Distribution and abundance of beluga whales in the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf during late July 1992

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Abstract: Three Twin Otter aircraft, each with three or four observers, were used to conduct a systematic survey of the southeast Beaufort Sea (4.5–6.3% coverage), Mackenzie estuary (15–29% coverage), and west Amundsen Gulf (2.9% coverage) over a 55-h period on 23–25 July 1992. Beluga whales (*Delphinapterus leucas*) were found throughout the estuary and offshore strata, with the highest density in Kugmallit Bay, Mackenzie estuary (1.137 beluga/km^2). Over 85% of the beluga were estimated to be offshore, where they were widely distributed at low densities (0.099–0.311 beluga/km^2). Data collected by primary observers (experienced in aerial surveys) yielded an estimate of 15 307 (95% CI 12 305 – 18 309) beluga visible at the surface. Six reviewers independently assessed which sightings made by secondary observers (community participants with limited aerial survey experience but with experience searching for beluga from boats) did not duplicate primary sightings. These were used to adjust the primary counts for missed-at-surface and about-to-surface beluga, and yielded an index of stock size of 19 629 (95% CI 15 134 – 24 125) visible beluga; this does not account for those far below the surface and therefore unavailable to the observers, or those outside the study area.

Résumé : Trois avions Twin Otter, chacun ayant à son bord trois ou quatre observateurs, ont servi à la tenue d'un relevé systématique dans la partie sud-est de la mer de Beaufort (couverture de 4,5–6,3%), de l'estuaire du Mackenzie (couverture de 15–29%) et de la partie ouest du golfe Amundsen (couverture de 2,9%); les opérations ont duré 55 h et se sont déroulées entre le 23 et le 25 juillet 1992. Des bélugas (*Delphinapterus leucas*) ont été observés partout dans l'estuaire et au large, la densité la plus élevée étant obtenue dans la baie Kugmallit, dans l'estuaire du Mackenzie (1137 béluga/km^2). On estime que plus de 85% des bélugas se trouvaient au large, où ils s'étaient répartis uniformément en faible densité (0,099–0,311 béluga/km^2). Les données recueillies par les observateurs principaux (qui avaient l'expérience des dénombrements aériens) indiquent qu'il y aurait eu 15 307 bélugas visibles à la surface de l'eau (IC 95%, 12 305 – 18 309). Six examinateurs ont évalué indépendamment lesquelles parmi les observations faites par des observateurs secondaires (des participants provenant des communautés de la région, qui avaient une expérience limitée de ce type de recensement aérien, mais étaient habitués à repérer les bélugas à partir d'embarcations) ne concordaient pas avec celles des observateurs principaux. Ces résultats de confirmation ont servi à ajuster les dénombrements principaux de manière à tenir compte des bélugas à la surface et manqués ou sur le point de faire surface. Ils ont porté l'indice du stock des bélugas visibles à 19 629 (IC 95%, 15 134 – 24 125). Cette évaluation ne tient pas compte du nombre de bélugas qui avaient plongé en profondeur, par conséquent qui échappaient à toute détection, ou qui se trouvaient à l'extérieur de la zone d'étude.
[Traduit par la Rédaction]

Introduction

The Beaufort stock of beluga whales (*Delphinapterus leucas*) winters in the Bering Sea and migrates to summering areas in the Beaufort Sea and Amundsen Gulf (Marko and Fraker 1981). From late June to late July or early August, many beluga aggregate in the warm estuarine waters of the Mackenzie River, while others are widely distributed offshore (Norton and Harwood 1985). The density of beluga in the estuary generally peaks during the first half of July and declines gradually thereafter until August, when most of the whales have moved offshore (Fraker and Fraker 1979). During the July aggregation period, subsistence harvesters have observed beluga moving in and out of the estuary and have noticed marked day to day changes in the relative numbers of beluga occupying the estuary (B. Day, P.O. Box 2120, Inuvik, NT X0E 0T0, Canada, personal communication).

Oil and gas exploration in the late 1970s led to extensive studies of the summer distribution of beluga in the Mackenzie estuary (e.g., Fraker and Fraker 1979, 1981). In the 1980s, efforts were expanded to include the offshore Beaufort Sea (e.g., Davis and Evans 1982; Norton and Harwood 1985). However, there has been no extensive concurrent systematic survey of both the estuary and offshore, and this has hampered our understanding of the size of the Beaufort beluga stock.

