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Abundance Estimates for Beluga (*Delphinapterus leucas*) in James Bay and the Belcher Islands-Eastern Hudson Bay Area in Summer 2024

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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.

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ABSTRACT

Systematic line-transect surveys were flown in James Bay and the Belcher Islands-eastern Hudson Bay area from July 18th to September 23rd, 2024. A total of 620 groups of beluga (1,154 individuals) were detected by primary observers, of which 547 had perpendicular distance measurements. A single gamma detection function was selected to model the probability of detection in both surveyed areas from the ungrouped distribution of perpendicular distances, which estimated an average effective strip half-width of 756 m (CV = 8.7%). A total of 481 groups with an average size of 1.91 (CV = 6%) animals were detected in James Bay over 4,033 km of survey lines, resulting in a surface abundance index of 4,349 (95% CI: 2,761–6,851) beluga. The Belcher Islands-eastern Hudson Bay area was split into a high coverage stratum, and two low-coverage strata located to the north and in Tasiujaq Lake (formerly Richmond Gulf). The plan was to survey the high coverage stratum twice to provide a more precise estimate of abundance, but unforeseen circumstances prevented the first survey of this stratum from being completed. On the second and complete survey of the high coverage area, 105 groups of beluga with an average size of 1.62 (CV = 10%) were detected over 8,327 km of transects. This yielded a surface abundance index of 479 (95% CI: 300–767) beluga. No beluga were observed in the northern low-coverage and Tasiujaq Lake strata. To ensure consistency in methodology with the 2024 survey, data from the eight surveys conducted in James Bay and the Belcher Islands-eastern Hudson Bay between 1985 and 2021 were reanalyzed by fitting gamma detection functions to perpendicular distance distributions. All surface abundance indices were corrected for availability and perception biases. For the 2024 survey, availability bias was estimated at 0.514 (CV = 3.6%). Applying a perception bias correction factor of 1.355 (CV = 7.9%) to the James Bay surface index resulted in a fully corrected abundance estimate of 11,455 (95% CI: 7,322–17,921). For Belcher Islands-eastern Hudson Bay, applying a perception bias correction factor of 1.600 (CV = 6.9%) to the surface index resulted in a corrected abundance of 1,491 (95% CI: 928–2,396) beluga in 2024. This BEL-EHB beluga abundance estimate is the lowest of the time series of nine surveys flown since 1985.

INTRODUCTION

The beluga (*Delphinapterus leucas*) has a nearly circumpolar range in the Arctic and subarctic (Reeves and Mitchell 1989). In Canada, beluga stocks have been identified based primarily on the disjunct distribution of summering aggregations (Sergeant 1973; Finley et al. 1982; Reeves and Mitchell 1987; Richard 2010). For the most part, separation of stocks has been supported by evidence for strong intra- and inter-annual site fidelity based on behavioural observations (Caron and Smith 1990), telemetry (Bailleul et al. 2012), genetics (Brennin et al. 1997; Brown Gladden et al. 1997, 1999; de March et al. 2002, 2004; de March and Postma 2003; Postma et al. 2012; Colbeck et al. 2013; Turgeon et al. 2012; Parent et al. 2023; Montana et al. 2024), and stable isotopes and contaminant loads (Rioux et al. 2012). The beluga shows strong philopatry to specific areas and migration routes are thought to be learned through the cultural transfer of information from females to calves (Colbeck et al. 2013; O'Corry-Crowe et al. 2020; Bonnell et al. 2022). These characteristics make beluga vulnerable to local depletion and may reduce their ability to adapt to local changes or re-colonize areas where they are extirpated (Wade et al. 2012; O'Corry-Crowe et al. 2018, 2020).

Four beluga stocks are recognized to inhabit or migrate along the Nunavik coasts: Ungava Bay (UNG), James Bay (JAM), western Hudson Bay (WHB) and Belcher Islands-eastern Hudson Bay (BEL-EHB) beluga. BEL-EHB beluga consists of a mixed stock composed of two genetically distinct populations (i.e., Belcher Islands [BEL] and Eastern Hudson Bay [EHB]) with overlapping summer distributions (Figure 1; Parent et al. 2023). Genetic studies (Turgeon et al. 2012; Parent et al. 2023) and satellite telemetry (Lewis et al. 2009; Bailleul et al. 2012; DFO 2024) have shown that the BEL-EHB and WHB stocks overwinter together in Hudson Strait and along the Labrador coast, sometimes travelling in Ungava Bay. Yet, interbreeding appears limited between genetic populations (Montana et al. 2024). A proportion of BEL-EHB beluga also remain in the Belcher Islands area throughout the year (Parent et al. 2023). Beluga in James Bay constitute a distinct breeding population and appear to undertake limited seasonal movements, mostly remaining in the James Bay and southern Hudson Bay areas (Bailleul et al. 2012; Parent et al. 2023).

In the 1800s, BEL-EHB beluga were thought to number around 12,500 animals. Commercial whaling during the eighteenth, nineteenth, and early twentieth centuries resulted in a sharp decline in abundance (Lawson et al. 2006; Hammill et al. 2017). Continued subsistence harvests have limited the recovery, with climate change and habitat modification being potential additional underlying factors (Sauvé et al. 2024). In 2001, a stock assessment estimated that if harvests were not reduced, the BEL-EHB stock would go extinct within two to three decades (Bourdages et al. 2002). A series of severe management measures, to which a relatively high compliance was observed (Lesage et al. 2001), slowed the population decline in the following years (e.g., DFO 2018). In recent history, beluga harvesting by Nunavik Inuit has been managed under the jurisdiction of Fisheries and Oceans Canada (DFO), generally under 5-year management plans. The signing of the Nunavik Inuit Land Claims Agreement (NILCA) transferred co-management responsibility to the Nunavik Marine Region Wildlife Board (NMRWB), the Eeyou Marine Region Wildlife Board (EMRWB), and DFO in 2007. The current management plan expires on January 31, 2026, requiring an update on the BEL-EHB stock status, abundance and trend.

Since 1985, beluga stock abundance estimation in the Belcher Islands-eastern Hudson bay and James Bay areas relies on systematic, visual aerial surveys covering the full extent of the summering distribution of the targeted stock. These surveys are carried out approximately every five years (Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024). The last survey of the BEL-EHB stock was flown in 2021, and yielded an abundance estimate (rounded to the nearest 100) of 2,500 beluga (95% CI: 1,400-4,300; St-Pierre et al. 2024). Prior to this survey, the BEL-EHB stock was considered to have been stable for at least a decade (Hammill et al. 2017). Yet, adding the 2021 estimate to the population dynamics model estimated a stock decline of 3% per year between 2015 and 2021 (Hammill et al. 2023). The 2021 BEL-EHB abundance estimate was the most precise, the lowest and most recent of the time series, leading to a major influence on population dynamics model results. Considering the renewal of the Nunavik beluga management plan in 2026, a new survey was flown in summer 2024 to update the BEL-EHB and JAM stocks statuses and trends.

In addition to presenting results from the 2024 survey, this study provides a re-analysis of the previous eight surveys to account for the recent emergence of improved analytical tools. Specifically, the distance sampling analysis carried out to estimate surface abundance indices uses the newly available gamma function in the 'mrds' package in R (Laake et al. 2022), which optimizes the use of empirical data when maximum probability of detection is away from the trackline, which is often the case for beluga aerial surveys.

METHODS

STUDY AREA AND DESIGN

The visual line-transect survey flown in summer of 2024 covered all of James Bay and the eastern Hudson Bay arc from the coastline to 81°W of longitude, which corresponds to 60 km west of the Belcher Islands (Figure 2). The stratification used in James Bay and the Belcher Island-eastern Hudson Bay area was the same as that of the survey conducted in 2021 (St-Pierre et al. 2024), and very similar to that of other surveys flown in the area between 2004 and 2015 (Gosselin 2005, Gosselin et al. 2009, 2013, 2017). The limits of each stratum lie in regions of relatively low density determined from previous aerial surveys, satellite tracking of beluga captured in eastern Hudson Bay and James Bay (Bailleul et al. 2012), and traditional ecological knowledge (Lewis et al. 2009). Transect lines were oriented in an east-west direction. There were 24 lines in James Bay (JB), 6 lines in the low coverage stratum of eastern Hudson Bay (HN), and 5 lines in Tasiujaq Lake (RG; Table 1,Figure 2). We planned on surveying the high coverage strata of the Belcher Island-eastern Hudson Bay area twice, using two independent sets of 35 and 36 lines referred to as HC1 and HC2, respectively. The Belcher Islands-eastern Hudson Bay area corresponds to the combination of the HN, HC, and RG strata. Lines in James Bay and in the low coverage areas of Belcher Islands-eastern Hudson Bay were spaced 18.5 km (10 nautical miles) apart, whereas spacing in the high coverage strata was 9.3 km (5 nautical miles). The length of transect lines and the area of each stratum were estimated using the North Pole Lambert Azimuthal Equal Area projection, with 76.8°W as the central meridian and 56.1°N as the reference latitude.

Coastal surveys were flown to detect beluga aggregations along the eastern Hudson Bay coastline and main estuaries. Particularly, the estuaries of the Little Whale and Nastapoka rivers were visited each time a transit was passing by, weather permitting. During coastal surveys, the planes flew offshore at a distance where observers determined that they would detect all animals between the plane and the coast. As in previous surveys, digital pictures were planned to be taken if large numbers of belugas were detected.

DATA COLLECTION

Flights in the James Bay stratum were conducted using one Partenavia P68C, while flights in the Belcher Islands-eastern Hudson Bay area were flown using one Partenavia P68C and one DeHavilland Twin Otter 300 flying at a target altitude of 305 m (1000 feet) and a target speed of

185 km/h (100 knots). The JB, HC1, and RG strata were flown with three observers in each plane, whereas two observers were onboard each plane in the HC2 and HN strata. In the Partenavia, primary observers were seated in the rear seats, while the secondary observer, when present, was seated in the copilot seat (front right). In the Twin Otter, primary observers were seated in the left and right last row seats, while the secondary observer, when present, was seated at the second seat row. All observer stations were equipped with bubble windows, except for the co-pilot station in the Partenavia, which had a large window instead. Observations made by the primary observers in each plane were used to estimate beluga surface density with equivalent effort on both sides of the plane, while observations by the secondary observer were used to calculate a perception bias estimate.

Observers measured the inclination angle of each sighting using clinometers (Suunto) when animals passed abeam. When groups were detected away from the transect line, the relative bearing was also measured using an angle meter. Position and altitude of the plane were recorded every 2 seconds using a GPS (Garmin GPSMap 78s, Garmin GPSMap 64s, and/or BadElf Pro+). Observers were instructed to give priority to the estimation of group size and time of observation, followed by inclination angle and other variables if time permitted.

Weather and observation conditions were recorded at the beginning and at regular intervals along the lines or whenever changes in sighting conditions occurred. The conditions noted included sea state (Beaufort scale), subjective visibility (5 levels: excellent, good, medium, low, null), cloud cover (percent), angle of searching area affected by sun reflection, along with sun reflection intensity (4 levels: 1- intense when animals were certainly missed in the center of reflection angle; 2- medium when animals were likely missed in the center of reflection angle, 3- low when animals were likely detected in center of reflection angle and 4- none when there was no reflection). All information was recorded on digital voice recorders by each observer.

SURFACE ABUNDANCE ESTIMATES

The density and abundance were estimated using the package ‘mrds’ (Laake et al. 2022) within the *R* environment (v 4.3.2; R Development Core Team 2023). Analyses were based on the perpendicular distance to each observed beluga group, defined as a cluster of beluga within a few body lengths of each other. The overall distribution of perpendicular distances was examined to determine if truncation was necessary to discard outliers at great distances from the track line. Five guidelines for identifying potential right truncation distances were considered: 1) no truncation; 2) removal of the observations with distances greater than that of an obvious gap in the observed perpendicular distances; removal of the furthest 3) 5% or 4) 10% of distance values; and 5) identification of the perpendicular distance at which the detection function reached a probability of detection [$g(w)$] of 0.15 (Buckland et al. 2001). These candidate right truncation distances were tested to evaluate if they improved the fit of the detection function near the track line while maintaining good overall fit. The most distant right truncation distance that yielded acceptable model fit (i.e., the p value of the Cramér-von Mises test W^2 statistic > 0,10) was retained. A Gamma distribution without adjustment term was fitted to the distribution of sighting distances as it allowed for the maximal probability of detection to be away from the track line, without having to apply left truncation to the closest observations to account for the potential blind area underneath the aircraft (e.g., Becker and Quang 2009). Adjustment terms were not considered upon fitting the gamma function to avoid overfitting the perpendicular distance data and deviations from the shape criteria given the use of covariates (Len Thomas, pers. comm.).

A binary index of cluster size (s = 1 vs s > 1) was included as a covariate upon fitting the detection function to account for the expected positive bias in detectability of beluga groups as opposed to singletons. In addition, the possibility that the AIC could be reduced by the inclusion of covariates was examined using a stepwise, forward selection approach. Starting with the gamma function with binary cluster size as sole covariate, additional individual covariates were tested and were considered to have significantly improved the model if their inclusion resulted in a decrease in AIC of at least two points (ΔAIC >2; Arnold 2010). Among covariates that improved the model, combinations of uncorrelated covariates were tested and retained if the inclusion of multiple covariates decreased the AIC by at least two points compared to the simpler model. Covariates that were considered included observer (five levels), sea state (three levels), glare intensity (three levels), cloud cover (numeric), visibility (two levels), and plane type (two levels; Partenavia P68C and DeHavilland Twin Otter). Sea state and visibility were considered inherently correlated, and so were glare intensity, cloud cover and visibility. These combination of variables were thus not included simultaneously in the same model.

Estimated group size at maximum detectability, $\hat{E}(s)$ (i.e. in areas not believed to be affected by distance and therefore not biased) was calculated using the size bias regression method (ln of cluster size [s_i] against the detection function value [g(x)]) if the regression was significant at α = 0.15; while the mean cluster size was otherwise used (Buckland et al. 2001).

In high density areas, observers sometimes did not have sufficient time to record detailed information about all beluga groups, and group size was recorded in priority. As a result, some observations lacked a measure of perpendicular distance. These observations were not used for the selection of the detection function, nor in the size-bias regression. However, observations without a recorded perpendicular distance measurement are assumed to be within truncation distance as it is expected that the effective search area was narrowed at higher densities. Hence, these observations without perpendicular distance were assumed to follow the same distribution as observations with distance measurements and were included in the estimation of encounter rates and expected cluster size for the estimation of surface density and abundance. To that effect, a uniform model was fitted to all observations using the Distance software (version 7.5 Release 2; Thomas et al. 2010) and the inverse of the strata-specific probability of detection estimated by the gamma detection function, $\hat{P}$ (with corresponding SE and degrees of freedom) as a multiplier.

The estimated indices of density ($\hat{D}_i$) and abundance ($\hat{N}_i$) of beluga at the surface during systematic survey of each stratum, *i*, were estimated in Distance using equations 1 and 2 (Buckland et al. 2001):

$$\hat{D}_i = \frac{n_i \cdot \hat{E}_i(s)}{2L_i \cdot \widehat{ESHW}_i} \qquad (1)$$

$$\hat{N}_i = \hat{D}_i \cdot A_i \qquad (2)$$

where n_i is the number of groups detected, $\hat{E}_i(s)$ is the expected cluster size, L_i is the sum of lengths of all transects, A_i is the area, and $\widehat{ESHW}_i$ is the effective strip half-width of stratum *i*. The $ESHW_i$ is defined as the distance at which the number of groups detected beyond $ESHW_i$ and missed within $ESHW_i$ is equal, such that:

$$\widehat{ESHW}_i = \int_0^w \hat{g}(x)dx \qquad (3)$$

where *w* is the right truncation distance, and $\int_0^w \hat{g}(x)dx$ is the area under the curve of the detection function $\hat{g}(x)$.

The associated variance in density and abundance of animals at the surface during the systematic survey was estimated by:

$$\widehat{var}(\hat{D}_i) = \hat{D}_i^2 \cdot \left[\frac{\widehat{var}[(n/L)_i]}{(n/L)_i^2} + \frac{\widehat{var}(\widehat{ESHW})}{(\widehat{ESHW})^2} + \frac{\widehat{var}[\hat{E}_i(s)]}{[\hat{E}_i(s)]^2}\right] \qquad (4)$$

$$\widehat{var}(\widehat{N}_i) = A_i^2 \cdot \widehat{var}(\widehat{D}_i) \quad (5)$$

The 95% confidence interval (CI) was estimated assuming the distribution of density is log-normally distributed, as suggested in Buckland et al. (2001):

$$(\widehat{D}_i / C , \widehat{D}_i \cdot C) \quad (6)$$

where:

$$C = exp\left[t_{df}(\alpha) \cdot \sqrt{var(\ln \widehat{D}_i)}\right] \quad (7)$$

$$var(\ln \widehat{D}_i) = \ln\left[1 + \frac{\widehat{var}(\widehat{D}_i)}{\widehat{D}_i^2}\right] \quad (8)$$

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 (1946) method adapted by Buckland et al. (2001):

$$df = \frac{\left[\sum_q [cv_q]^2\right]^2}{\sum_q [cv_q]^4 / df_q} \quad (9)$$

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

The overall surface abundance in Belcher Islands-eastern Hudson Bay was defined as the sum of abundance indices for the Tasiujaq lake stratum (RG), the second survey of the Belcher Islands-eastern Hudson Bay high coverage stratum (HC2), and the Belcher Island-eastern Hudson Bay low coverage (HN) stratum. The surface density estimated from the first survey of the Belcher Islands-eastern Hudson Bay high coverage stratum (HC1) was not used to calculate a surface abundance index since only 24% of the planned transects were flown.

Adjustment of the 1985-2021 time series

Beluga surface abundance estimates from previous surveys of the Belcher Islands-eastern Hudson Bay area have been derived using half-normal or hazard rate detection functions (Kingsley 2000; Gosselin et al. 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024), which assume maximum probability of detection on the track line. To account for the blind area under the plane, left truncation had to be used, resulting in somewhat subjective decisions and underuse of sightings within the maximum probability of detection. Since the development of the 'mrds' package in R (Laake et al. 2022), the gamma function is available for use in distance sampling analyses. This function optimizes the use of existing data when maximum probability of detection is away from the trackline. To make the surface abundance estimate from the 2024 survey directly comparable to previous surveys, gamma detection functions were also fitted to survey-specific sightings as described above for line transect surveys flown since 1993.

The 1985 aerial survey of the Belcher Islands-eastern Hudson Bay area was not conducted following a line-transect design but using a strip-transect design, with observers recording all beluga observations within a 1,000 m-wide strip on each side of the aircraft (Smith and Hammill 1986). Analysis of strip transect surveys assumes that all animals within the strip have been detected (Buckland et al. 2001); however, this assumption is often violated and can lead to negatively biased population estimates (Burnham and Anderson 1984). As in the 2021 assessment, the line-transect surveys flown between 1993 and 2024 were re-analyzed as strip-transect surveys assuming a strip width of 1,000 m (St-Pierre et al. 2024). For each survey, only beluga observed between a minimum distance of 53 m from the plane (i.e., the minimum perpendicular distance measured in all eight line-transect surveys, except for one outlier measured at 25 m which was deemed a measurement error given the field of view of the plane) and a maximum distance of 1,053 m were used in the analysis to replicate a 1,000 m-wide strip. For each of the eight surveys, the ratio between the total surface abundance index from the strip-transect method and the corresponding line-transect estimate derived using the gamma detection function was calculated. The average ratio and corresponding variance was used to adjust the 1985 strip-transect survey estimate to make it comparable with the line-transect estimates.

CORRECTIONS FOR AVAILABILITY AND PERCEPTION BIASES

Abundance estimates obtained using aerial surveys can be affected by two main sources of bias: 1) observers not detecting whales located within the area being surveyed because they are diving (availability bias), and 2) observers not detecting animals that are at or near the surface and within the observer's field of view (perception bias; McLaren 1961; Marsh and Sinclair 1989; Laake et al. 1997; Fleming and Tracey 2008; Melville et al. 2008). Availability and perception bias corrections were calculated and their reciprocal applied as multipliers (with corresponding SE) to surface abundance indices to generate fully corrected abundance estimates. The uncertainty associated with fully corrected abundance estimates ($\widehat{N_c}$) was calculated according to properties of error propagation:

$$CV_{\widehat{N_c}} = \sqrt{CV_{\hat{N}}^2 + CV_{\hat{a}}^2 + CV_{p(0)}^2} \quad (10)$$

where $\hat{a}$ and *p(0)* are the availability and perception bias estimates, respectively.

