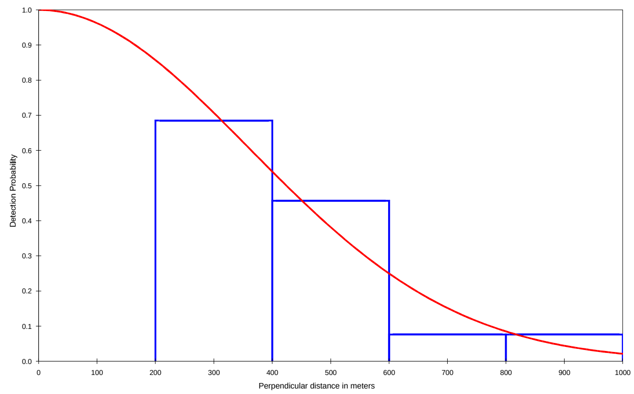
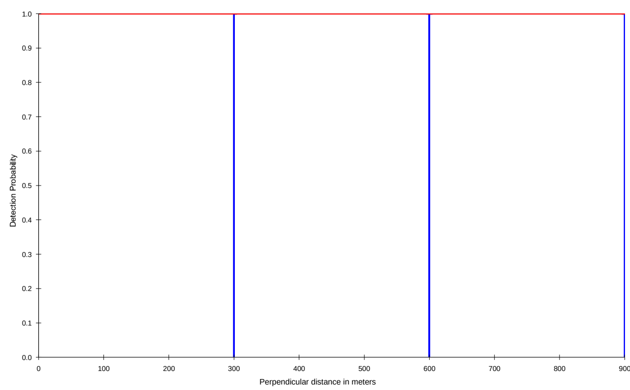


Figure 5. Distribution of on-transect bowhead whale sightings for aerial surveys conducted along the eastern Baffin Island coast.

a



b



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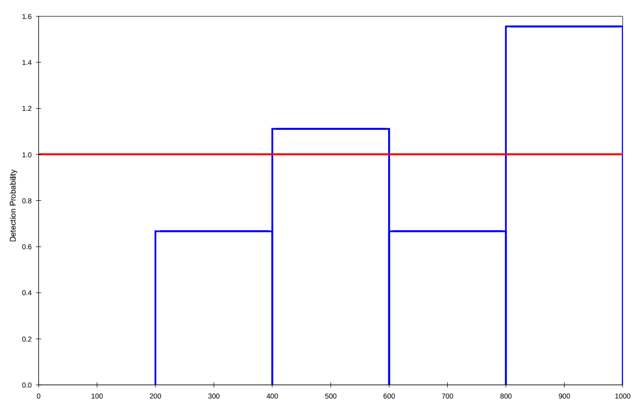


Perpendicular distance in meters

Figure 6. Plots depicting frequency histograms of sighting distances as a function of detection probability (bars outlined in blue) and the detection function model (red line) fit for analyses conducted by Cosens *et al.* (2006), for a) Eclipse Sound, Prince Regent Inlet and Gulf of Boothia 2002 surveys; b) southern Gulf of Boothia, Foxe Basin and Fury and Hecla Strait 2003 surveys; and c) Admiralty Inlet and eastern Baffin Island coastal and fiords surveys 2003.