In February 1992, the Fisheries Joint Management Committee (FJMC), Department of Fisheries and Oceans (DFO), and Environmental Studies Research Funds (ESRF) hosted a workshop on Beaufort beluga to (*i*) examine the present status

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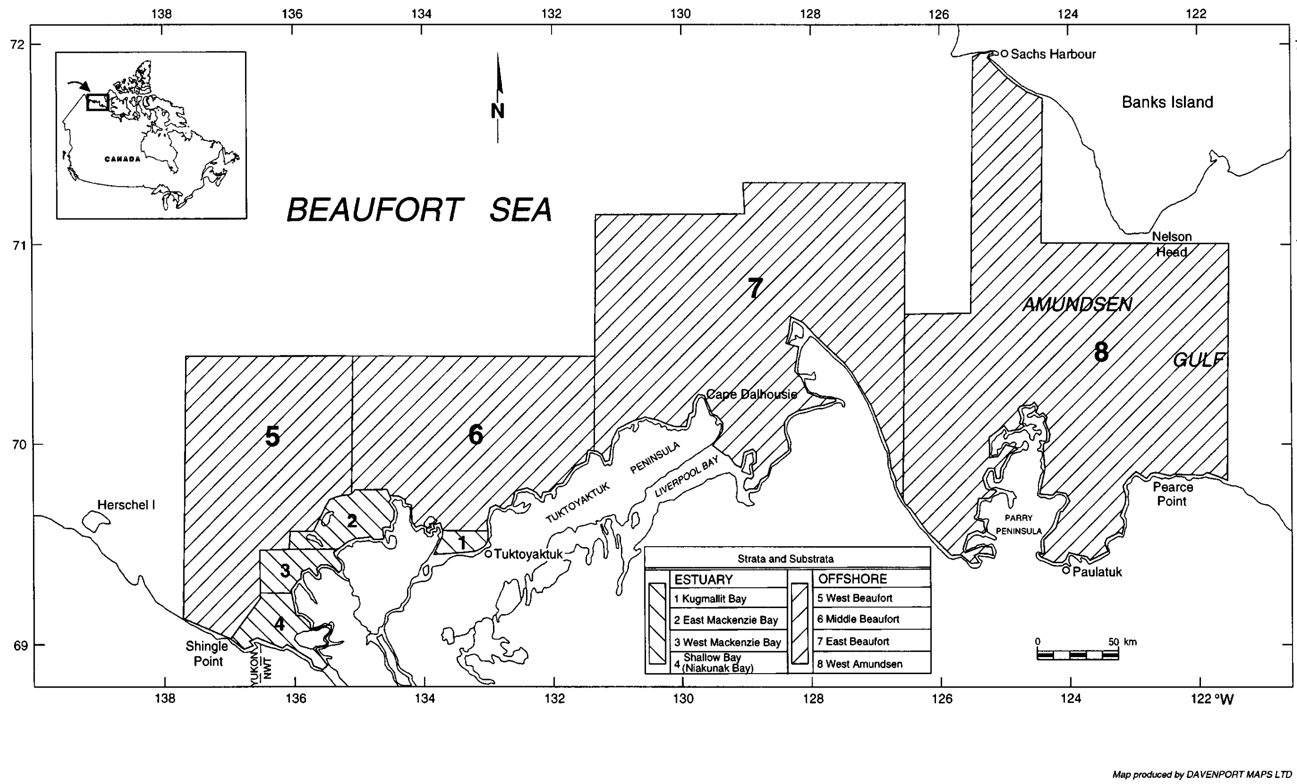
Fig. 1. Stratum and substratum boundaries for the Beaufort Sea, Mackenzie estuary, and Amundsen Gulf aerial survey, 23–25 July 1992.



of the Beaufort beluga stock, (*ii*) recommend the best methods for continued monitoring of the stock in response to human activities and environmental changes, and (*iii*) define research priorities. Thirty-one participants representing a cross section of hunters, government agencies, and technical advisors reached a consensus on these three goals (Duval 1993). The aerial survey reported here was undertaken to address a research priority recommended by the workshop participants.

Methods

Data collection

A systematic aerial survey was conducted over the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf on 23–25 July 1992 (Fig. 1). The primary objective of the survey was to collect observations of beluga that could be used to estimate the number visible at the surface. Raw data from the survey are archived in Harwood and Norton (1996).