Availability correction

The availability bias correction is based on beluga surface interval data from independent satellite telemetry projects and time-in-view from the aircraft based on flight characteristics. The availability correction is calculated using models describing the surface [*E(sf)*] and dive [*E(dv)*] intervals as a two-state, continuous-time Markov process (Laake et al. 1997). *E(sf)* and *E(dv)* represent the mean duration of surface and dive intervals, respectively, weighted by the number of dives recorded for each tagged individual. Time-depth data were obtained from nine beluga equipped with temperature depth-satellite relayed data loggers (TD-SRDLs; Sea Mammal Research Unit, St. Andrews, UK) in the eastern Hudson Bay arc in 2003 and 2004 (see Bailleul et al. 2012 for details regarding logger deployment and St-Pierre et al. (2024) for data screening and analysis).

A dive was defined as an excursion below 4 m. This threshold was assumed to correspond to the depth beyond which beluga would become invisible to a passing aircraft, and is consistent with the 5 m depth at which models representing adult beluga could be detected and differentiated from narwhal models in the waters of Repulse Bay, in Nunavut (Richard et al. 1994). Dive duration was calculated as the time elapsed until the animal came back above 4 m, and surface duration was the time between consecutive dives. The availability at a perpendicular distance *x* can be estimated by adding: 1) the probability that an animal is at the surface when a plane flies overhead, and 2) the probability that an animal that is diving when the plane arrives overhead will surface within the observer's field of view while the plane passes overhead. The period during which a beluga is available for detection depends on the diving behaviour of the animal and on the time interval *w(x)* that a point at the surface of the water, located at a perpendicular distance *x* from the track line, remains in the field of view of the observers. An availability correction factor, or the inverse of the estimated proportion of time available at the surface, $1/\hat{a}$, was calculated for the 2024 survey using equation 4 in Laake et al. (1997):

$$\hat{a} = \frac{E(sf)}{E(sf)+E(dv)} + \frac{E(dv)\left[1-e^{-w(x)/E(dv)}\right]}{E(sf)+E(dv)} \qquad (11)$$

The time period *w(x)* depends on the aircraft speed, *v*, and on the searching pattern of the observers. Observers were assumed to have had a conical field of view on each side of the aircraft, limited horizontally forward by an angle Φ_1 and backward by an angle Φ_2, thus *w(x)* was estimated using the following formula from Forcada et al. (2004), and Gómez de Segura et al. (2006):

$$w(x) = \frac{x}{v}\,[\cot(\emptyset_1) + \cot(\emptyset_2)] \qquad (12)$$

We used forward and backward viewing angles of 30° and 20°, based on measurements conducted from primary observer seats in the Partenavia P86. Such measurements were not taken in the Twin Otter, however the distribution of relative angles from sightings recorded during the survey did not suggest differential field of views among aircraft types (Appendix 1). Plane speed, *v*, was assumed to be constant at the target speed of 100 knots or 51.4 m/s. The availability correction factor, $1/\hat{a}$, was calculated using a perpendicular distance (*x*) corresponding to that at which the gamma detection curve used to estimate surface abundance indices reached its apex.

The CV around the average availability bias was calculated using a bootstrap procedure that accounted for three sources of variability: 1) the intra-individual variation in surface and dive intervals; 2) the inter-individual variation between average surface (*E(sf)*) and dive (*E(dv)*) intervals among the 9 tagged beluga; and 3) the variation in viewing angles associated with observer's positioning in the aircrafts and visual search pattern. For each of the 500 bootstrap iterations, the surface and dive interval data was resampled with replacement, generating telemetry samples that matched the row count of the original dataset. Similarly, beluga detections were resampled with replacement to generate a distribution of perpendicular distances of size *n*, corresponding to the number of groups detected for which perpendicular distance was within right truncation distance from the aircraft. A gamma detection curve with the same covariates as the original function was fitted to each of the bootstrap beluga detection samples, and the perpendicular distance at the apex of these detection functions extracted. Finally, the Φ_1 and Φ_2 viewing angles were drawn from a uniform distribution ranging from 20°-40° and 10°-30°, respectively, as some observations were recorded at Φ_1 and Φ_2 angles down to 0°(Appendix 1). The range of potential viewing angles were considered to be the same among aircraft types used to fly the survey (Appendix 1). The standard errors around stratum-specific availability biases were calculated as the standard deviations of the 500 stratum-specific bootstrap estimates of $\hat{a}$.

Perception correction

The 2024 James Bay survey and the first survey (pass) of the high coverage stratum (HC1) in the Belcher Islands-eastern Hudson Bay area were flown in a double platform configuration, making it possible to estimate perception bias. While the secondary observer was always seated on the right side of the plane in Partenavia aircrafts, the secondary observer was seated either on the right or the left side in Twin Otter planes. In all aircraft, the two observers seated on the same side of the plane were isolated from each other visually by an opaque curtain, and aurally by headset intercom while they searched the same area, i.e., in an independent observer configuration (Burt et al. 2014). Sightings detected while both observers were actively searching for animals (i.e., "on effort") were used to estimate perception bias via mark-recapture distance sampling (MRDS) methods (Laake and Borchers 2004) using the package "mrds" (Laake et al. 2022).

Duplicate beluga sightings, i.e., groups of animals detected by both the primary and secondary observers, were identified through coincidence in location based on the difference in: 1) time of recording, and 2) clinometer measurement. As in previous surveys, thresholds of 10 s and 10° were used to identify duplicates (St-Pierre et al. 2024). For observations lacking a clinometer measurement, only the time threshold was considered.

MRDS analyses require that perpendicular distance and covariate values be identical for duplicate sightings. In cases where primary and secondary observers recorded different clinometer or covariate values, the average (for continuous covariates, i.e., perpendicular distance, cluster size, cloud cover) or the value with the larger negative impact on detectability (for categorical covariates, i.e., Beaufort, glare intensity and visibility) was retained.

MRDS analyses consist of two functions: 1) a multiple covariate distance sampling (MCDS) detection function for detections pooled across the two front-rear observers, and 2) a MRDS detection function to estimate the probability of detection on the track line (Buckland et al. 2001, Buckland et al. 2009). Both functions used the right truncation distance identified for the analysis of the single-platform dataset. For the MCDS function, a gamma model without adjustment term and including binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as a covariate was fitted to perpendicular distances. Additional covariates (see Surface abundance estimates section above) were included if their use reduced the AIC by at least two points. An MRDS model with the point-independence assumption was implemented, which models the potential decrease in detectability among observers as distance increases (Burt et al. 2014). Indeed, detection probabilities may be correlated between the primary and secondary observers although they acted independently, for example due to factors such as group size (e.g., observers may be more likely to both detect larger groups than smaller groups as distance increases). This configuration assumes that platforms are symmetrical and that sightings are independent only on the track line, which is more robust then a configuration assuming independent detection at all perpendicular distances (Buckland et al. 2009, Burt et al. 2014). By definition, perpendicular distance is included as a covariate in all point-independence MRDS models (Buckland et al. 2009). Observer (primary vs secondary) was also considered as a covariate (i.e., so $p_{1|2} \neq p_{2|1}$) and retained if selected by AIC (Burt et al. 2014). The best fitting MRDS model was selected and estimates of *p(0)* for the primary observer were then used to correct the surface abundance estimates calculated using data from the primary observers, assuming that *p(0)* was the same for primary observers on the right and left side of the aircraft.

Adjustment of the 1985-2021 time series and 2024 BEL-EHB survey

Because both availability and perception bias estimates are derived from the distribution of perpendicular distances used to fit the detection function, they are subject to change when right and left truncation distances are applied to the data. As a result, the availability bias estimate was recalculated for surveys conducted between 1993 and 2021 using the distance at the apex of survey-specific gamma detection functions in Equation 11. The 1985 survey was flown using strip-transect methods, implying that perpendicular distances associated with observations were not recorded, precluding the use of equations 10 to 12 to estimate availability. Instead, the average of availability correction factors estimated for perpendicular distances measured for each beluga detection recorded during surveys flown between 1993 and 2024 was applied to the 1985 survey.

Similarly, the perception bias was recalculated using gamma functions in MCDS models fitted to the 2015 and 2021 surveys, which were flown in a double-platform configuration, yielding survey-specific estimates of *p(0)*. Surveys prior to 2015 were flown as single platform and thus, no survey-specific perception bias estimate could be calculated for these surveys. Instead, all double-platform beluga detections from the 2015 and 2021 surveys, as well as the 2024 JB and

HC1 strata were pooled to fit a gamma function in MCDS, yielding a combined estimate of *p(0)* which was applied to correct abundance estimates for surveys flown between 1985 and 2011. Similarly, the second survey (pass) of the high coverage stratum (HC2) and the low coverage stratum (HN) in the Belcher Islands-eastern Hudson Bay area were flown as single platform, and with different observers than the JB survey and the HC1 survey. As for surveys prior to 2015, no survey-specific *p(0)* could be estimated for these strata and the combined *p(0)* was applied to correct the 2024 Belcher Islands-eastern Hudson Bay abundance estimate.

ESTUARY COUNTS

Beluga detected in the Little Whale River and Nastapoka River estuaries were assumed to represent total counts and were added to fully corrected abundance estimates. That is, the maximum number of beluga counted either by visual observers or from non-overlapping areas of adjacent pictures were considered a census of estuary abundance and were therefore not corrected for availability and perception biases.

RESULTS

SURVEY COMPLETION

The 25 lines planned in James Bay were completed from July 18th to July 26th with a three-day interruption due to weather between July 20th and 22nd (Table 1; Figure 3Figure 2). Of the 35 lines planned for the first survey of the Belcher Islands-eastern Hudson Bay high coverage stratum (HC1), only eight were completed while five were partially flown between July 31st and August 10th, with a seven-day interruption between August 1st and August 7th due to weather and aircraft maintenance (Table 1; Figure 3). Survey activities were temporarily suspended from August 10th to August 24th due to unforeseen circumstances, before resuming. The HC1 survey was discontinued due to the time elapsed since its initiation, to ensure that any potential directional movements of beluga within the stratum would not compromise abundance estimates. The partial data collected during the HC1 survey (n = 33 or 5.3% of sightings) was included to fit the detection curve and to estimate the perception bias. However, sightings from this aborted pass were not included in the calculation of surface abundance indices for the Belcher Islands-eastern Hudson Bay area. All 36 lines planned for the second survey of the Belcher Islands-eastern Hudson Bay high coverage stratum (HC2) were flown in six days from August 28th to September 13th, with a five-day interruption between August 29th and September 2nd and several short interruptions on September 4th, 5th, 8th, 9th, and 11th. However, four sections of lines extending over 14, 18, 40 and 72 km (or 1.7% of the stratum) and located northeast of the Belcher Islands (i.e., between 78.0°W-79.4°W and 56.5°N-57.3°N, Figure 3) could not be completed due to persistent fog over the area. The six lines of the Belcher Islands-eastern Hudson Bay low coverage stratum (HN) were flown on September 6th, while the five lines of the Tasiujaq Lake (RG) stratum were completed in a single day on August 9th.

The eastern Hudson Bay coast was surveyed from south of Long Island (54°38.0'N; Punngavik) to north of Inukjuak (58°40.0'N; Upimgiviarjuk) in three segments completed on July 30th, September 5th, and September 7th (Figure 3). In addition, the coastline of Tasiujaq Lake was surveyed on July 30th, while the coastline of Long Island was surveyed on September 5th. The Nastapoka River estuary was surveyed on September 7th, while the Little Whale River estuary was surveyed on four occasions, on July 30th, September 7th, September 10th, and September 13th.

BELUGA SIGHTINGS

A total of 620 groups of beluga or 1,154 individuals were detected by the primary observers during the survey of James Bay and Belcher Island-eastern Hudson Bay (Table 1; Figure 4,Figure 5 and Figure 6). Of these, 481 groups of beluga for a total of 907 individuals were detected in James Bay (Table 1; Figure 1). Totals of 57 and 190 beluga individuals were observed on the first (HC1; incomplete; Figure 5) and second (HC2; Figure 6) surveys of the Belcher Island-eastern Hudson Bay high coverage strata, respectively (Table 1). No beluga were observed in Tasiujaq Lake and in the Belcher Island-eastern Hudson Bay low coverage stratum (Table 1; Figure 6).

No beluga were sighted during coastal surveys, except for one individual detected 59 km southeast of Inukjuak (Figure 7). No beluga were observed during surveys of the Nastapoka and Little Whale rivers. The beluga sighted during the coastal flights was not considered in the systematic survey estimate of the Belcher Islands-eastern Hudson Bay since it was not detected in an estuary.

DETECTION CURVE

Of the 621 groups of beluga detected in James Bay and Belcher Islands-eastern Hudson Bay, 547 had perpendicular distance measurements and were used to fit a detection curve. The distribution of perpendicular distances from the track line showed an obvious gap between 3,152 m and 3,815 m, with two observations made between 3,815 and 3,849 m (Figure 8). The distance of 3,152 m was therefore considered as a candidate threshold for right truncation. Other right truncation guidelines suggested truncation distances of 1,619 m (re. $g(x)$ = 0.15), 1,687 m (re. 5% of further sightings), and 1,291 m (re. 10% of further sightings). The 1,687 m truncation provided a good model fit based on the p value of the W^2 statistic of the Cramér-von Mises test, and was applied to the perpendicular distance data upon fitting detection functions. The only covariate that further improved the model fit was the observers (7,407, ΔAIC = 10), which was retained for further analyses (Table 2). This generated ten detection curves (one per observer × 2 cluster sizes; Figure 9) with an average (± SE) effective strip half-width (ESHW) of 756 ± 66 m.

GROUP SIZE

The regression of the natural log of cluster size [ln(s)] against the probability of detection $g(x)$ was not significant (p = 0.88) for the 519 groups with available perpendicular distance and within truncation distances, therefore the average cluster size was used in all strata. Across all strata, group size ranged from 1 to 30 beluga, with a global mean group size of 1.84 beluga (CV = 5%). The 408 groups detected in James Bay had a mean group size of 1.91 (CV = 6%, Table 3; Figure 10A). In the high coverage stratum, the 33 groups detected during the first pass yielded a mean group size of 1.73 (CV = 17%) while the 105 groups detected during the second pass yielded a mean group size of 1.62 (CV = 10%; Table 3; Figure 10B). Strata-specific average group sizes were used to calculate surface abundance indices.

ENCOUNTER RATES

The encounter rate in James Bay was 0.101 groups·km^{-1} (CV=21%; Table 3). Despite incomplete coverage during the first survey in the high coverage stratum of Belcher Islands-eastern Hudson Bay, encounter rates were comparable between the two surveys flown over this stratum (HC1: 0.017 groups·km^{-1}, CV = 83%; HC2: 0.013 groups·km^{-1}, CV = 21%), and 6 to 8 times lower than the encounter rate in James Bay.

DENSITY AND ABUNDANCE ESTIMATES

The surface abundance indices before correcting for availability and perception biases were 4,349 beluga (95% CI: 2,761-6,851) for James Bay, and 479 beluga (95% CI: 300-767) for Belcher Islands-eastern Hudson Bay (Table 3). Surface densities were 0.056 beluga per km^2 for James Bay (CV = 21%) and 0.006 beluga per km^2 (CV = 23%) during the second survey of the Belcher Islands-eastern Hudson Bay high coverage strata (HC2; Table 3). The first survey of the Belcher Islands-eastern Hudson Bay high coverage strata yielded a surface density of 0.009 beluga per km^2 (CV = 85%), however this estimate was not used to calculate surface abundance because of the incomplete coverage of the survey area.

In James Bay, encounter rate, group size, and the detection function accounted respectively for 46%, 4%, and 50% of the variance of density. The same components accounted for respectively 26%, 2%, and 72% of the variance of density for the first survey of the high coverage stratum (HC1) in Belcher Islands-eastern Hudson Bay, and 2%, 1%, and 97% of the variance of density for the second survey of the high coverage stratum (HC2).

AVAILABILITY CORRECTION FACTORS

For the 2024 survey, availability bias was estimated at 0.514 (CV = 4%). Correcting the surface abundance indices from this survey considering the proportion of animals that are available at the surface and not submerged (availability bias) produced a partially corrected abundance index of 8,455 beluga for James Bay (CV =22%, 95% CI: 5,548-12,886) and 931 beluga for the Belcher Islands-eastern Hudson Bay area (CV = 24%, 95% CI: 591-1,469).

PERCEPTION CORRECTION FACTORS

From the 2024 survey data, 215 unique beluga sightings were recorded while both observers flying in a double platform configuration were on effort. Based on a coincidence in location, using time and clinometer thresholds of 10 s and 10°, 128 sightings were identified as duplicates detected by both the primary and secondary observers. In the MRDS analysis, a gamma key function without adjustment term and with binary cluster size as a covariate (AIC = 3,017) was fitted to the 208 primary sightings remaining after right truncating the data at 1,687 m. The only covariate that further improved the MCDS model fit was the observers (3,008, ΔAIC = 9), which was retained for further analyses (Table 4). In the MRDS model, the inclusion of observer type (primary vs secondary) reduced the AIC by 18 points and was therefore retained. This yielded a detection function with an average (± SE) ESHW of 864 ± 89 m (Figure 11). This model yielded a primary *p(0)* of 0.7382 (CV = 8%; Table 5) which was used to correct the James Bay abundance estimate and a secondary *p(0)* of 0.5363 (CV = 12%).

The 213, 166 and 215 unique beluga sightings recorded while both observers flying in a double platform configuration were on effort during the 2015, 2021 and 2024 surveys, respectively, were pooled. Of these, 205 were identified as duplicates. Data was right-truncated at 1,550 m. Including observers and Beaufort (AIC = 8,094) as covariates in the gamma detection function reduced the AIC by 23 points compared to the gamma model with binary cluster size alone (AIC = 8,117), thus these covariates were retained (Table 6). In the MRDS model, the inclusion of observer type (primary vs secondary) reduced the AIC by 27 points and was retained. The resulting detection function had an average ESHW of 759 ± 83 m (Figure 12). The primary and secondary *p(0)* estimated by this model combining the 2015, 2021 and 2024 double-platform data were 0.6248 (CV = 7%; Table 5) and 0.4828 (CV= 9%), respectively. The primary *p(0)* was used to correct the 2024 Belcher Islands-eastern Hudson Bay abundance estimate.

Correcting further for the proportion of animals available at the surface that are detected by observers, i.e. perception bias, resulted in fully-corrected abundance estimates of 11,455 beluga for James Bay (CV = 23%, 95% CI: 7,322-17,921) and 1,491 beluga for the Belcher Islands-eastern Hudson Bay area (CV = 25%, 95% CI: 928-2,396; Table 5).

ADJUSTING HISTORICAL ABUNDANCE ESTIMATES

Appendices 2 to 8 present model selection results, gamma detection curves providing the best fit, derived encounter rates, surface density indices, and re-estimated surface abundances for surveys flown between 1993 and 2021. Surface abundance estimates derived from gamma models were strongly correlated with estimates previously published and derived from hazard rate models combined with left truncation of the distance data (Pearson's $r = 0.96$; Figure 13A; Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024), although gamma-derived surface abundance indices were, on average, 6% ($P < 0.001$) and 1% ($P < 0.001$) lower than their equivalent derived from hazard-rate detection curves for the BEL-EHB and JAM stocks, respectively.

The average strip-to-line ratio calculated using the 1993 to 2024 survey data was of 1.387 (CV = 17%) and 1.460 (CV = 20%), for the James Bay and Belcher Islands-eastern Hudson Bay areas, respectively. The 1985 strip-transect surface abundance indices for each stratum were multiplied by the corresponding ratio, yielding surface abundance estimates of 1,682 (CV = 30%) beluga for James Bay and 1,413 (CV = 27%) beluga for the Belcher Islands-eastern Hudson Bay area.

Appendices 7 and 8 respectively present the MCDS model selection results and gamma detection curves retained for the MRDS model used to estimate the perception bias correction from the 2015 and 2021 survey data. For both surveys, the only covariate retained in the mark-recapture function to estimate the probability of detection on the track line was observer type (primary vs secondary). MRDS models yielded primary *p(0)* estimates of 0.436 (CV = 24%) and 0.643 (CV = 11%) for the 2015 and 2021 surveys, respectively (Table 5).The corresponding perception bias correction factors were applied to survey results from 2015 and 2021 (Table 5).

For surveys flown prior to 2015 in a single platform configuration, the perception bias estimate of 0.625 (CV = 7%), calculated by combining the 2015, 2021 and 2024 double-platform data, was applied (Table 5). Resulting newly corrected abundance estimates were strongly correlated with estimates published previously (St-Pierre et al. 2024; Pearson's $r = 0.92$; Figure 13B). However, newly corrected abundance estimates were respectively 15% ($P < 0.001$) and 21% ($P < 0.001$) smaller than previously published fully-corrected BEL-EHB and JAM stock abundance estimates (St-Pierre et al. 2024).