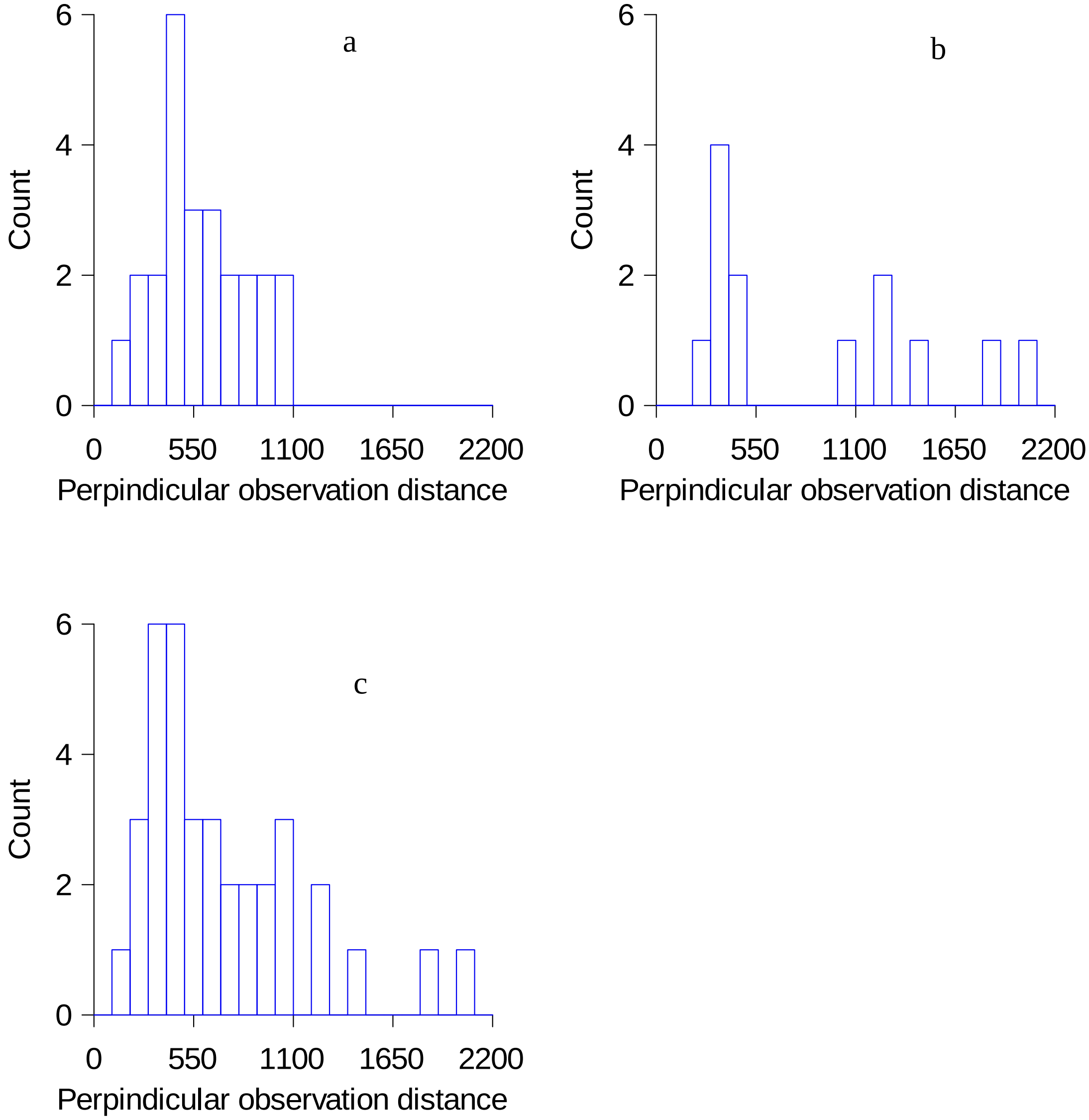


Figure 7. Frequency histogram of sighting distances for pooled sightings, for a) primary, b) secondary, and c) combined platforms. Note that the frequency distribution of distance measurements for primary and secondary platforms is not significantly different (KS, p = 0.084).