The survey area was divided into two major operational strata on the basis of oceanographic features and the expected rate of encounter with beluga: the Mackenzie estuary stratum (called the estuary stratum), where beluga were expected to be clumped, and the offshore stratum (southeast Beaufort Sea and west Amundsen Gulf), where beluga were expected to be more widely distributed. The estuary was divided into four substrata on the basis of previous surveying patterns, each characterized by warm (10–18°C), turbid, and shallow (<5 m) waters from the Mackenzie River during summer (Fraker et al. 1979). The estuary stratum covered an approximate surface area of 3500 km^2.

The offshore stratum, covering an approximate surface area of 74 400 km^2, also had four substrata and is characterized by deeper (5–300 m), colder (0–4°C), clearer, and in some areas, ice-covered waters. The boundary between the estuary and offshore strata was the 5-m isobath for all but the western side of the estuary, where the boundary was a diagonal along the 3-m isobath between Shingle Point and the southwest portion of west Mackenzie Bay (Fig. 1).

In the estuary stratum, a strip-transect method was used (Caughley 1977). Standard transect lines established by Fraker (1977) were flown between 12:00 and 19:00 on 23 July 1992 in four substrata of the Mackenzie estuary: Kugmallit Bay, west Mackenzie Bay, east Mackenzie Bay, and Shallow Bay (also referred to as Niakunak Bay in the literature; Fig. 1). The transects were spaced at intervals of 3.2 km in all substrata except west Mackenzie Bay, where they were spaced at 4.8 km; the larger transect interval was established in west Mackenzie Bay because that area serves primarily as a migration corridor between the Shallow Bay and east Mackenzie Bay concentration areas.

The strip width was 0.8 km (0.4 km per side), reduced from the traditional 1.6 km (Fraker and Fraker 1981; Smith et al. 1985; Richard et al. 1990) because of the reduced detectability of beluga between 400 and 800 m from the flight path (Davis and Evans 1982; Norton and Harwood 1985). The strip was defined by marks on the bubble windows that represented a 50- to 450-m swath next to the flight path (clinometer readings of 81°–35° from the horizon inclusive). The observers' head positions were "fixed" by instructing them to initially establish and maintain the desired head position according to the window marks, and this was checked during the survey by each observer.

The density of beluga in the offshore stratum was estimated using a line-transect method (Burnham et al. 1980; Buckland et al. 1993). This method was applicable to the clear offshore stratum, where fewer sightings were expected, so the time spent obtaining the perpendicular angle was unlikely to result in missed sightings. The four offshore substrata, west Beaufort Sea, middle Beaufort Sea, east Beaufort Sea, and west Amundsen Gulf, were surveyed between 14:00 on 24 July and 19:00 on 25 July 1992.

In total, 20 north–south transect lines were flown, spaced at intervals of 30′ or 60′ longitude. The southern end point for each offshore

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transect was the shore, except for those north of the Mackenzie estuary, where the southern end point was the seaward limit of the estuary stratum. The northern end point for the offshore transects was the 9/10 ice edge, although it was not possible to reach this target in many cases, owing to fog associated with the ice edge and the range of the aircraft.

In the offshore stratum, observers measured the angle from the horizon, using a Suunto PM/360S clinometer, when the whale or whale group was perpendicular to the aircraft. Calculations using this angle and the survey altitude were used to estimate the lateral distance of the sighting from the flight path.

Three de Havilland Twin Otter series 300 aircraft, each with three or four observers, were used to conduct the survey. Each aircraft was equipped with a Global Positioning System for navigation and a radar altimeter for maintaining the desired survey altitude of 305 m above sea level (asl). The alternative survey altitude of 152 m asl was used in east Mackenzie Bay because of a low cloud ceiling (windows were re-marked for the 50- to 450-m swath, 72°–19° from horizontal inclusive). Surveys were not attempted if the ceiling was below 152 m. Ground speed for the survey was targeted at 200 km·h^{-1}, averaged 191 km·h^{-1}, and ranged from 169 to 214 km·h^{-1}. All search positions in all aircraft were equipped with bubble windows.

As rough seas and glare from the sun significantly reduce the detectability of marine mammals in aerial surveys (Davis et al. 1982; Holt and Cologne 1987; Harwood and Stirling 1992), surveying was attempted only when sea states were Beaufort 0 (calm, sea like a mirror), 1 (light air, ripples but without crests), 2 (light breeze, small wavelets with crests that do not break), or 3 (gentle breeze, large wavelets with crests that are beginning to break). To minimize glare, most of the survey was conducted while the sun was most directly overhead (11:00–17:00). All observers used sunglasses.