DISCUSSION

The 2024 survey of James Bay and the Belcher Islands-eastern Hudson Bay area is the ninth of a series of systematic surveys flown since 1985 (Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024). The basic approach was similar although the altitude and the use of bubble windows changed over time. Bubble windows were mostly used, except in 1985, 1993 and 2011. The use of bubble windows may affect the detection of beluga near the track line. However, the gamma function is expected to be adjusted to the survey-specific distribution of detections at all distances from the track line, thus accounting for the variability associated with the use of bubble windows. Accordingly, the ESHW estimated for line-transect surveys flown with bubble windows (average = 745 ± 28 m) did not differ ($P = 0.58$) from that flown without bubble windows (average = 776 ± 52 m), supporting little effect of bubble windows on surface abundance indices. The target survey altitude was of 305 m (1,000 feet) for all years, except in 1993 and 2011 when it was 457 m (1,500 feet). A series of 14 surveys conducted both at 457 m and 305 m in the St. Lawrence

Estuary in 2003 and 2005 indicated that changes between these two altitudes had no effect on the estimation of beluga abundance (Gosselin et al. 2007). Different observers had different searching patterns during surveys, which are accounted for upon fitting the detection curve for each survey.

The strata-specific abundance estimates derived from this survey were calculated using the same distance sampling methods and correction factors as in past studies (St-Pierre et al. 2024). However, a gamma detection curve was fitted to perpendicular distance data to avoid left truncation of the data, which is required by functions assuming maximal detectability on the track line. To ensure comparability of the 2024 abundance estimates with estimates from previous surveys, the 1985-2021 time series was adjusted by refitting detection curves using a gamma key function. This yielded abundance estimates that are highly correlated but 15-21% smaller than previously published values. While part of this difference is attributable to changes in surface abundance estimates (Figure 13A), most of it is due to smaller corrections being applied for perception bias in the present study. This is explained by the inclusion of the observer (primary vs secondary) covariate in the mark-recapture model used to estimate detectability on the track line in the present study. This covariate improved model fit for all MRDS models. Its inclusion in mark-recapture models resulted in different *p(0)* estimates for the primary and the secondary observers (i.e., $p_{1|2} \neq p_{2|1}$), thus accounting for potential inter-annual differences in searching patterns and detectability among visual observers. The higher estimate for primary *p(0)* than secondary *p(0)* is likely due to the most experienced observers generally being assigned primary observer seats during flights.

Observations without a perpendicular distance accounted for 0 to 23% of beluga detections from surveys flown between 1993 and 2024. These observations were assumed to have been within truncation distance. This assumption may not be fully realistic, and may introduce a positive bias to abundance estimates. However, because the gamma detection curve accounts for the potential blind area underneath the aircraft without having to apply left truncation to observations, it enables the use of a larger range of the perpendicular distance distribution. Therefore, the potential positive bias introduced by the inclusion of observations without a perpendicular distance is expected to be smaller in this study than in previous assessments relying on both left and right truncation to fit the detection curve (Gosselin et al. 2017; St-Pierre et al. 2024).

In 2024, the James Bay survey and the first survey of the high coverage stratum (HC1) in the Belcher Islands-eastern Hudson Bay area were flown in a double-platform configuration, enabling the estimation of a perception bias through mark-recapture distance sampling. For the 2024 James Bay survey, the difference between the primary (0.738, CV = 7.9%) and secondary (0.536, CV =12.0%) *p(0)* was particularly marked, underscoring the importance of collecting survey-specific data to estimate the perception correction bias whenever possible. Because the survey crew changed between the 2024 HC1 and HC2 Belcher Islands-eastern Hudson Bay surveys and no double platform data was available to estimate *p(0)* during the latter, a perception bias estimated by combining the 2015, 2021 and 2024 double-platform data was applied to correct the BEL-EHB beluga abundance estimates. This overall *p(0)* value was also used to correct surface abundance indices from surveys flown prior to 2015 in a single-platform configuration.

This study is the first to consider individual observers as a potential covariate upon fitting the detection curve for beluga visual surveys carried out in Nunavik. Among considered covariates, observers was the sole covariate that improved the AIC of the detection curve for the 2024 survey data. This covariate integrates variation in detectability associated with specificities of the platform used by each observer, as well as inter-individual variations in searching patterns, identification abilities, and observer-specific reactions to survey conditions such as glare and sea state (i.e., observers may differentially alter their searching pattern when they feel conditions are negatively affecting detectability at greater distances or on portions of their searching area). Observers therefore appears as a covariate that is worth considering when analyzing systematic line-transect survey data.

A total of 14 and 37 beluga were captured in James Bay and estuaries of Eastern Hudson Bay (i.e., Nastapoka and Little Whale Rivers), respectively, and equipped with satellite tags from 1993 to 2009 (Bailleul et al. 2012). However, it was not possible to calculate meaningful surface and dive intervals in the context of availability for detection from a survey plane from the settings of most of these tags. Specifically, most (n = 28/37) of the tags installed on beluga tracked in eastern Hudson Bay did not record data on individual dives, but as 6-h summaries. In addition, tag data from beluga tracked in James Bay was extracted using a threshold of 6 m to define surface and dive times, which is deeper than the depths of 2 m and 5 m at which beluga were estimated to be detectable from an aircraft in murky and clear water, respectively (Kingsley and Gauthier 2002; Richard et al. 1994). Correction factors for the availability bias were therefore calculated from nine individuals tagged in the eastern Hudson Bay area in 2003 and 2004 for which individual dive data was available, and a dive threshold of 4 m was used. Ideally, diving data from whales equipped with satellite transmitters during the period of the survey and in the survey areas should be used to calculate availability bias. Transmitters were not deployed during the 2024 survey, thus it was assumed that beluga diving behaviour has not changed over the years and that the 9 belugas tagged were representative of beluga from both James Bay and the Belcher Islands-eastern Hudson Bay area. While tag data did reveal variability in beluga diving patterns both within and between BEL-EHB and JAM summer habitats (Bailleul et al. 2012), how this may translate into strata-wide differential availability for detection during aerial surveys is unknown. The correction for availability bias was calculated separately for each survey based on the detection curve fit to perpendicular distances at which observations had been recorded, yielding correction factors ranging from 0.514 to 0.663 (Table 5). Overall, correction factors did not show any temporal trend. Because the diving data used to estimate availability bias represent combined data from animals tagged in 2003 and 2004, the variability observed in estimated availability bias among years mirrors differences in the distribution of perpendicular distances among surveys, suggesting potential differences in observer searching patterns.

In previous Nunavik studies, the CV associated with the survey-specific availability bias correction factor only accounted for inter-individual variation in average surface and dive intervals among the 9 tagged beluga (St-Pierre et al. 2024; Sauvé et al. 2023). In this study, a bootstrap procedure was developed to account for additional sources of uncertainty when calculating the variance associated with the availability bias, including intra-individual variation in surface and dive interval, as well as observation-specific time in view. Time in view is a function of perpendicular distance from the plane, aircraft speed, and the forward and backward angles defining the observer's field of view. Although observers are instructed to record observations when animals are abeam as much as possible, some observations have been recorded during marine mammals surveys flown in the same platforms from 0° (i.e., directly forward) to 180° (i.e., directly behind) of relative angle (Appendix 1). Observers therefore happen to deviate from the forward and backward obstructed viewing angles of 30° and 20°, respectively, which are generally measured during surveys. While intra-individual variation in surface and dive intervals from tracking data had a negligible effect on the CV of the availability bias, incorporating variation in searching angles increased the CV 2- to 6-fold, further emphasizing the impact of observer-related variability in visual survey estimates. Nevertheless, some sources of uncertainties associated with beluga availability to be detected from a plane are still unaccounted for in the bootstrap-derived CVs. The depth to which beluga are detectable depends on water turbidity, which varies both within and among strata covered in the James

Bay and Belcher Islands-eastern Hudson Bay areas. Assessing the impact of using different depth thresholds to define dive and surface durations on availability bias estimate, and collecting turbidity data specific to the survey area would improve the estimation of the uncertainty associated with beluga availability bias.

ABUNDANCE ESTIMATES FROM THE 2024 SURVEY

James Bay stock

With a value of 11,455 (95% CI = 7,322-17,921) beluga, the corrected abundance estimate for the James Bay stock from 2024 survey data is within the range of values observed since 1995.

In 2024, beluga were detected throughout James Bay, with high numbers of detections southeast of Akimiski Island and along the northwest coast of the bay (Figure 4). Similar spatial distributions of sightings were observed in previous surveys of James Bay, with a large number of sightings to the southeast of Akimiski Island, particularly during the 1985, 2004 and 2021 surveys, and a high proportion of sightings in the northwest portion of the bay in the 1993, 2001, 2008, 2011, and 2015 and 2021 surveys (Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024). During the 2024 survey, ~36% of the belugas sighted in James Bay were in the southern half of the bay, and ~61% in the northwestern zone. Beluga are also found along the Ontario coast of Hudson Bay (Richard 2005), and the variability in sightings in the northwestern James Bay area among surveys (e.g., 2004 survey; Gosselin 2005) may reflect movements between the two areas. Although beluga summering in James Bay are considered as a distinct breeding population, telemetry and genetic information from this area are limited to the eastern portion of James Bay, and information about beluga summering along the Ontario coast of Hudson Bay is lacking (Bailleul et al. 2012, Postma et al. 2012, Parent et al. 2023).

Belcher Islands-eastern Hudson Bay stock

The fully-corrected 2024 abundance estimate for the Belcher Islands-eastern Hudson Bay area (1,491 beluga, 95% CI = 928-2,396) is significantly lower than all the survey estimates since 2004, except for the 2011 survey which has a particularly large confidence interval (Table 5; range: 2,858-8,506). The CV associated with the 2024 BEL-EHB beluga survey (25%) is comparable to the CVs from the 2021 (29%), 2008 (22%) and 1985 (26%) surveys, and slightly lower than those from other surveys of the time series (range: 33 –51%).

Two common sources of uncertainty when conducting surveys of small populations with clumped distributions are the occurrence of a few large clusters (uneven distribution of group size among sightings) and variable encounter rates (uneven distribution of clusters among lines), which represent clumping at two different scales (Gosselin et al. 2007). Because average group size is a multiplier in the estimation of density, the occurrence of a few large beluga groups can greatly increase both the abundance estimate itself and its variance, due to an increase in the variance component associated with the estimation of group size. This effect was observed in the 2008, 2011, and 2015 surveys when a few large groups increased the mean cluster size by 50% to nearly 300%, resulting in higher abundance estimates and wide confidence intervals (Gosselin et al. 2009, 2013, 2017). In 2024, the only observations with group sizes larger than 10 individuals were two groups of 15 and 20 individuals sighted at the northern edge of HC and 60 km west of the Belcher Islands, respectively (Figure 6). As a result, group size accounted for 2 and 1% of the variance of density for the first and second surveys of the high coverage stratum, respectively. Similarly, in 2021, the only observation made during the systematic survey with a group size larger than 11 individuals was one group of 30 belugas sighted near the mouth of Little Whale River (St-Pierre et al. 2024).

At a broader spatial scale, the distribution of clusters among survey lines (i.e., the spatial distribution of beluga in the study area) may be influenced by beluga behaviour and environmental conditions (e.g., Bailleul et al. [2012] showed that sea surface temperature influences the dispersal of foraging individuals). In the 2024 survey of the Belcher Islands-eastern Hudson Bay area, encounter rates accounted for only 26% (HC1) and 2% (HC2) of the variance of density. This is due to beluga sightings being particularly spread among survey lines (Figure 6), with beluga detected on 58% of transect lines during the HC2 survey. It therefore appears that distribution of beluga groups in the study area did not have a large influence on the estimation of density and abundance for the 2024 survey of Belcher Islands-eastern Hudson Bay.

Beluga are known to form summer aggregations in and around estuaries. Accordingly, during several previous surveys of the Belcher Islands-eastern Hudson Bay area, large beluga aggregations were sighted in estuaries of the Nastapoka and/or Little Whale River, with estuary maximal counts of 167, 289, 354 and 474 beluga during the 2015, 2021, 2011 and 1985 surveys, respectively (Table 5). Throughout the time series, the maximal number of beluga observed in estuaries during coastal surveys were considered as a census, and were added to the corrected systematic survey estimates without applying any availability correction factor as individuals remain mostly available to the overhead plane when they are in the shallow waters of the estuaries. In addition, when large beluga aggregations were detected in estuaries, photographs were taken to facilitate cluster size estimation. Because of the limited area to visually scan in estuaries and/or of the photographic surveys, no correction for perception bias was applied to estuary counts as it is assumed that all beluga present are detected by observers or on photographs. The addition of estuary counts to fully corrected abundance estimates from systematic surveys assume that there is little movements between these estuaries and offshore areas during the survey period such that belugas in estuaries are unlikely to be observed on transect lines during the survey. Although these assumptions may not always be respected, this method represents a means to include large estuary beluga counts in the abundance estimates. With abundances in BEL-EHB ranging between 8,506 and 1,491 individuals, counts of a few hundred individuals observed in estuaries may contribute significantly to systematic survey estimates. Group sizes larger than 100 individuals have only been detected once during systematic surveys offshore of the Nastapoka Islands, at the mouth of Little Whale River. It is therefore assumed that these large groups observed in estuaries split into smaller groups as they move offshore where they may be detected on systematic survey lines. The fission-fusion dynamics of beluga groups between estuaries and offshore areas, and precise estimation of availability correction factors in areas surrounding estuaries may warrant further investigation. With the 2008 survey, the 2024 survey of the Belcher Islands-eastern Hudson Bay is the second of the time series during which no beluga aggregation was detected during coastal and estuary flights despite repeated passes over Little Whale River on different days (Table 5). Therefore, the low 2024 abundance estimate is unlikely to be attributable to potential underestimation of beluga numbers that could have resulted from a coastal distribution.

Systematic line-transect survey methods assume that movements of animals over the strata are random, i.e., that there is no migration during the period of the survey. Migration could have a positive bias on the systematic survey estimates. If a concentration of animals is migrating in the same direction as the survey lines are covered by the planes, this concentration of animals would then be oversampled, i.e., the effective spacing between lines and the expansion factor (ratio line spacing / ESWH) would be overestimated. A large group of animals extending over several systematic lines would be detected on more lines than they would have, had the counts been instantaneous and not allowing animal migration. Conversely, if the migration goes in the opposite direction than the survey plane, there would be a negative bias on the abundance estimate. The 2024 survey of the Belcher Islands-eastern Hudson Bay was conducted in a limited timeframe (i.e., 18 days for HC2 and HN), which is comparable to previous surveys of the same area, thereby minimizing potential biases (Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024). The period during which the HC2 (August 28th - September 13th) and HN (September 6th) were covered is slightly later than during previous surveys (Appendix 9). Yet, the spatial distribution of beluga sightings across the Belcher Islands-eastern Hudson Bay area is consistent with previous surveys, with beluga observed throughout the HC stratum and none sighted in the HN stratum (Figure 6). Moreover, beluga equipped with satellite-linked recorders in the Little Whale or Nastapoka rivers during summer (1993-2004) remained within the aerial survey area until September 16, after which they began moving northward (DFO 2024). Although this satellite tag dataset is somewhat dated, fall beluga migration has been delayed by an average of 10 days per decade since 1990 (Niemi et al. 2019). This suggests that beluga migration out of the Belcher Islands-eastern Hudson Bay area likely occurs later now than when these tags were deployed. Lastly, no beluga sightings or harvests were reported by Uumajuit Wardens in Northeastern Hudson Bay or Hudson Strait during the first two weeks of September 2024, further suggesting that beluga northward migration had not begun by the time the 2024 survey was completed. Therefore, there is no indication that the 2024 BEL-EHB beluga survey estimate could represent an underestimate of stock size due to directional movement of individuals during the period of the survey.

The 2024 JAM beluga abundance estimate is within the range of previous estimates for this stock. In contrast, the BEL-EHB beluga abundance estimate is the lowest of the time series of nine surveys flown since 1985. The 2024 Belcher Islands-eastern Hudson Bay survey was associated with the largest correction for availability bias of the time series, coupled with the same correction for perception bias as applied to most (7 out of 9) surveys of this area. Therefore, the low 2024 surface abundance index before these corrections were applied explains on its own the low 2024 fully-corrected abundance estimate. This estimate is consistent with results from the 2021 survey which also yielded a low and precise abundance estimate (St-Pierre et al. 2024), and which suggested a 3% annual decline in the BEL-EHB stock since 2015 (Hammill et al. 2023). There is no reason to believe that the 2024 survey is negatively biased compared to previous surveys. Integrated population models can buffer inter-survey variations in abundance estimates by including additional information on the stock such as age and sex structure, reproductive rates and harvest statistics. Such a model was implement for the James Bay and BEL-EHB beluga stocks to better understand stock abundance and trend over the past 40 years (Van de Walle et al. 2025).

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TABLES

Table 1. Survey effort and number of belugas detected in the different areas and strata during the visual line-transect survey of James Bay and the Belcher Islands-eastern Hudson Bay area in summer 2024. The James Bay stratum was surveyed with a low coverage (10 NM or 18.5 km spacing between transects). The survey of the Belcher Islands-eastern Hudson Bay area was stratified with a low coverage (10 NM or 18.5 km spacing) stratum in the north (HN), a central stratum which was surveyed twice with high coverage (5 NM or 9.3 km spacing, HC1 and HC2), and the Tasiujaq Lake (RG) stratum which was surveyed with a spacing of 5 NM or 9.3 km. The number of groups and individuals with perpendicular distance retained for effective strip half-width (ESHW) estimation after right truncation at 1,687 m are also provided. In addition to these sightings, one beluga with a perpendicular distance was detected during a coastal flight and was included in the data used for ESHW estimation.

Area and stratum	Dates of completion (day/month)	Stratum area (km^2)	Number of lines	Total track length (km)	Number of groups	Number of individuals	Groups (individuals) without distance	Groups (individuals) used for ESHW
James Bay	18/07 – 26/07	78,324	24	4,033	481	907	73 (127)	385 (721)
Belcher Islands-eastern Hudson Bay								
HC1	31/07 – 10/08	78,490	13	2,005	33	57	0	33 (57)
HC2	28/08 – 13/09	78,490	36	8,327	105	189	1(20)	100 (163)
HN	06/09	18,917	6	1,354	0	0	0	0
RG	09/08	705	5	95	0	0	0	0

Table 2. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 519 beluga observations recorded during the 2024 line-transect survey conducted in James Bay and eastern Hudson Bay. Binary cluster size was included a priori in the gamma function, and additional covariates were retained if their inclusion resulted in a decrease in AIC of at least 2 point. Perpendicular distances were right-truncated at 1,687 m. The model retained for surface abundance index estimation is displayed in bold type.

Covariate	AIC	ΔAIC	No. parameters	Effective strip half-width (*CV*)
Observer + Cluster size (1 vs 2+)	**7,407**	**0**	**6**	**756 (8.7%)**
Cluster size (1 vs 2+)	7,417	10	2	757 (4.8%)
Platform type + Cluster size (1 vs 2+)	7,419	12	3	757 (5.6%)
Beaufort + Cluster size (1 vs 2+)	7,419	12	5	757 (7.2%)
Cloud coverage + Cluster size (1 vs 2+)	7,419	12	3	757 (5.8%)
Visibility + Cluster size (1 vs 2+)	7,419	12	4	757 (6.7%)
Cluster size (numeric)	7,420	13	2	757 (5.1%)
Glare intensity + Cluster size (1 vs 2+)	7,423	16	5	757 (7.4%)

Table 3. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2024. These estimates consider the number of groups within the right truncation distance of 1,687 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC2, HN and RG areas (see Figure 2 for location of areas). Density from HC1 was not used to calculate a surface abundance index due to incomplete coverage of the strata.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	408	1.9118 (5.92)	0.1012 (20.60)	0.0290 (20.61)	0.0555 (21.44)	**4,349 (2,761-6,851)**
Belcher Islands- eastern Hudson Bay						**479 (300-767)**
HC1	*33*	*1.7273 (16.76)*	*0.0165 (83.01)*	*0.0049 (83.02)*	*0.0085 (84.69)*	-
HC2	*105*	*1.6190 (10.28)*	*0.0126 (20.77)*	*0.0038 (20.83)*	*0.0061 (23.23)*	*479 (300-767)*
HN	0	0	0	0	0	0
RG	0	0	0	0	0	0

Table 4. Selection of the detection function used to estimate the perception bias for the James Bay stratum, using a Gamma detection function with potential covariates fitted to 208 beluga observations recorded in double platform configuration during the 2024 line-transect survey conducted in James Bay and the eastern Hudson Bay HC1 stratum. Perpendicular distances were right-truncated at 1,687 meters. The model retained to estimate p(0) is displayed in bold type.