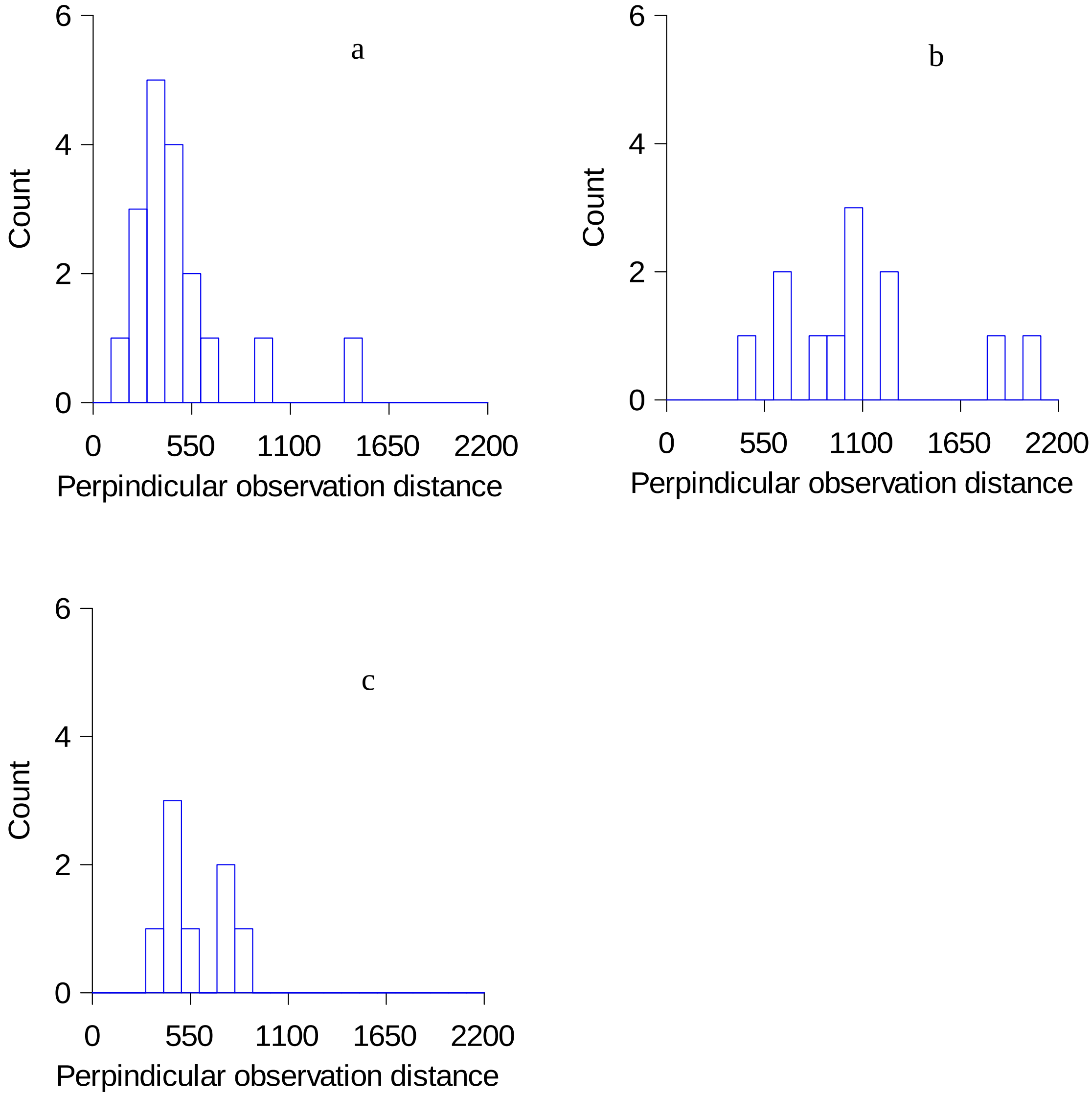
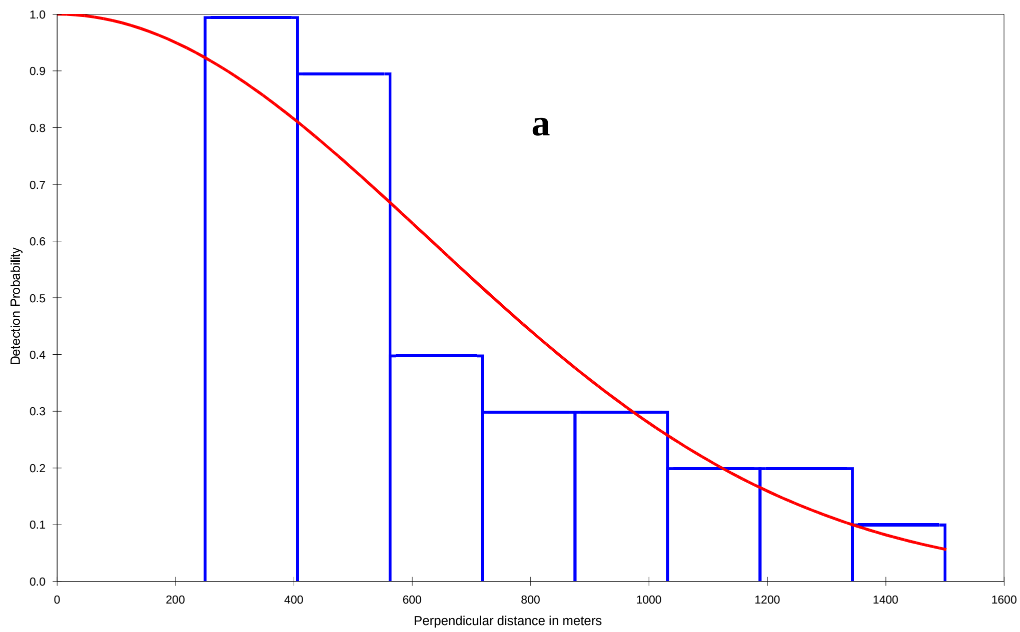


Figure 8. Frequency histogram of sighting distances for pooled sightings, for survey blocks 1, 2 and 3, illustrated as, respectively: a) Eclipse Sound/Prince Regent Inlet; b) Admiralty Inlet/Eastern Baffin Island; and c) Gulf of Boothia/Foxe Basin.