Covariate	AIC	ΔAIC	No. parameters	Effective strip half-width (*CV*)
Observer + Cluster size (1 vs 2+)	**3,008**	**0**	**4**	**864 (10.3%)**
Cluster size (numerical)	3,016	8	3	860 (9.8%)
Cluster size (1 vs 2+)	3,017	9	3	860 (8.2%)
Cloud coverage + Cluster size (1 vs 2+)	3,017	9	4	860 (9.6%)
Platform type + Cluster size (1 vs 2+)	3,018	10	4	860 (31.4%)
Glare intensity + Cluster size (1 vs 2+)	3,019	11	6	861 (13.0%)
Visibility + Cluster size (1 vs 2+)	3,019	11	6	861 (19.2%)
Beaufort + Cluster size (1 vs 2+)	3,022	14	6	860 (14.7%)

Table 5. Abundance estimates of beluga stocks in James Bay and the Belcher Islands-eastern Hudson Bay area estimated from nine systematic aerial surveys between 1985 and 2024. Abundance estimates have been corrected for availability bias, perception bias, and belugas counted in estuaries. Availability and perception bias estimates are presented for each survey year. The 1985 survey data were collected using strip-transect techniques[a] while the other eight surveys flew along similar lines, but data were collected using line-transect techniques[b]. The 1985 survey strip-transect estimates were multiplied by a strip-to-line ratio before correcting for availability and perceptions biases and then adding estuary counts (see St-Pierre et al. 2024 for details).

Stratum	Year	Surface abundance estimate (CV)	Availability bias estimate (CV)	Perception bias estimate (CV)	Estuary counts	Corrected abundance (CV %)
James Bay	1985	1,682 (29.6)	0.562 (9.5)	0.625 (6.9)	0	4,788 (31.9)
	1993	3,135 (24.6)	0.663 (5.7)	0.625 (6.9)	0	7,573 (26.2)
	2001	6,374 (23.4)	0.568 (5.1)	0.625 (6.9)	5	17,958 (24.9)
	2004	5,830 (32.3)	0.521 (4.2)	0.625 (6.9)	0	17,930 (23.6)
	2008	9,256 (70.4)	0.577 (2.6)	0.625 (6.9)	0	25,686 (70.8)
	2011	7,597 (28.4)	0.551 (5.0)	0.625 (6.9)	0	22,063 (29.6)
	2015	5,455 (22.5)	0.547 (4.7)	0.436 (23.8)	0	22,847 (33.1)
	2021	4,920 (20.7)	0.530 (2.2)	0.643 (10.9)	0	14,427 (23.8)
	2024	4,349 (21.4)	0.514 (3.6)	0.738 (7.9)	0	11,455 (23.1)
Belcher Islands-eastern Hudson Bay	1985	1,413 (26.6)	0.562 (9.5)	0.625 (6.9)	474	4,497 (26.0)
	1993	1,029 (37.6)	0.663 (5.7)	0.625 (6.9)	18	2,504 (38.4)
	2001	921 (44.1)	0.568 (5.1)	0.625 (6.9)	39	2,634 (44.3)
	2004	1,647 (22.2)	0.521 (4.2)	0.625 (6.9)	5	5,069 (33.2)
	2008	1,559 (20.4)	0.577 (2.6)	0.625 (6.9)	0	4,326 (21.7)
	2011	1,490 (47.0)	0.551 (5.0)	0.625 (6.9)	354	4,681 (44.1)
	2015	1,991 (46.1)	0.547 (4.7)	0.436 (23.8)	167	8,506 (51.0)
	2021	876 (29.7)	0.530 (2.2)	0.643 (10.9)	289	2,858 (28.5)
	2024	479 (23.3)	0.514 (3.6)	0.625 (6.9)	0	1,491 (24.6)

[a] *Smith and Hammill 1986*

[b] *Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024; this study.*

Table 6. Selection of the detection function used to estimate the perception bias for surveys flown in a single platform configuration (i.e, surveys flown prior to 2015, and the HC2 Belcher Islands-eastern Hudson Bay stratum of the 2024 survey), using a gamma detection function with potential covariates fitted to 562 beluga observations recorded in double platform configuration during the 2015, 2021 and 2024 (James Bay and HC1 eastern Hudson Bay strata). Perpendicular distances were right-truncated at 1,550 m. The model retained for p(0) estimation is displayed in boldface.

Covariate	AIC	ΔAIC	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Observer + Beaufort + Cluster size (1 vs 2+)	**8,094**	**0**	**0.668**	**16**	**759 (11.0%)**
Observer + Cloud coverage + Cluster size (1 vs 2+)	8,096	2	0.593	14	760 (10.5%)
Observer + Cluster size (1 vs 2+)	8,098	4	0.539	13	762 (10.3%)
Beaufort + Cluster size (1 vs 2+)	8,106	12	0.834	6	768 (6.5%)
Visibility + Cluster size (1 vs 2+)	8,108	14	0.742	5	767 (8.7%)
Cloud coverage + Cluster size (1 vs 2+)	8,113	19	0.844	4	770 (5.2%)
Cluster size (1 vs 2+)	8,117	23	0.839	3	772 (4.5%)
Glare intensity + Cluster size (1 vs 2+)	8,118	24	0.802	6	771 (6.8%)
Platform type + Cluster size (1 vs 2+)	8,119	25	0.812	4	772 (11.1%)
Observer + Visibility + Cluster size (1 vs 2+)	Very poor fit	-	0.001	15	-

FIGURES

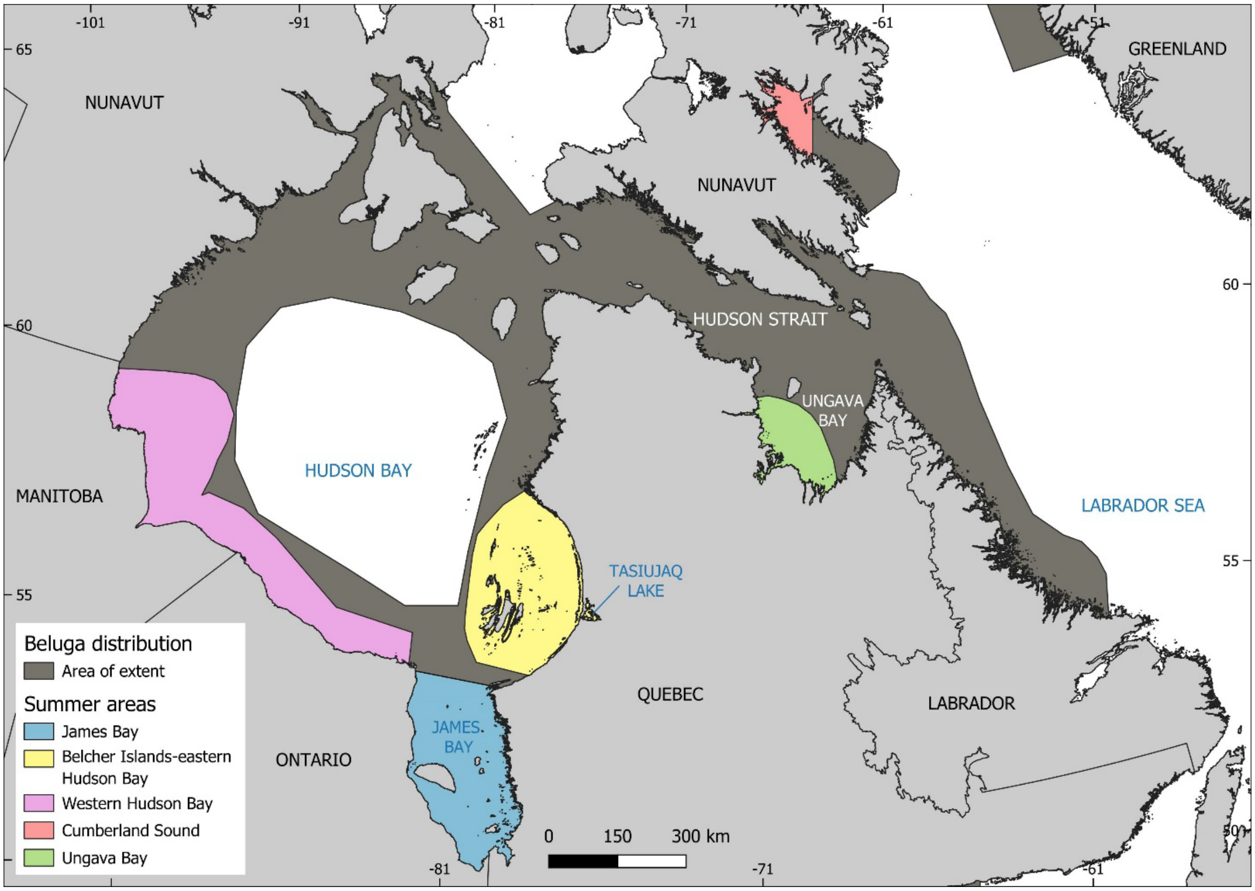

Figure 1. Distribution of beluga in eastern Canada and recognized management stocks. Adapted from COSEWIC (2020).

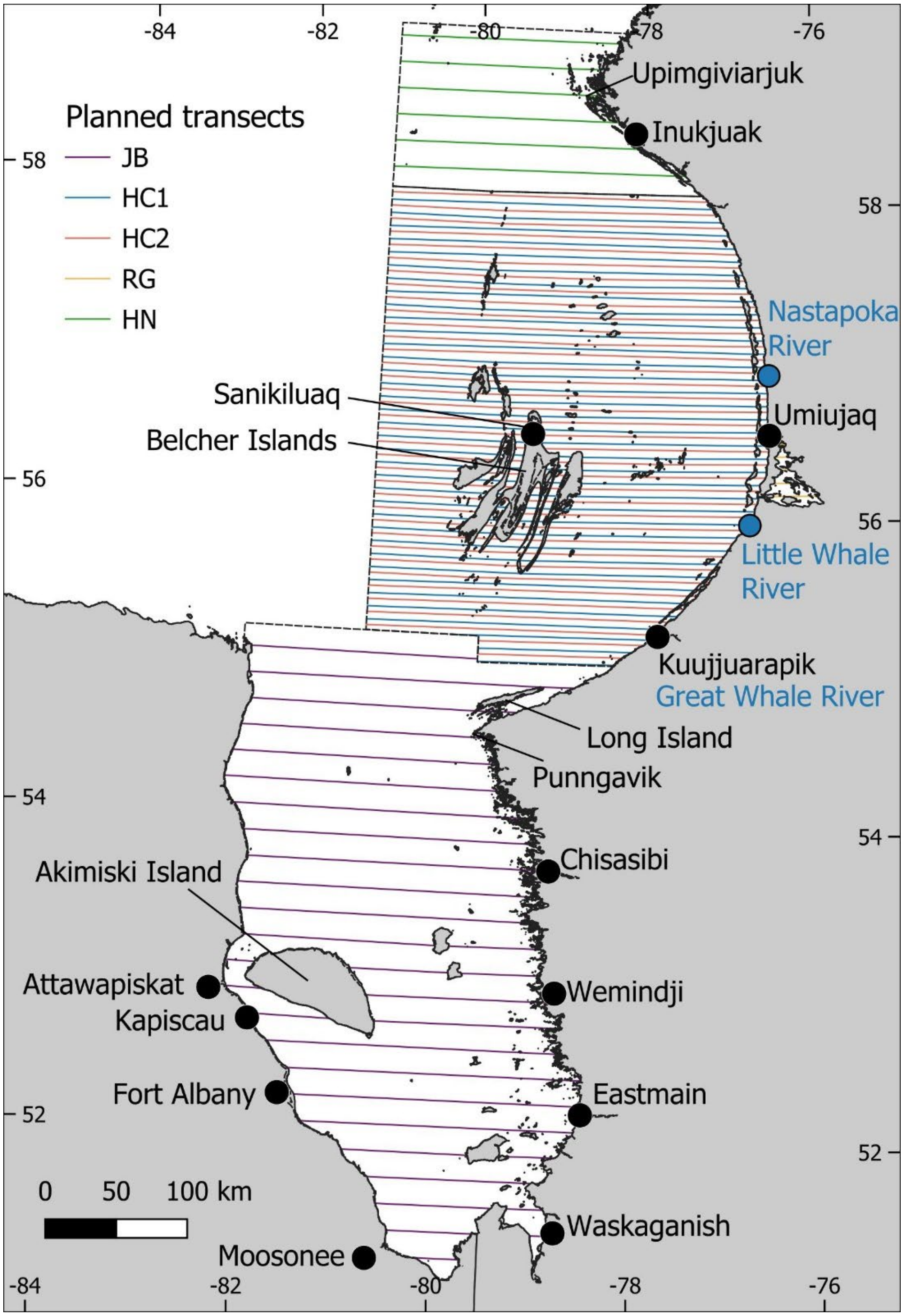

Figure 2. Transect lines planned in James Bay and the Belcher Islands-eastern Hudson Bay area for the systematic line-transect aerial beluga survey in summer 2024. The thin dashed lines show the limits of James Bay (JB) and the low (HN) and high coverage (HC) strata in the Belcher Islands-eastern Hudson Bay area. The HC stratum was planned to be surveyed twice (HC1 and HC2), with transects spaced 9.3 km (5 nautical miles) apart during each pass. The JAM and HN strata were each planned to be flown once, using a transect spacing of 18.5 km (10 nautical miles).

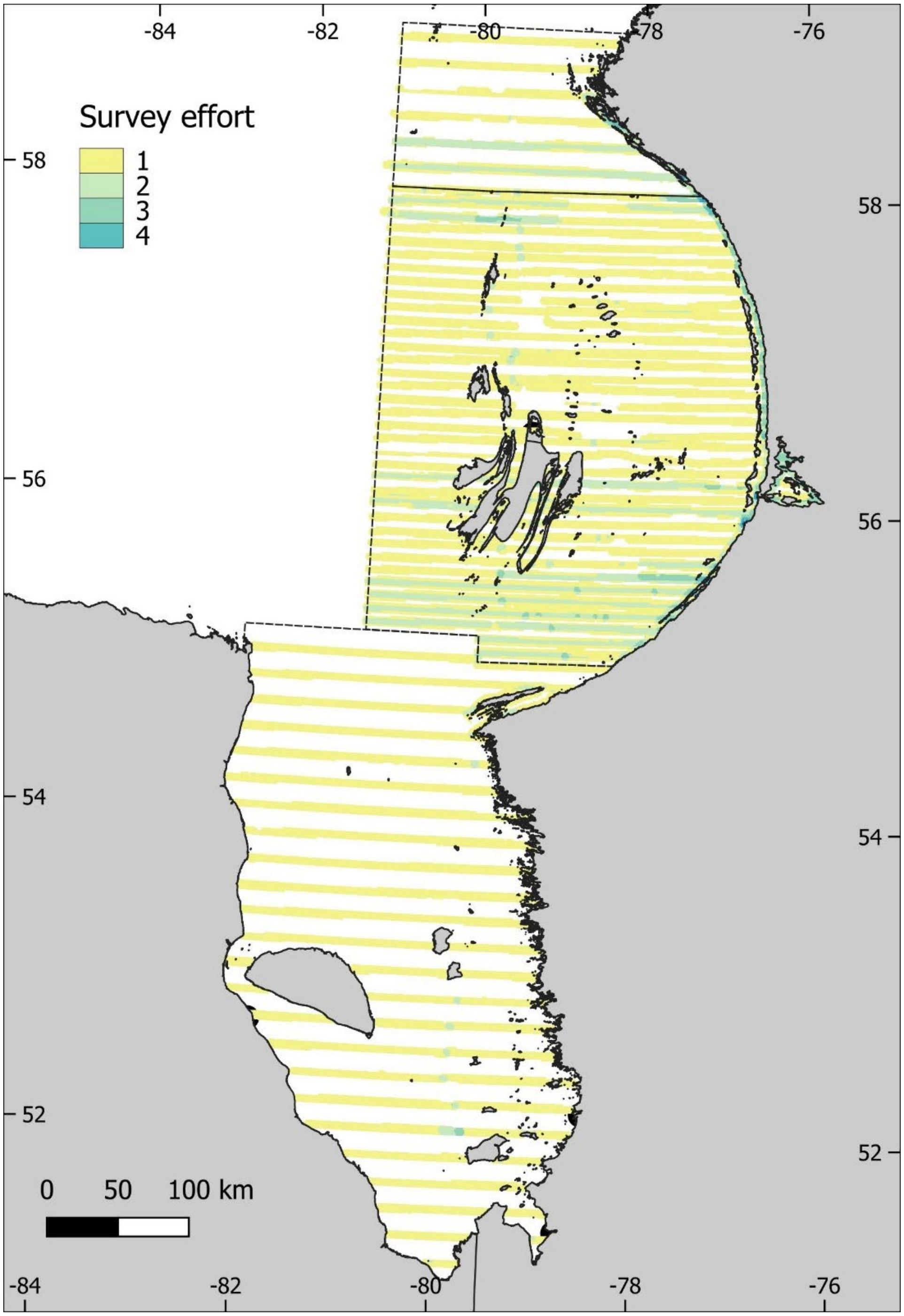

Figure 3. Realized survey effort in James Bay and the Belcher Islands-eastern Hudson Bay area for the systematic line-transect aerial beluga survey, as well as along the eastern Hudson Bay coastline, Long Island, Tasiujuaq Lake, Nastapoka River and Little Whale River in summer 2024. Survey effort was derived from survey tracks and observer logs, and calculated as the area from the track line to one effective strip half width (ESHW) on primary observer's side of the aircraft while each primary observer was on effort.

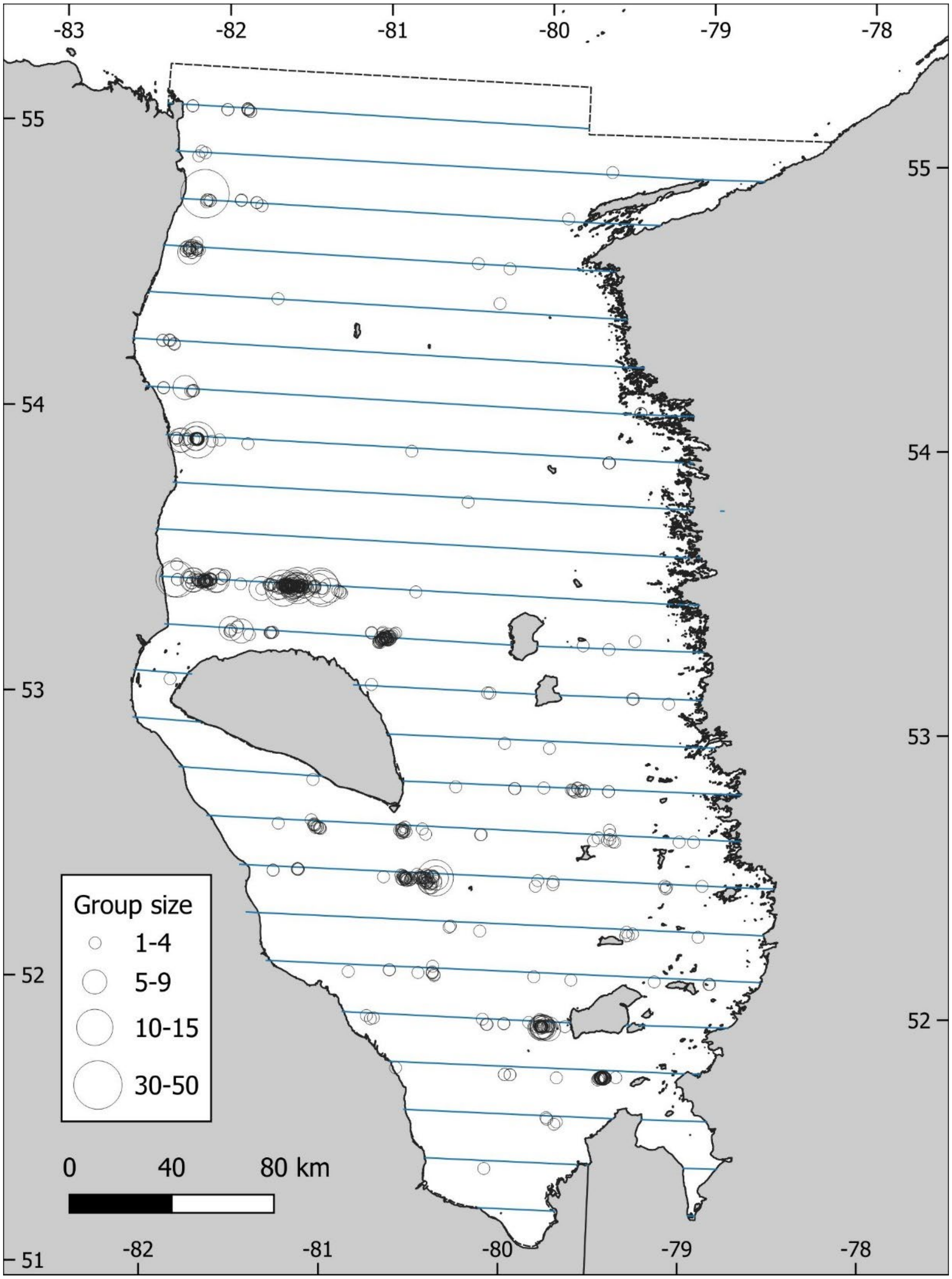

Figure 4. Geographic distribution of detected beluga groups and lines surveyed in James Bay (JB) during the 2024 aerial survey. Transect spacing in the JB stratum was 18.5 km (10 nautical miles).

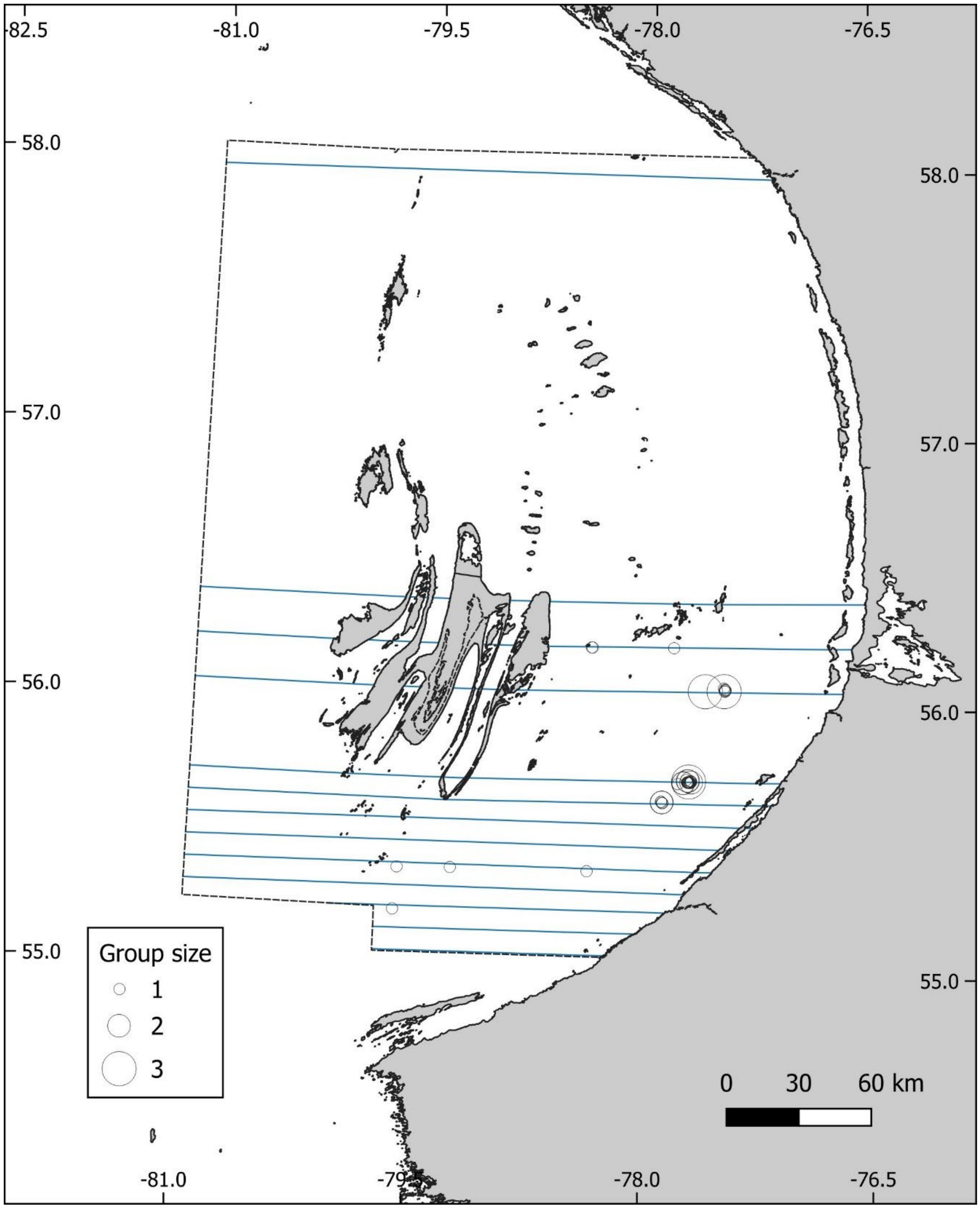

Figure 5. Geographic distribution of detected beluga groups and lines surveyed on the first survey (pass) in the Belcher Islands-eastern Hudson Bay high coverage area (HC1). The planned transect spacing in HC1 was 9.3 km (5 nautical miles).

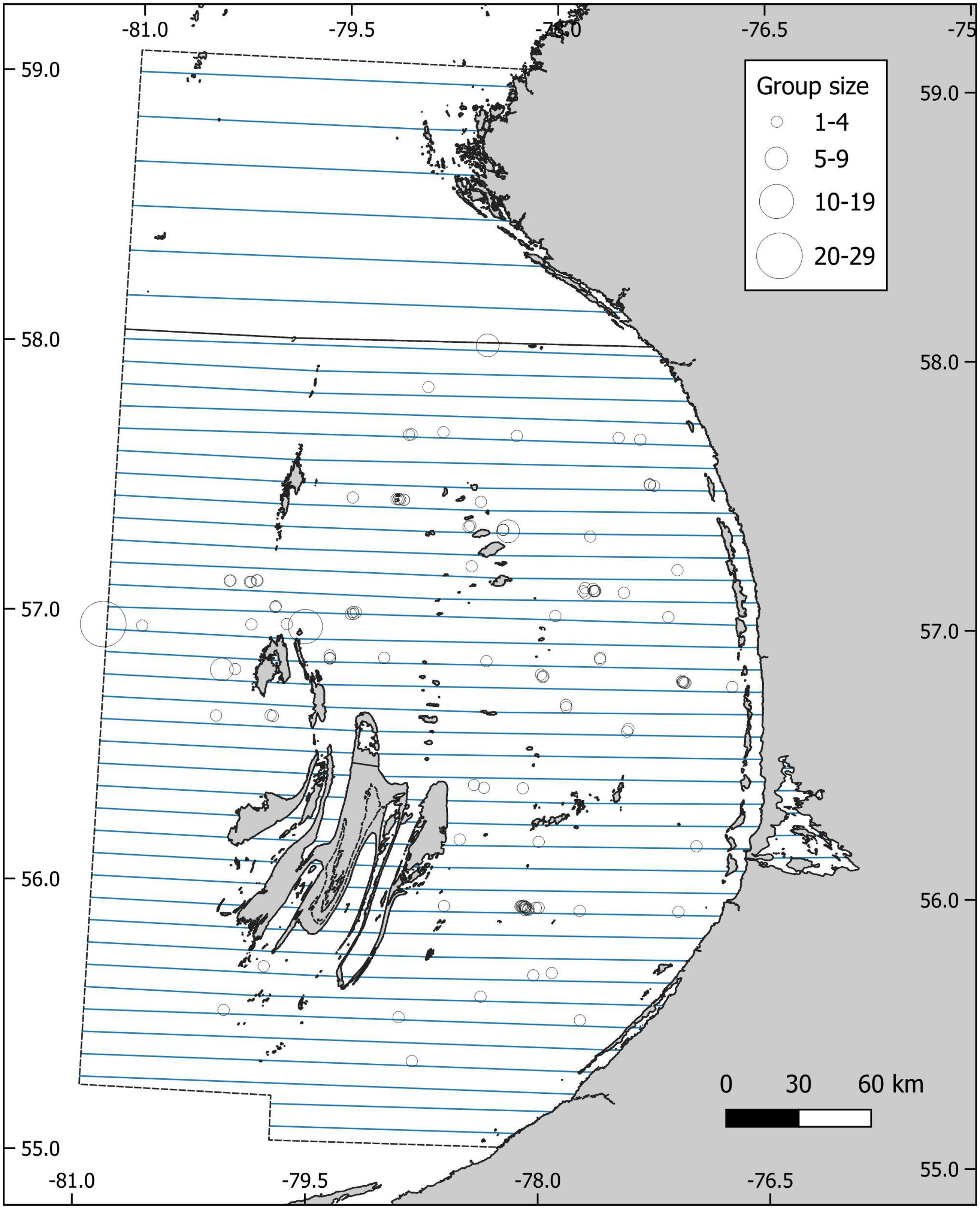

Figure 6. Geographic distribution of detected beluga groups and lines surveyed in summer 2024 used to calculate surface density and abundance of beluga in the Belcher Islands-eastern Hudson Bay area. Strata included in analyses were the second survey (pass) in the high coverage (HC2) stratum, along with the first (and only) surveys in the low coverage (HN) and Tasiujuaq Lake (RG) strata. Transect spacing was 9.3 km (5 nautical miles) in HC2 and RG, while it was 18.5 km (10 nautical miles) in HN.

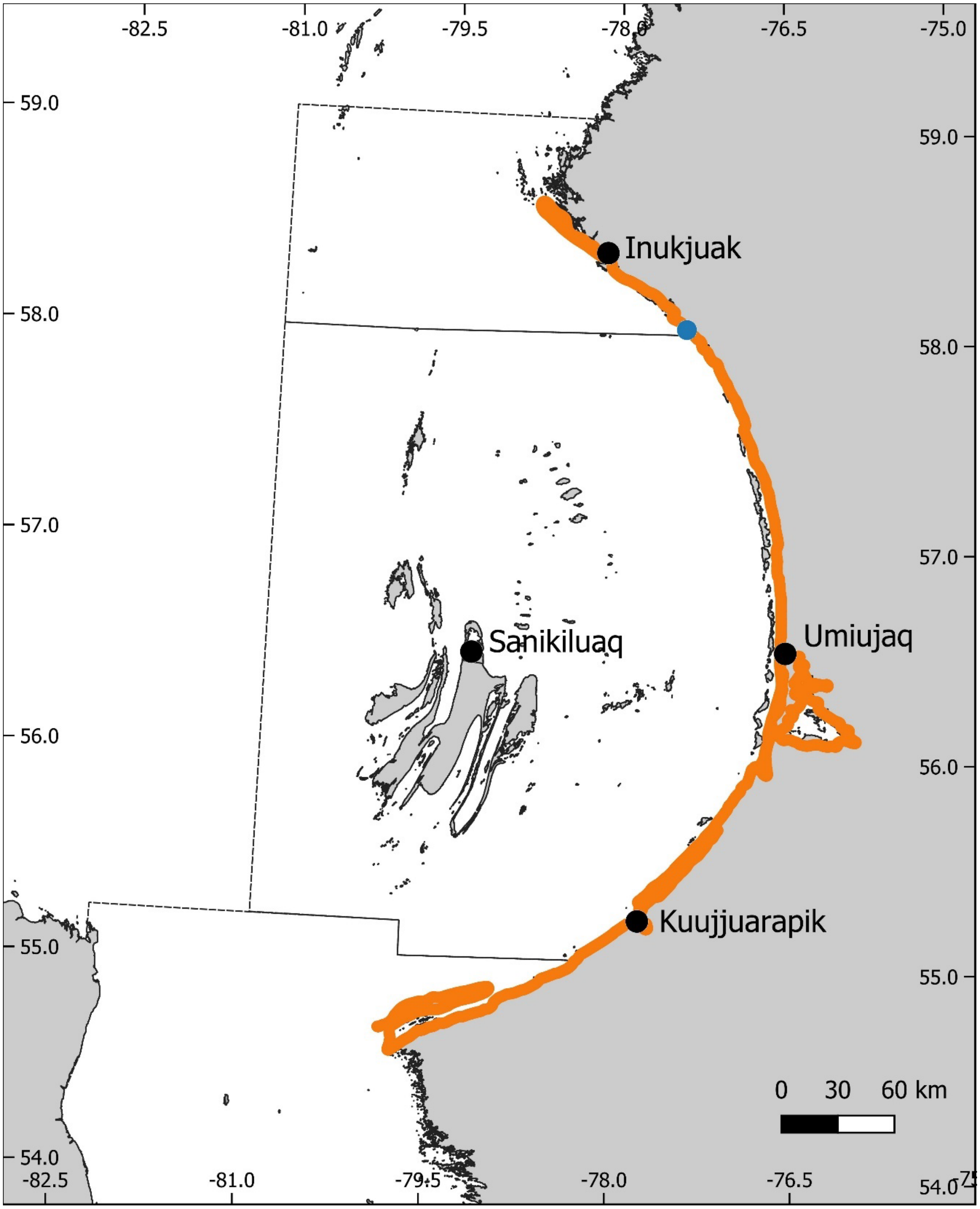

Figure 7. Geographic distribution of the beluga group (group size = 1, blue circle) detected during the coastal survey (orange line) flown in summer 2024. This single observation was no included in the BEL-EHB abundance estimate as it was detected outside of estuaries.

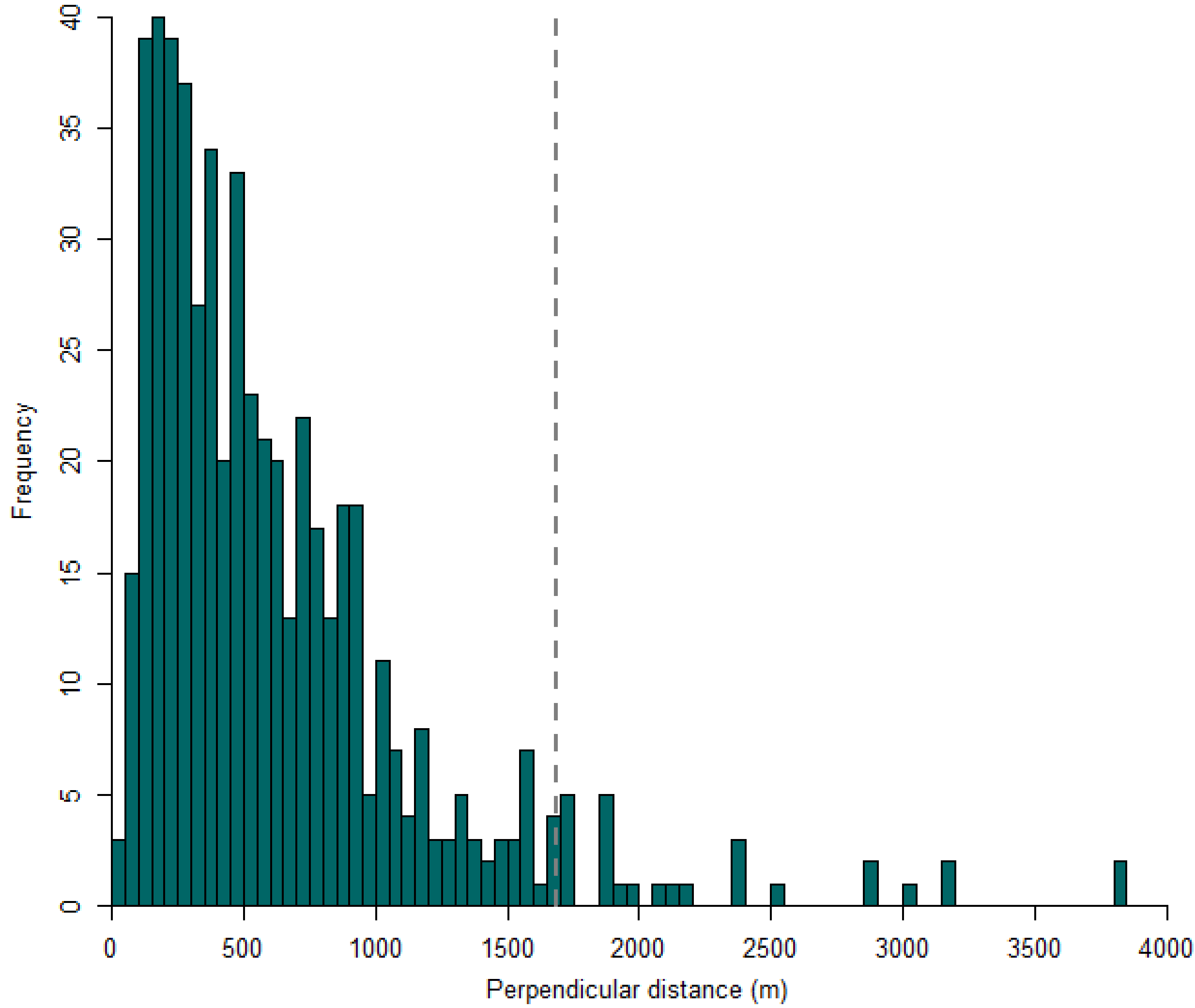

Figure 8. Distribution of perpendicular distances from the track line of 547 beluga groups detected during the aerial visual line transect surveys conducted in James Bay and Belcher Islands-eastern Hudson Bay in the summer of 2024. The right truncation of 5% of the most distant sightings (dashed grey line) when fitting the detection curve resulted in a maximal perpendicular distance of 1,687 m.

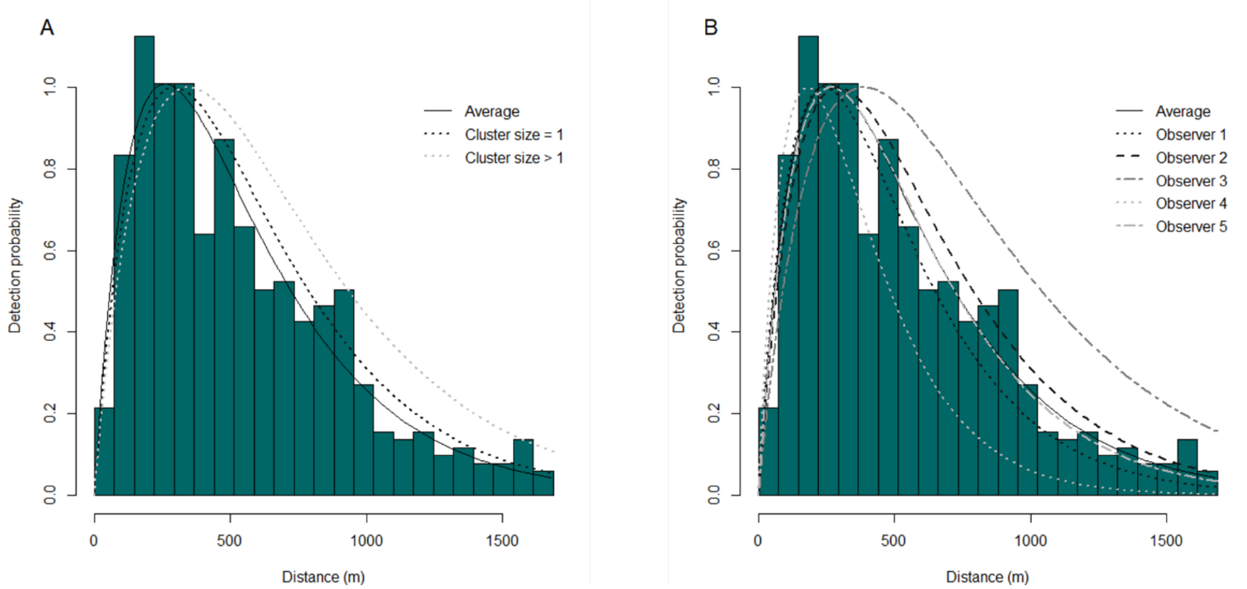

Figure 9. Distribution of perpendicular distances of 519 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area. The detection curve was fitted to ungrouped distances, with observer and binomial cluster size (i.e., cluster size =1 vs cluster size > 1) as covariates. The maximal perpendicular distance included in the data was 1,687 m. In panel A, observer is fixed to Observer 3 while in panel B, cluster size is fixed to = 1.