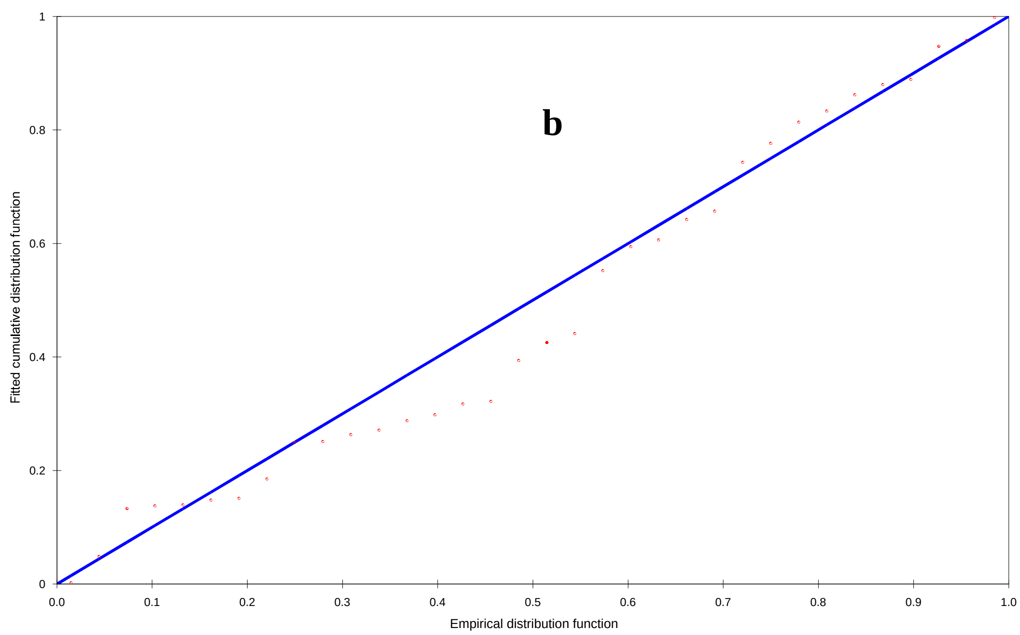


Figure 9. a) Frequency histogram of pooled sighting data used to fit the global detection function (red line). The detection function was fit with a half-normal key; convergence was achieved with 18 function evaluations; overall probability of detection, p = 0.35 (se = 0.06); effective strip width (ESW) = 528.07 (se = 89.93); b) QQ plot depicting the goodness of fit of the detection function to the data; KS, p = 0.44; Cramer-von Mises (CVM) W-sq = 0.098, 0.500 < p <= 0.600; CVM C-sq: = 0.079, 0.400 < p <= 0.500.

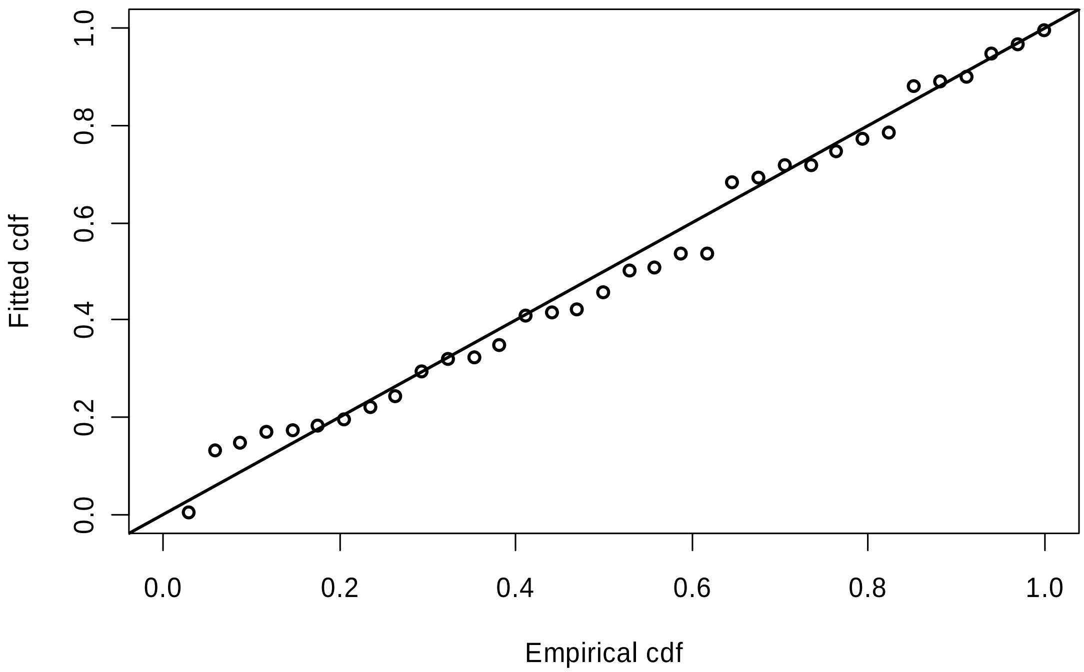


Figure 10. QQ plot depicting the goodness of fit of the detection function to the double-observer mark-recapture data; KS, p = 0.87; Cramer-von Mises (CVM) = 0.04, p = 0.93; CVM.