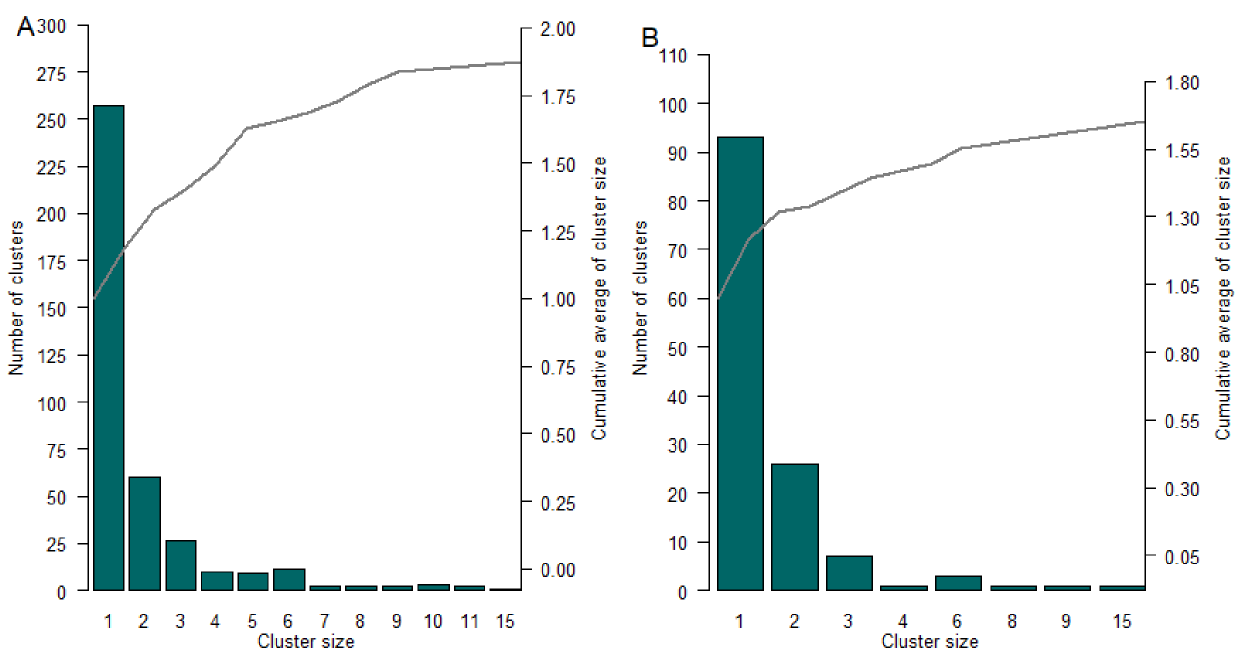

Figure 10. Frequency distribution of beluga group sizes recorded by primary observers and within right truncation distance in James Bay (A) and in the Belcher Islands-eastern Hudson Bay area (B) during the 2024 aerial survey. The cumulative average of cluster size shows the effect of large clusters on the expected cluster size.

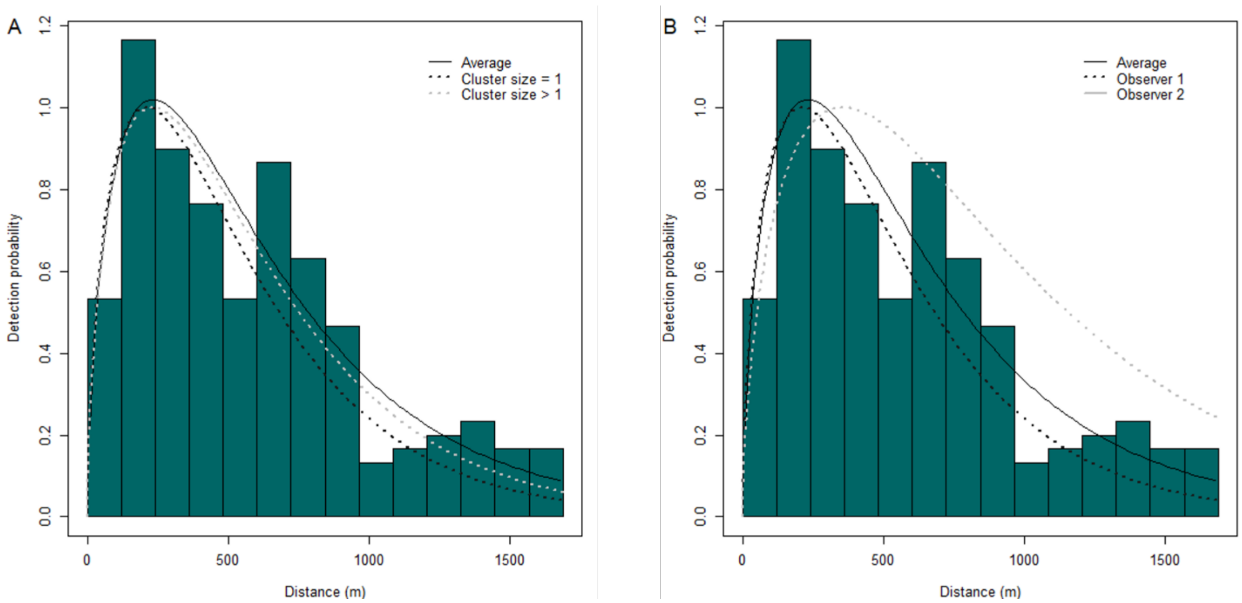

Figure 11. Distribution of perpendicular distances of 208 groups of beluga detected by primary observers in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2024 survey while both primary and secondary observers flying in a double platform configuration were on effort. A gamma detection curve was fitted to ungrouped distances, with binomial cluster size (i.e., cluster size = 1 vs cluster size > 1) and observer as covariates. The maximal perpendicular distance included in the data was 1,687 m. In panel A, observer is fixed to Observer 1, while in panel B, cluster size is fixed to = 1.

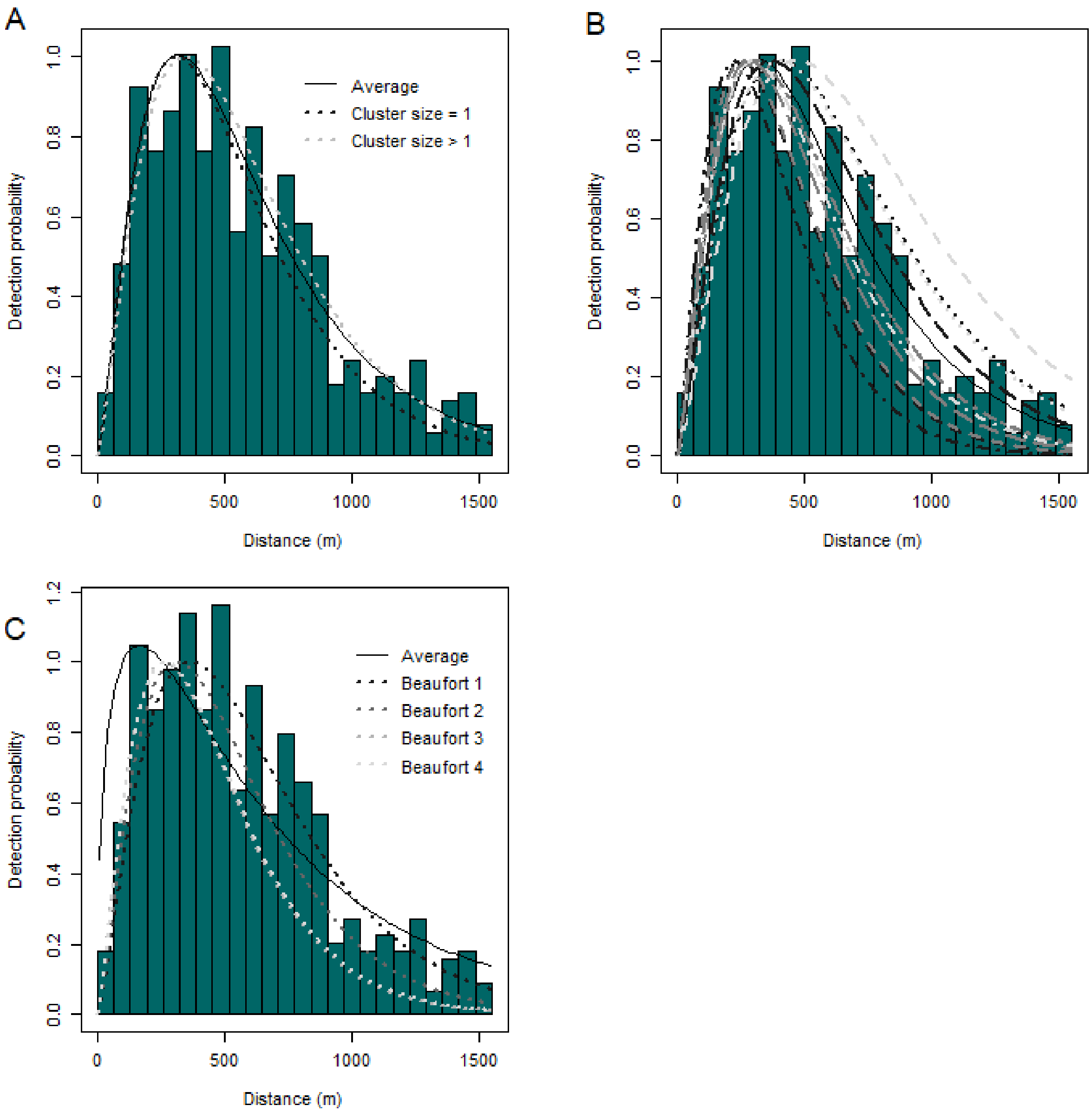

Figure 12. Distribution of perpendicular distances of 562 groups of beluga detected by primary observers in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2015, 2021, and 2024 survey while both primary and secondary observers flying in a double platform configuration were on effort. A gamma detection curve was fitted to ungrouped distances, with binomial cluster size (i.e., cluster size =1 vs cluster size > 1), observer (11 levels), and Beaufort (4 levels) as covariates. The maximal perpendicular distance included in the data was 1,550 m.

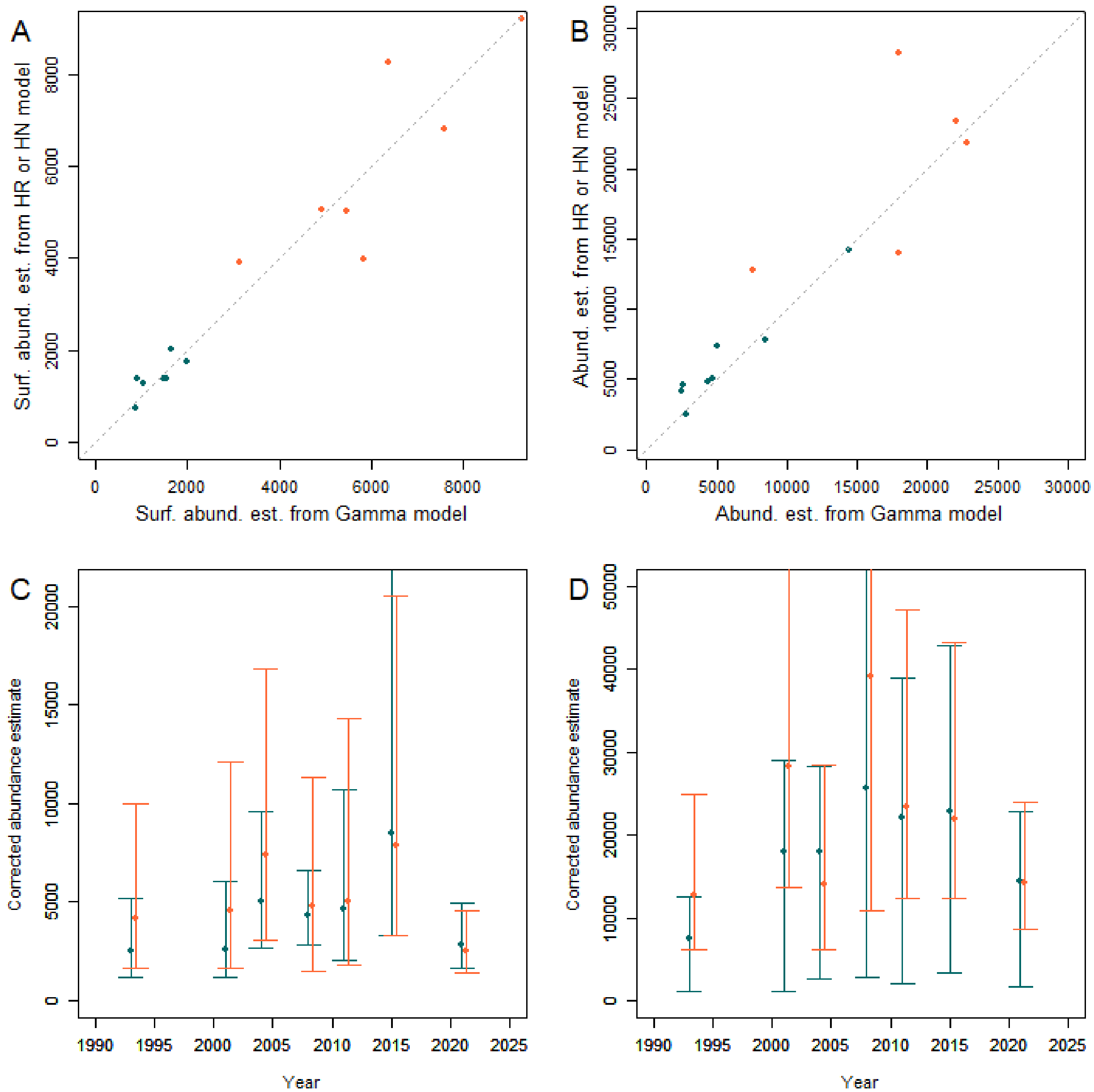

Figure 13. Top panels: correlation between (A) surface abundance estimates (surf. abund. est.) derived from gamma detection curves fitted in this study and those derived from half-normal or hazard rate detection functions combined with left truncation of the data; and between (B) previously published corrected abundance estimates (see St-Pierre et al. 2024) and those recalculated using surface abundance estimates and associated correction factors estimated in this study. Green and orange circles represent surveys of the Belcher Islands-eastern Hudson Bay and James Bay areas, respectively. The dashed grey line displays the identity line. Surveys flown using line-transect techniques between 1993 and 2021 are represented. Bottom panels: previously published corrected abundance estimates (orange circles, see St-Pierre et al. 2024) and abundance estimates from this study (green circles) for (C) the Belcher Islands-eastern Hudson Bay and (D) the James Bay beluga stocks. Error bars display 95% confidence intervals associated with survey estimates.

APPENDIX 1. DISTRIBUTION OF RELATIVE ANGLES RECORDED DURING SYSTEMATIC AERIAL SURVEYS

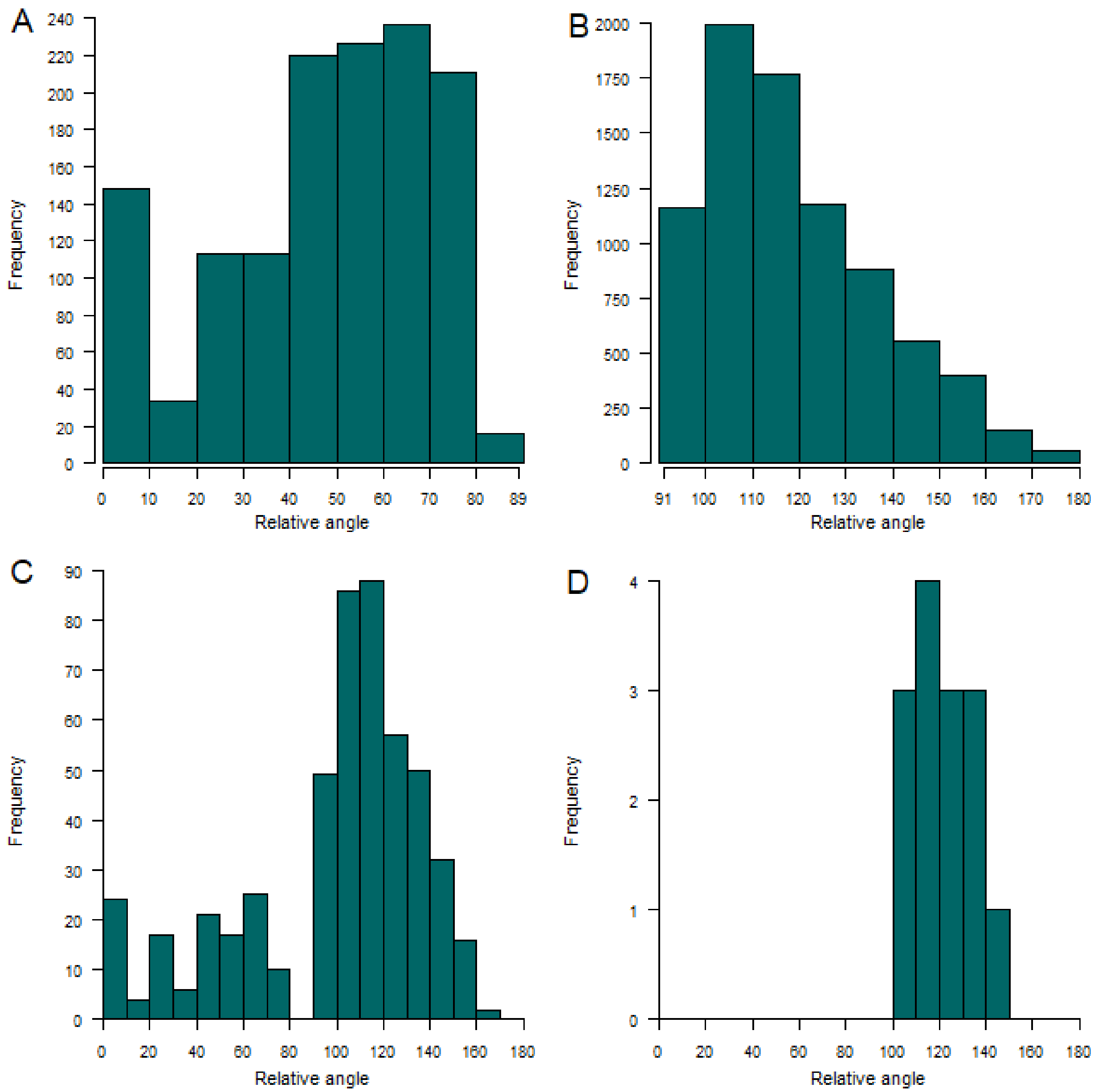

Figure A1.1. Distribution of relative angles from beluga observations recorded by observers A) ahead (n = 1,319) and B) past (n = 8,145) abeam during 82 aerial visual surveys flown between 2001 and 2024 in eastern Canada. Survey platforms include Cessna 337, Partenavia P86, and de Havilland Twin Otter aircrafts. Panels (C) and (D) display platform-specific relative angles recorded ahead and past abeam for Partenavia P86 and Kenn Borek Havilland Twin Otter, respectively. Observers were instructed to record observations abeam whenever possible. Accordingly, these observations taken ahead and past abeam represent 1.5% and 9.3% of all observations (n = 87,883) recorded during surveys.

APPENDIX 2. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 1993 SURVEY

Table A2.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 188 beluga observations recorded during the 1993 line-transect survey conducted in James Bay and eastern Hudson bay (see Kingsley 2000 for details). Perpendicular distances were right-truncated at 2,592 meters. Boldface identifies the model retained to estimate strata-specific surface abundances.

Covariate	No. observations	AIC	ΔAIC	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Cluster size (1 vs 2+)	**188**	**2,725**	**0**	**0.4322**	**2**	**828 (6.7%)**
Cluster size	188	*Did not converge*	-	-	**2**	**-**

Table A2.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 1993 (see Kingsley 2000 for details). Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC and HNS areas.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	124	2.28 (14.96)	0.0261 (15.13)	0.0158 (16.03)	0.0359 (24.63)	**3,135 (1,907-5,153)**
Belcher Islands- eastern Hudson Bay						**1,029 (497-2,130)**
HC	56	1.95 (23.98)	0.0080 (16.09)	0.0049 (17.30)	0.0096 (29.01)	652 (364-1,167)
HNS	8	4.47 (31.95)	0.0062 (69.90)	0.0037 (68.63)	0.0166 (89.59)	377 (58-2,456)

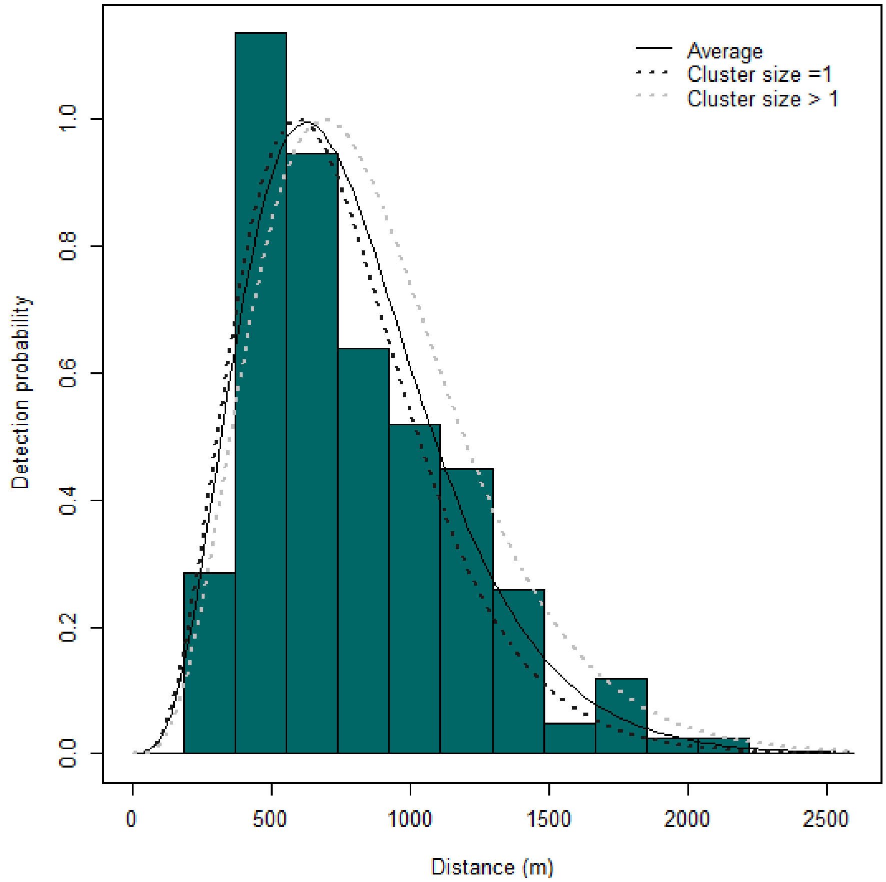

Figure A2.1. Distribution of perpendicular distances of 188 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 1993 survey for which a perpendicular distance was recorded. A gamma function without adjustment term and with binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as sole covariate was fitted to ungrouped distances. The maximal perpendicular distance included in the data was 2,592 m.

APPENDIX 3. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2001 SURVEY

Table A3.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 368 beluga observations recorded during the 2001 line-transect survey conducted in James Bay and eastern Hudson Bay (see Gosselin et al. 2002 for details). No right truncation was applied to perpendicular distances. Boldface identifies the model retained to estimate strata-specific surface abundances.

Covariate	No. observations	AIC	ΔAIC	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Cluster size (1 vs 2+)	**368**	**5,309**	**0**	**0.1248**	**3**	**794 (4.3%)**
Observer + Cluster size (1 vs 2+)	368	*Did not converge*	-	-	4	-
Cluster size (numeric)	368	*Did not converge*	-	-	4	**-**

Table A3.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2001 (see Gosselin et al. 2002 for details). Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC and HNS areas.

Area and stratum	**Number of groups**	**Expected group size**	**Encounter rate (groups/km)**	**Surface density (groups/km^2)**	**Surface density (individuals/km^2)**	**Surface abundance index**
James Bay	304	1.8112 (7.96)	0.0641 (22.07)	0.0403 (22.35)	0.0730 (23.39)	**6,374 (3,963-10,251)**
Belcher Islands- eastern Hudson Bay						**921 (388-2,186)**
HC	64	2.46 (30.46)	0.0094 (31.42)	0.0059 (31.69)	0.0146 (44.11)	921 (388-2,186)
HNS	0	0	0	0	0	0

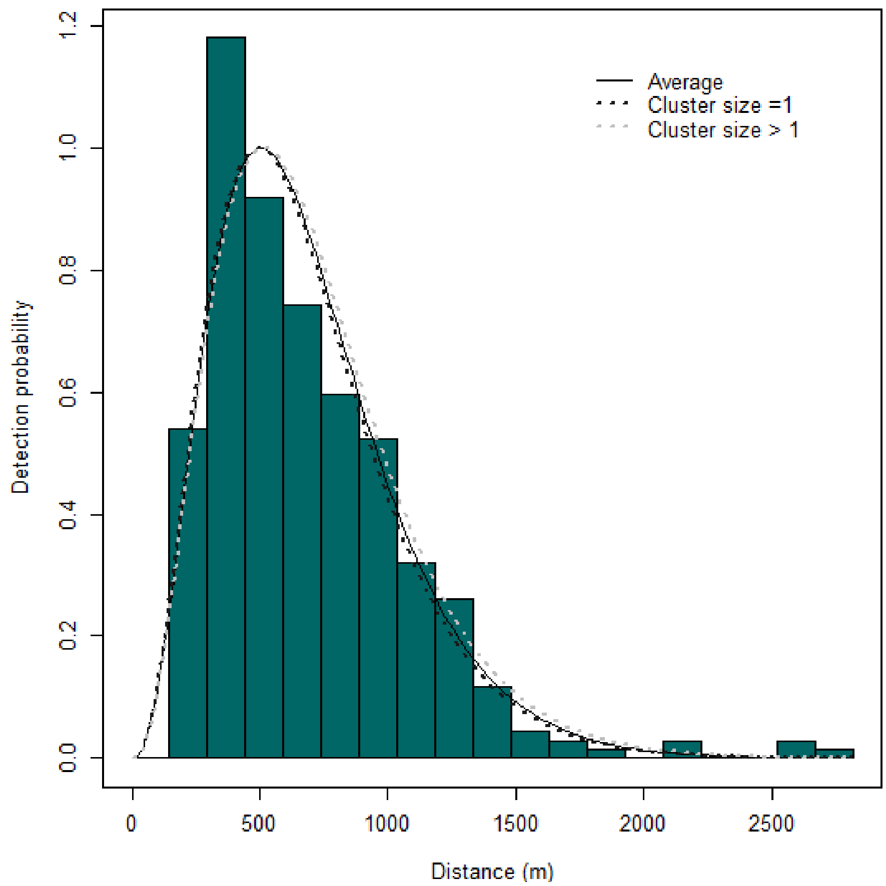

Figure A3.1. Distribution of perpendicular distances of 368 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2001 survey for which a perpendicular distance was recorded. A gamma function without adjustment term and with binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as sole covariate was fitted to ungrouped distances. The maximal perpendicular distance included in the data was 2,817 m.

APPENDIX 4. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2004 SURVEY

Table A4.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 279 beluga observations recorded during the 2004 line-transect survey conducted in James Bay and eastern Hudson Bay (see Gosselin 2005 for details). Perpendicular distances were right-truncated at 1,206 m. Boldface identifies the model retained to estimate the strata-specific probabilities of detection used as a multiplier upon fitting a uniform model including observations lacking a perpendicular distance (n = 76).

Covariate	No. observations	AIC	ΔAIC	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Cluster size (numerical)	279	3,866	**0**	0.6491	3	661 (6.6%)
Cluster size (1 vs 2+) + Region*	279	3866	0	0.8956	4	660 (7.0%)
Cluster size (1 vs 2+)	**279**	**3,867**	**1**	**0.6740**	**3**	**662 (6.0%)**
Observer	279	3,879	13	0.8728	11	659 (12.07%)

**During the 2004 survey, there has been an observer crew change coinciding with the change in geographic stratum covered during the survey. In the original analysis, a separate detection function was fitted to James Bay and eastern Hudson Bay observations (Gosselin 2005). Here, we considered the region (James Bay versus eastern Hudson Bay) as covariate in the detection function model. Since this variable did not improve AIC by at least two points compared to the simpler model, it was not retained.*

Table A4.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2004 (see Gosselin 2005 for details). These estimates consider the number of groups within the right truncation distance of 1,206 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC, HNS and RG areas.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	242	2.1116 (11.83)	0.0435 (18.36)	0.0334 (18.37)	0.0705 (21.85)	**5,930 (3,841-9,155)**
Belcher Islands- eastern Hudson Bay						**1,647(877-3,093)**
HC	101	2.0792 (12.20)	0.0151 (31.50)	0.0116 (31.50)	0.0241 (33.78)	1,548 (794-3,018)
HNS	1	6	0.0010 (99.20)	0.0008 (99.40)	0.0046 (99.40)	99 (10-982)
RG	0	0	0	0	0	0

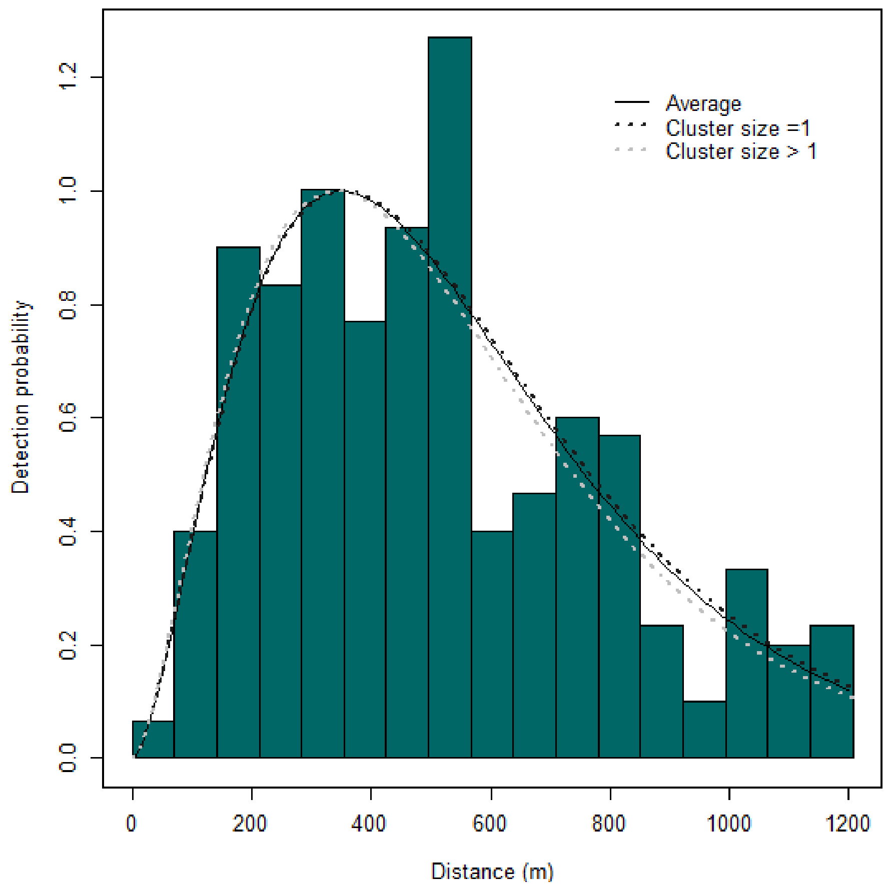

Figure A4.1. Distribution of perpendicular distances of 279 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2004 survey. A gamma function without adjustment term and with binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as sole covariate was fitted to ungrouped distances. The maximal perpendicular distance included in the data was 1,206 m.

APPENDIX 5. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2008 SURVEY

Table A5.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 283 beluga observations recorded during the 2008 line-transect survey conducted in James Bay and eastern Hudson Bay (see Gosselin et al. 2009 for details). Perpendicular distances were right-truncated at 1,702 m. Some covariate data were missing, resulting in the different models being fitted to varying subsets of the observations. As a result, AIC values are not directly comparable among models, and the model which covariates optimized both the p-value of the Cramér-Von Mises statistic (W^2) and the number of observations retained to fit the detection curve (boldface type) was selected to estimate the strata-specific probabilities of detection used as a multiplier upon fitting a uniform model including observations lacking a perpendicular distance (n = 98).

Covariate	No. observations	AIC	ΔAIC with null model	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Visibility + Cluster size (1 vs 2+)	243	3,505	-	0.3145	5	830 (9.8%)
Beaufort + Cluster size (1 vs 2+)*	245	3,518	0	0.7113	5	814 (15.8%)
Cluster size (1 vs 2+)	**245**	**3,534**	**16**	**0.4246**	**3**	**832 (6.5%)**
Cluster size	245	3,534	16	0.4201	3	832 (6.2%)
Glare intensity + Cluster size (1 vs 2+)	245	3,535	17	0.4939	6	829 (9.6%)
Observer + Cluster size (1 vs 2+)	245	3,538	20	0.5909	6	831 (10.1%)

**The Beaufort variable was not retained despite improving model fit because the relationship between the probability of detection and Beaufort was inconsistent, with sea state both negatively and positively influencing the probability of detection depending on levels.*

Table A5.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2008 (see Gosselin et al. 2009 for details). These estimates consider the number of groups within the right truncation distance of 1,702 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC, HN and RG areas. Density in HC was estimated as the effort-weighted average of the density estimates of HC1 and HC2.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	195	4.2462 (32.41)	0.0456 (62.46)	0.0279 (62.46)	0.1183 (70.37)	**9,256 (2,560-33,468)**
Belcher Islands- eastern Hudson Bay						**1,559 (1,042-2,334)**
HC1	*95*	*3.1684 (16.56)*	*0.0141 (18.92)*	*0.0086 (18.93)*	*0.02723 (25.15)*	*1,745 (1,065-2,859)*
HC2	*42*	*2.7381 (29.27)*	*0.0111 (17.97)*	*0.0068 (18.00)*	*0.0186 (34.36)*	*1,191 (610-2,327)*
HN	1	1	0.0008 (100.94)	0.0005 (101.11)	0.0005 (101.11)	13 (2-104)
RG	0	0	0	0	0	0

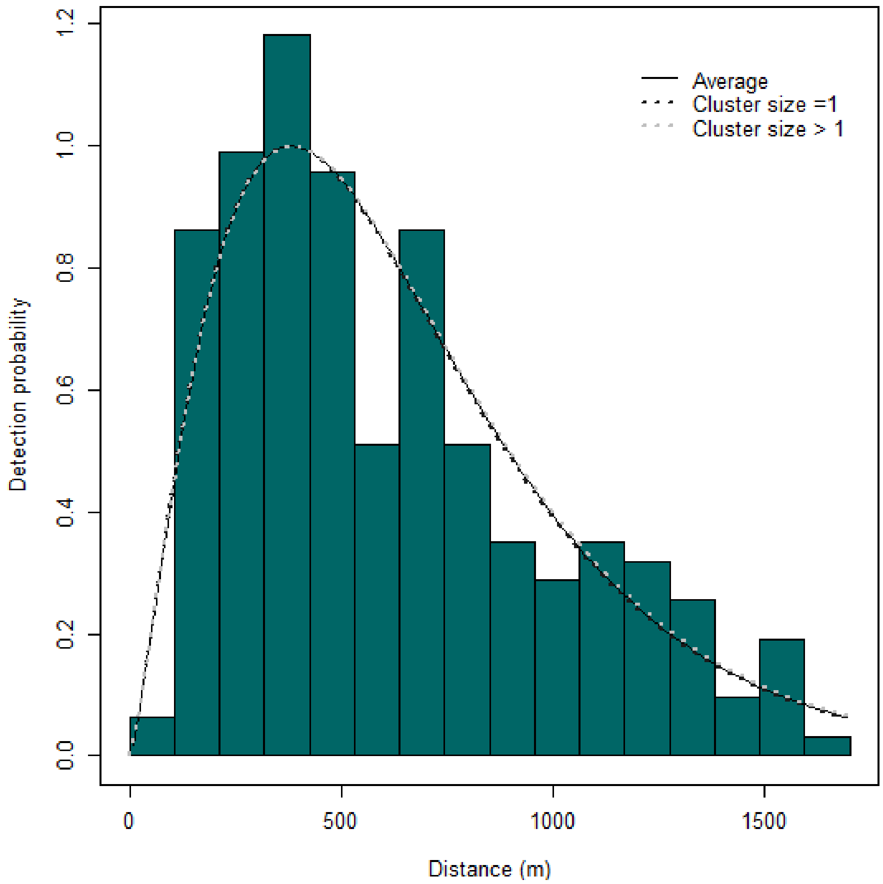

Figure A5.1. Distribution of perpendicular distances of 245 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2008 survey. A gamma detection function without adjustment term was fitted to ungrouped distances, with binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as the sole covariate. The maximal perpendicular distance included in the data was 1,702 m.

APPENDIX 6. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2011 SURVEY

Table A6.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 234 beluga observations recorded during the 2011 line-transect survey conducted in James Bay and eastern Hudson Bay (see Gosselin et al. 2013 for details). Perpendicular distances were right-truncated at 1,509 m. Some covariate data were missing, resulting in the different models being fitted to varying subsets of the observations. As a result, AIC values are not directly comparable among models, and the model which covariates optimized both the p-value of the Cramér-Von Mises statistic (W^2) and the number of observations retained to fit the detection curve (boldface type) was selected to estimate the strata-specific probabilities of detection used as a multiplier upon fitting a uniform model including observations lacking a perpendicular distance (n =4) or covariate data (n = 10).

Covariate	No. observations	AIC	ΔAIC with null model	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Cloud coverage + Cluster size (1 vs 2+)	**224**	**3,167**	**-**	**0.8772**	**4**	**724 (7.5%)**
Beaufort + Cluster size (1 vs 2+)	226	3,190	-	0.5091	6	720 (8.4%)
Glare intensity + Cluster size (1 vs 2+)	234	3,304	0	0.7407	6	715 (9.5%)
Cluster size (1 vs 2+)	234	3,309	5	0.5731	3	725 (6.4%)
Visibility + Cluster size (1 vs 2+)	234	3,309	5	0.7081	5	721 (8.5%)
Cluster size	234	3,309	5	0.6209	3	725 (7.9%)
Observer + Cluster size (1 vs 2+)	234	3,311	7	0.5126	7	719 (11.2%)

Table A6.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2011 (see Gosselin et al. 2013 for details). These estimates consider the number of groups within the right truncation distance of 1,509 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC, HN and HS areas.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	173	3.3295 (15.55)	0.0414 (23.80)	0.0292 (23.80)	0.0971 (28.44)	**7,597 (4,334-13,319)**
Belcher Islands- eastern Hudson Bay						**1,490 (614-3,616)**
HC	61	3.2295 (38.00)	0.0091 (27.57)	0.0064 (27.58)	0.0205 (46.96)	1,490 (614-3,616)
HS	0	0	0	0	0	0
HN	0	0	0	0	0	0

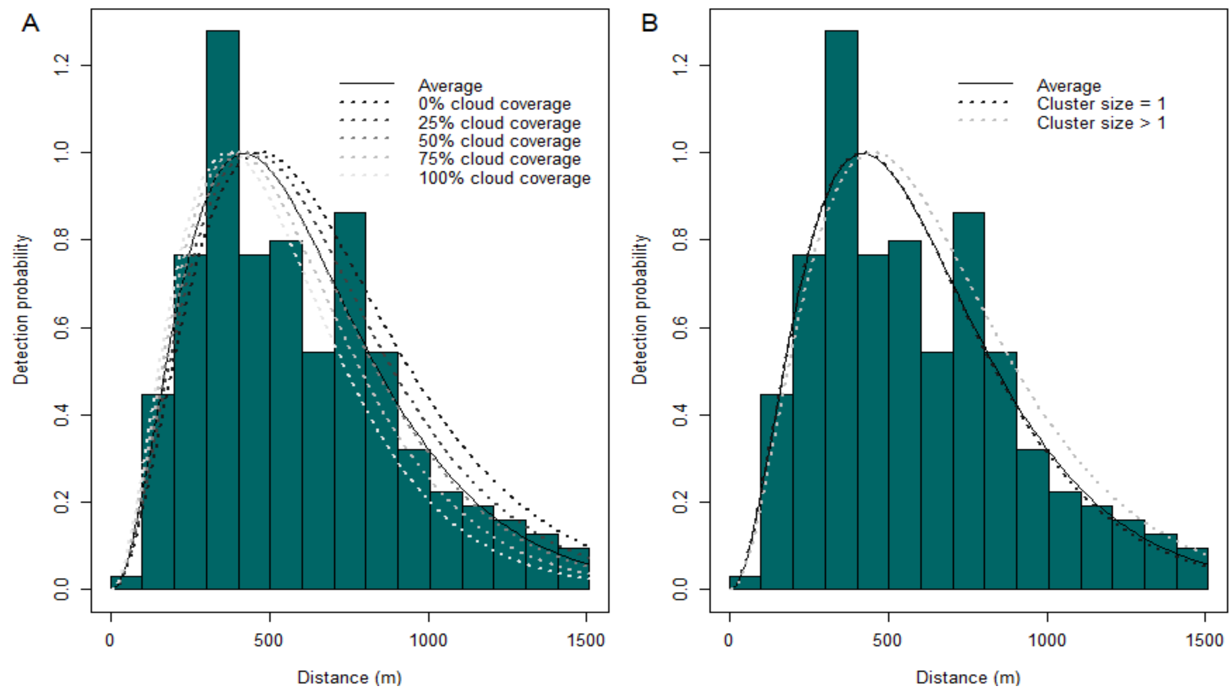

Figure A6.1. Distribution of perpendicular distances of 224 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2011 survey. A gamma detection function without adjustment term was fitted to ungrouped distances, with cloud coverage and binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as covariates. The maximal perpendicular distance included in the data was 1,509 m.