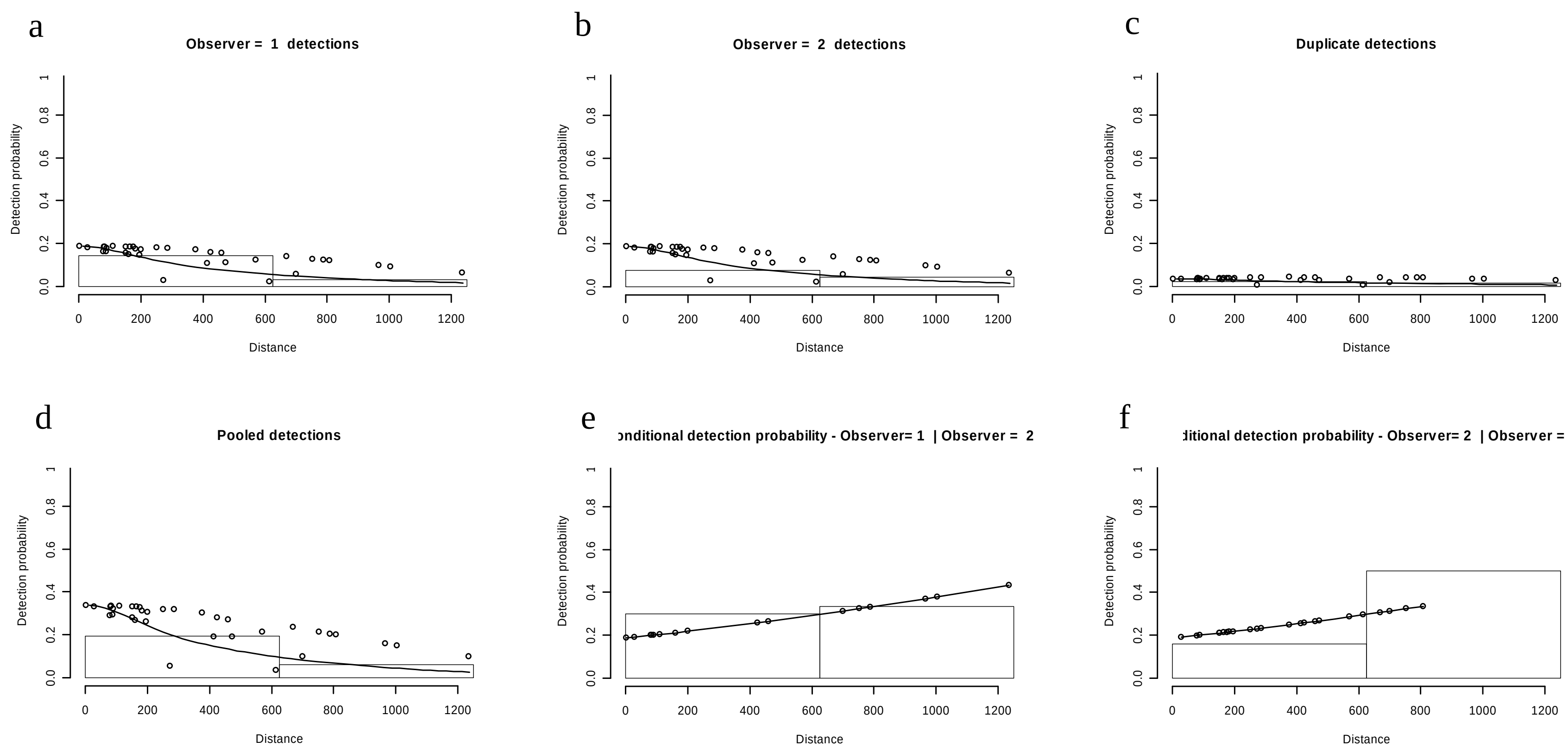


Figure 11. Plots summarizing the output of double-observer mark-recapture data analysis, illustrating detections by primary and secondary platforms individually (plots a and b), detections seen by both observers (c), and pooled detections (d). The plots in e and f depict the proportion of platform 1 detections seen by platform 2 and platform 2 detections seen by platform 1, respectively.