APPENDIX 7. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2015 SURVEY

Table A7.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 297 beluga observations recorded during the 2015 line-transect survey conducted in James Bay and eastern Hudson Bay (see Gosselin et al. 2017 for details). Perpendicular distances were right-truncated at 1,415 m. Boldface type identifies the model retained to estimate the strata-specific probabilities of detection used as a multiplier upon fitting a uniform model including observations lacking a perpendicular distance (n = 10).

Covariate	No. observations	AIC	ΔAIC with null model	W^2 p-value	No. parameters	Effective strip half-width (*CV*)
Cluster size (1 vs 2+)	**297**	**4,153**	**-**	**0.9600**	**3**	**669 (5.6%)**
Observer + Cluster size (1 vs 2+)	297	4,155	2	0.9593	5	666 (7.8%)
Visibility + Cluster size (1 vs 2+)	297	4,155	2	0.9563	4	669 (6.5%)
Glare intensity + Cluster size (1 vs 2+)	297	4,156	3	0.9205	5	668 (7.0%)
Beaufort + Cluster size (1 vs 2+)	297	4,159	6	0.9611	6	669 (8.4%)

Table A7.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2015 (see Gosselin et al. 2017 for details). These estimates consider the number of groups within the right truncation distance of 1,415 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC, HN, HS and RG areas. Density in HC was estimated as the effort-weighted average of the density estimates of HC1 and HC2.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	191	2.0209 (9.09)	0.0449 (20.53)	0.0343 (21.09)	0.0692 (22.97)	**5,455 (3,473-8,567)**
Belcher Islands- eastern Hudson Bay						**1,991 (828-4,786)**
HC1	53	6,5849 (53.38)	0.0068 (21.62)	0.0052 (22.15)	0.0340 (57.79)	2,474 (850-7,199)
HC2						1,164 (680-1,992)
HC2-north	*18*	*1.3889 (24.15)*	*0.0101 (23.66)*	*0.0019 (24.15)*	*0.0107 (29.88)*	*219 (119-402)*
HC2-south	*44*	*1.4318 (16.28)*	*0.0166 (28.67)*	*0.0127 (29.07)*	*0.0182 (33.32)*	*945 (480-1,862)*
HN	1	1	0.0010 (98.61)	0.0008 (98.73)	0.0008 (98.73)	15 (2-123)
HS	0	0	0	0	0	0
RG	0	0	0	0	0	0

Table A7.3. Selection of the detection function used to estimate the perception bias, using a Gamma detection function with potential covariates fitted to 190 beluga observations recorded in double platform configuration during the 2015 line-transect survey conducted in James Bay and eastern Hudson Bay. Perpendicular distances were right-truncated at 1,415 m.

Covariate	AIC	ΔAIC	No. parameters	Effective strip half-width (*CV*)
Cluster size (1 vs 2+)	**2,778**	**0**	**3**	**707 (7.0%)**
Beaufort + Cluster size (1 vs 2+)	2,778	0	6	699 (9.3%)
Glare intensity + Cluster size (1 vs 2+)	2,778	0	6	699 (9.2%)
Visibility + Cluster size (1 vs 2+)	2,781	3	4	707 (7.9%)
Observer + Cluster size (1 vs 2+)	*Very poor fit*[1]	-	4	-

[1]*Cramer Von Mises W^2 p-value < 0.05.*

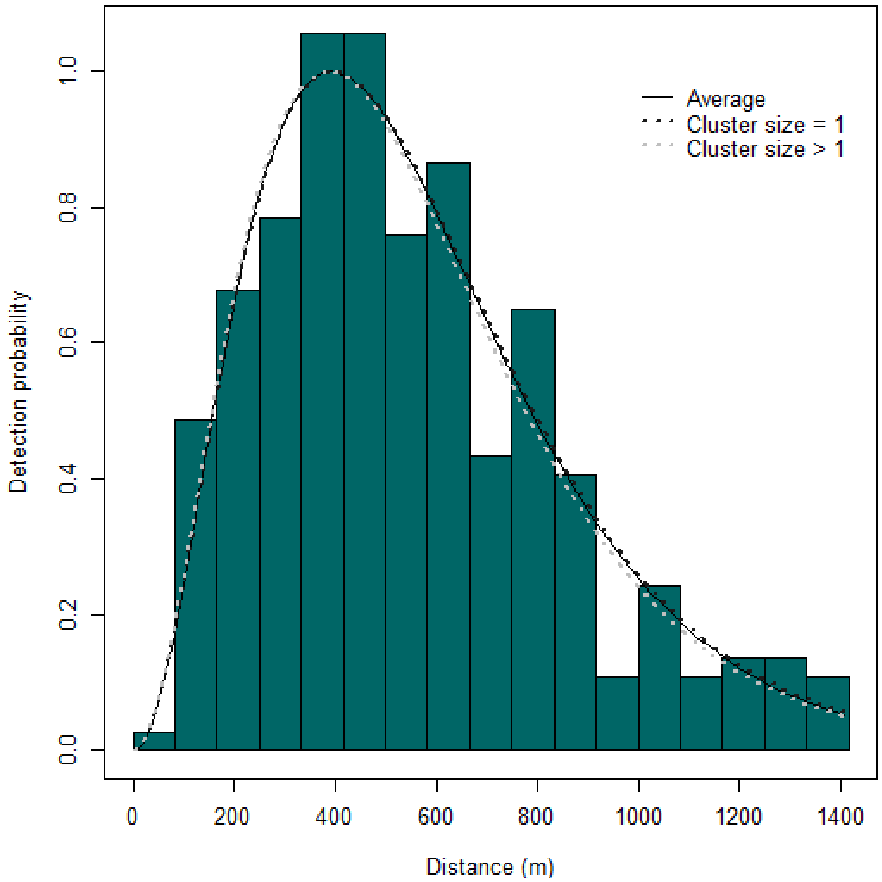

Figure A7.1. Distribution of perpendicular distances of 297 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2015 survey. A gamma detection function without adjustment term was fitted to ungrouped distances, with cluster size (i.e., cluster size = 1 vs cluster size > 1) as sole covariate. The maximal perpendicular distance included in the data was 1,415 m.

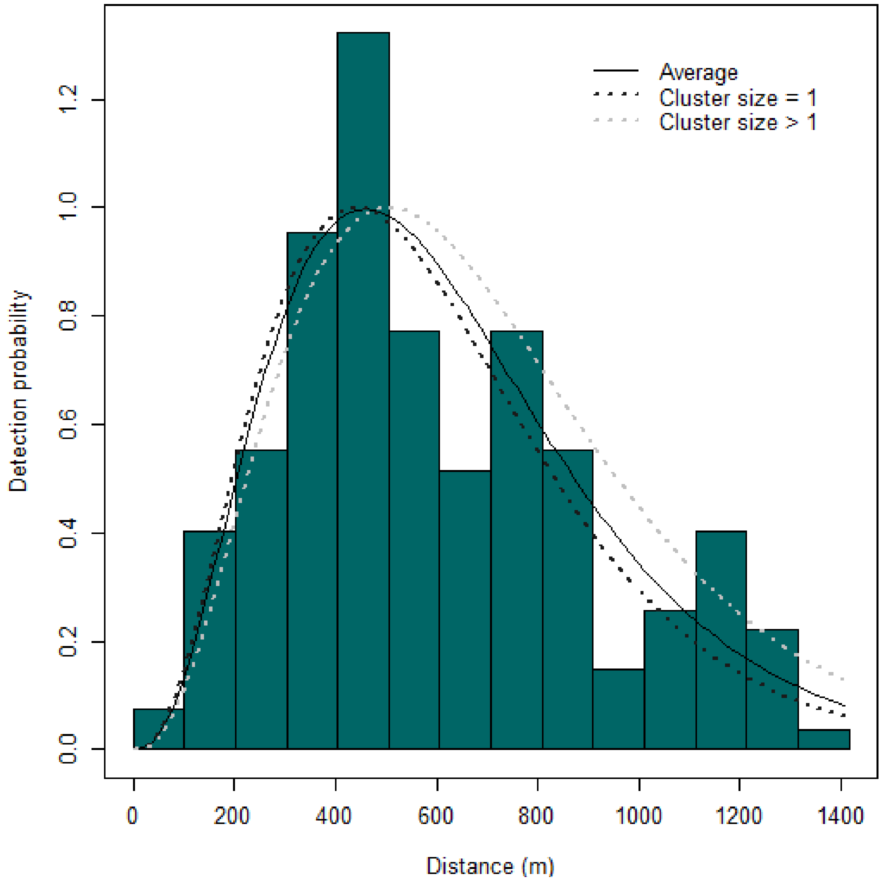

Figure A7.2. Distribution of perpendicular distances of 190 groups of beluga detected by primary observers in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2015 survey while both primary and secondary observers flying in a double platform configuration were on effort. A gamma detection function with no adjustment term was fitted to ungrouped distances, with binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as sole covariate. The maximal perpendicular distance included in the data was 1,415 m.

APPENDIX 8. ADJUSTMENT OF ABUNDANCE ESTIMATES FOR THE 2021 SURVEY

Table A8.1. Selection of the detection function to estimate the effective strip half-width, ESHW in meters using a Gamma detection function with potential covariates fitted to 341 beluga observations recorded during the 2021 line-transect survey conducted in James Bay and eastern Hudson Bay (see St-Pierre et al. 2024 for details). Perpendicular distances were right-truncated at 1,938 m. Boldface type identifies the model retained to estimate the strata-specific probabilities of detection used as a multiplier upon fitting a uniform model including observations lacking a perpendicular distance (n = 81).

Covariate	AIC	ΔAIC	No. parameters	Effective strip half-width (*CV*)
Beaufort + Cluster size (1 vs 2+)	**4,879**	**0**	**5**	**759 (8.0%)**
Platform type + Cluster size (1 vs 2+)	4,896	17	4	768 (6.5%)
Cluster size (1 vs 2+)	4,898	19	3	769 (5.2%)
Cluster size (numeric)	4,898	19	3	769 (6.0%)
Glare intensity + Cluster size (1 vs 2+)	4,900	21	6	768 (8.0%)
Visibility + Cluster size (1 vs 2+)	4,900	22	5	768 (7.2%)
Cloud coverage + Cluster size (1 vs 2+)	*Did not converge*	-	11	-
Observer + Cluster size (1 vs 2+)	*Did not converge*	-	10	-

Table A8.2. Surface density and abundance indices for James Bay and the Belcher Islands-eastern Hudson Bay area in summer of 2021 (see St-Pierre et al. 2024 for details). These estimates consider the number of groups within the right truncation distance of 1,938 m, and the number of groups that were detected without perpendicular distances but that were assumed to be closer than the right truncation. Parentheses show coefficient of variation (%) and 95% CI for abundance indices. The Belcher Islands-eastern Hudson Bay surface estimate is the sum of the HC, HN and RG areas. Density in HC was estimated as the effort-weighted average of the density estimates of HC1 and HC2.

Area and stratum	Number of groups	Expected group size	Encounter rate (groups/km)	Surface density (groups/km^2)	Surface density (individuals/km^2)	Surface abundance index
James Bay	255	1.7647 (6.55)	0.0573 (19.63)	0.0356 (19.64)	0.0063 (20.70)	**4,920 (3,234-7,483)**
Belcher Islands- eastern Hudson Bay						**876 (490-1,565)**
HC1	*76*	*1.8421 (11.77)*	*0.0085 (29.62)*	*0.0066 (29.64)*	*0.0122 (31.89)*	*955 (508-1,778)*
HC2	*36*	*3.3056 (25.19)*	*0.0041 (44.08)*	*0.0030 (44.12)*	*0.0099 (50.81)*	*774 (296-2,021)*
HN	1	1	0.0010 (94.57)	0.0007 (94.87)	0.0007 (94.87)	13 (2-98)
RG	0	0	0	0	0	0

Table A8.3. Selection of the detection function used to estimate the perception bias, using a Gamma detection function with potential covariates fitted to 165 beluga observations recorded in double platform configuration during the 2021 line-transect survey conducted in James Bay and eastern Hudson Bay. Perpendicular distances were right-truncated at 1,938 m.

Covariate	AIC	ΔAIC	No. parameters	Effective strip half-width (*CV*)
Visibility + Cluster size (1 vs 2+)	**2,319**	**0**	**6**	**651 (8.7%)**
Cloud coverage + Cluster size (1 vs 2+)	2,324	5	4	655 (9.1%)
Cluster size (1 vs 2+)	2,225	6	3	658 (7.3%)
Cluster size (numeric)	2,325	6	3	658 (7.8%)
Platform type + Cluster size (1 vs 2+)	2,327	8	4	658 (9.2%)
Glare intensity + Cluster size (1 vs 2+)	2,328	9	6	655 (13.4%)
Beaufort + Cluster size (1 vs 2+)	*Did not converge*	**-**	**6**	**-**
Observer + Cluster size (1 vs 2+)	*Did not converge*	-	11	-

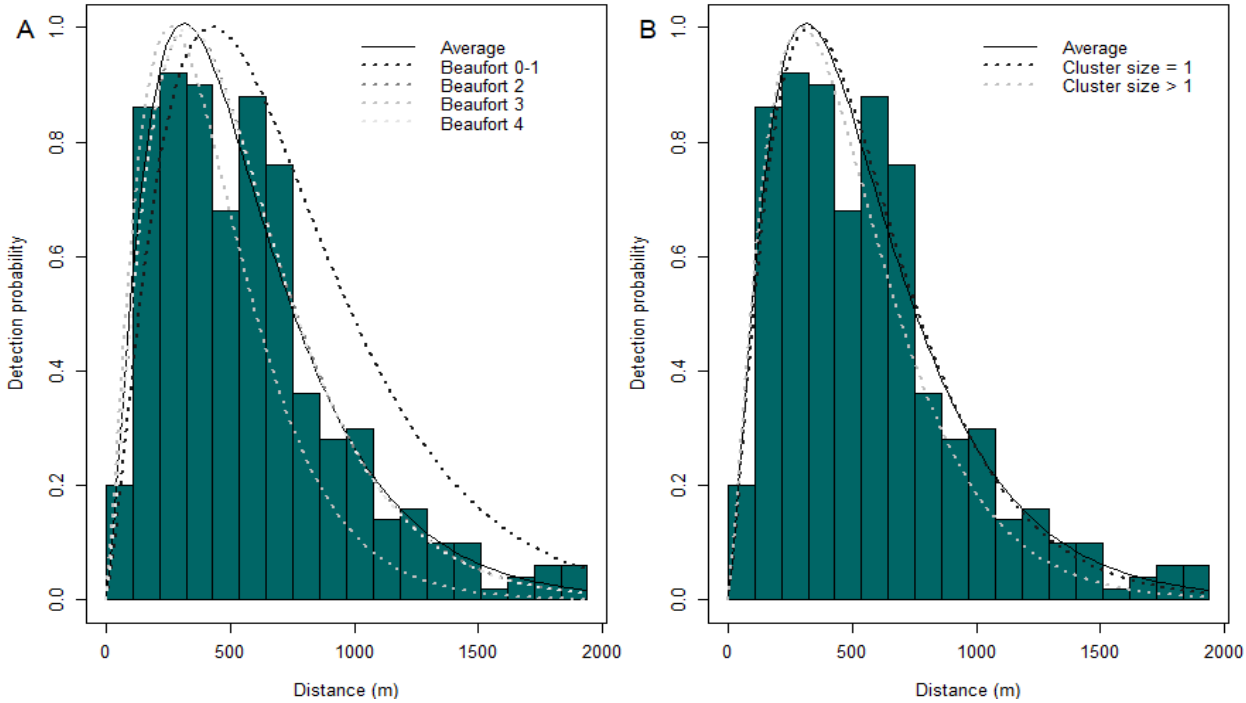

Figure A8.1. Distribution of perpendicular distances of 341 groups of beluga detected in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2021 survey. A gamma detection function without adjustment term was fitted to ungrouped distances, with Beaufort sea state and binary cluster size (i.e., cluster size = 1 vs cluster size > 1) as covariates. The maximal perpendicular distance included in the data was 1,938 m. In panel A, cluster size is fixed to = 1 while in panel B, Beaufort is fixed to 2.

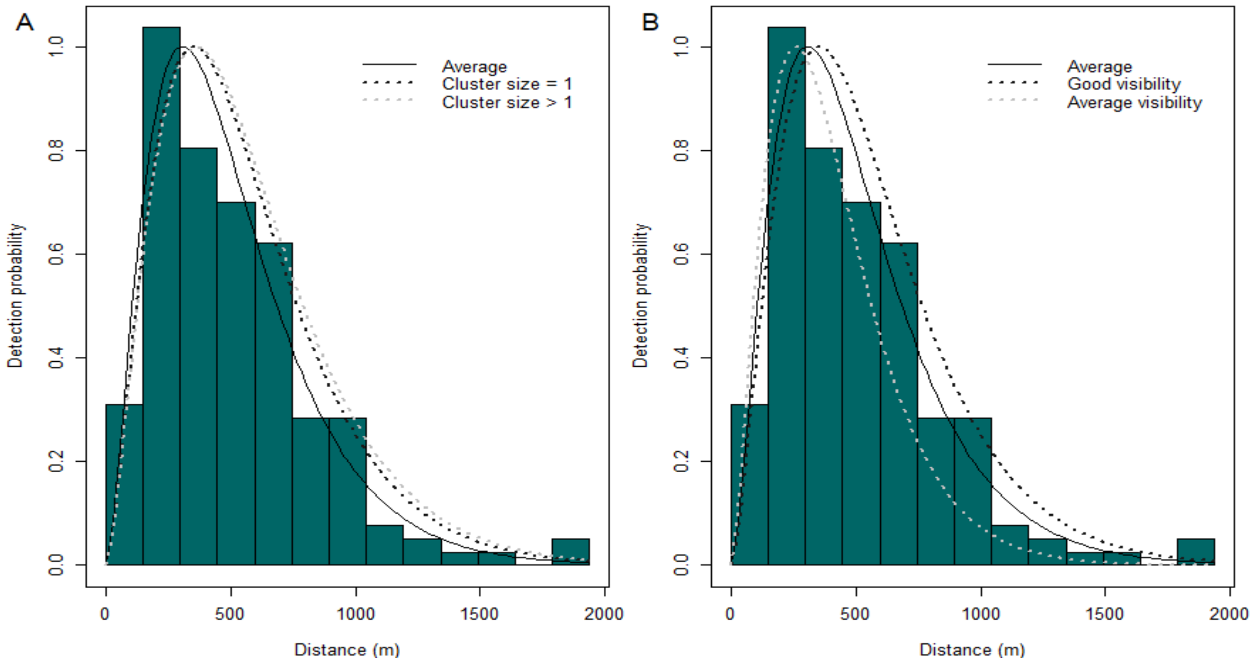

Figure A8.2. Distribution of perpendicular distances of 165 groups of beluga detected by primary observers in James Bay and the Belcher Islands-eastern Hudson Bay area during the 2021 survey while both primary and secondary observers flying in a double platform configuration were on effort. A gamma detection function with no adjustment term was fitted to ungrouped distances, with Beaufort sea state as sole covariate. The maximal perpendicular distance included in the data was 1,938 m. In panel A, visibility is fixed to good while in panel B, cluster size is fixed to = 1.

APPENDIX 9. TIMEFRAME FOR THE COMPLETION OF SURVEYS OF THE BELCHER ISLANDS-EASTERN HUDSON BAY FROM 1985-2021

Table A9.1. Timeframe during which the beluga aerial surveys of the Belcher Islands-eastern Hudson Bay area were flown between 1985 and 2021. In 2008, 2015 and 2021, the high coverage stratum of the area was covered twice within the indicated period.

Survey year	Survey period
1985	July 29-August 5
1993	'August'
2001	August 18-August 27
2004	August 12-August 30
2008	July 23-August 19
2011	July 26-August 17
2015	August 8-September 3
2021	July 26-August 23