There were six observers with previous aerial survey experience, and these were designated primary observers. There were four community observers and they were designated secondary observers. While they had little or no previous aerial survey experience, each had extensive (i.e., 5–20 years) experience searching for beluga from boats during hunting. Prior to the survey, all observers were briefed on survey procedures, and all but one of the secondary observers participated in at least one 2-h practice flight.

Each aircraft had two primary observers who occupied the second left and second right seats behind the bulkhead. Each aircraft had at least one secondary observer, who occupied the rear left seat. One aircraft had an extra secondary observer, who occupied the right rear seat. During the survey, the left and right primary observers traded seats on alternating transects to allow a comparison of the observations of each with those of the secondary (rear) observer. Primary and secondary observers were separated visually by the physical distance between them (4.6 m) and because they used bubble windows, which require the head to be partially inserted into the bubble. Observers could not hear each other during the survey because of the noise of the aircraft's engines and because push-to-talk (rather than voice-activated) microphones were used for any necessary communication. Pilots did not alert observers to any beluga they sighted ahead or to the side of the aircraft.

The usual flight time was 5–6 h/day. To minimize fatigue, observers rested during ferrying flights to and from the survey area, during 1- to1.5-h refuelling stops, and during transit flights between transects (3–4 min between estuary transects and 9–10 min between offshore transects). The length of time required to survey a transect ranged from 10 to 16 min in the estuary stratum and from 20 to 50 min in the offshore stratum.

At the beginning of each transect, each observer recorded on their own individual audio tape recorder the transect start time using a synchronized digital watch (minutes and seconds), transect number, direction of flight (compass points), seat position, glare level (nil, moderate, or strong; forward or back), and sea state (Beaufort scale of wind force). Primary observers also recorded the concentration of ice according to five categories (0/10, 1/10–3/10, 4/10–6/10, 7/10–9/10, >9/10), and other survey conditions such as fog and low cloud. These were recorded at the beginning and end of each transect, and along the transect when changes were encountered. At the end of the transect, end time was recorded.

For each marine mammal sighted, observers independently recorded information on species, number in the group, time of sighting, number of degrees from horizontal (for the offshore transects only), relative size and colour of whale (e.g., white (adult), large gray (subadult), small gray (calf, either young of the year or 1 year old), behaviour (e.g., tail splashing; calf lying on mother's back), and direction of whale movement. A group of beluga was defined as two or more individuals within an estimated five body lengths of each other (Norton and Harwood 1985). A sighting consisted of either an individual whale or a group of whales.

To ensure a consistent and uninterrupted search, we did not depart from the transect lines to circle groups of beluga that were sighted. Clear and calm waters in the offshore afforded observers a consistent period of time to estimate group size. In the estuary, it would not have been fruitful to circle groups of beluga because of the turbidity of the water and the large number of rapid and partial sightings.

Data analysis

The data set was scrutinized and transects with interrupted coverage (e.g., fog, low cloud, areas with strong forward glare) or questionable or incomplete data records (e.g., malfunction of tape recorder) were identified and coded accordingly (see Harwood and Norton 1996). We used only data collected according to the established criteria, with no known shortcomings (88.2% of sightings) or with known shortcomings that would not seriously hamper our calculation of the index of stock size (e.g., 9.8% with sighting times recorded to the nearest minute instead of second). Data collected by the secondary observers were used only for the second stage of the analysis, which involved identifying definite nonduplicate sightings by six independent reviewers and calculating an adjustment factor for missed-at-surface and about-to-surface beluga. Data collected using line-transect methods in the estuary stratum or during unfavourable surveying conditions were not used in any of the analyses.

For 21 and 24 July 1992, the locations of the broken (2/10–6/10) and solid (>9/10) ice edges were obtained from maps prepared during ice-reconnaissance surveys flown by the Atmospheric Environment Service (AES). Whale sightings used in calculating the abundance indices formed the basic data set, and these were plotted using time of observation, transect start and end times, and mean ground speed. Observers recorded the direction of movement of beluga that they sighted, and these were plotted on the whale distribution maps in cases where definite and directed movement was noted.

Index of stock size

Using the data collected by the primary observers in the estuary stratum, the total number of beluga visible at the surface was estimated separately for each of the four estuary substrata. Traditionally, a ratio estimator based on the density of whales would be used to estimate the number of beluga seen (Caughley 1977). However, because the number of whales present in an area is not a direct function of the area of the sample (see Smith et al. 1985; Richard et al. 1990), and calculating the area would introduce another source of variability, little or no efficiency is gained by including area in the analysis. For this data set, the estimate of the number of beluga visible at the surface and the associated sampling standard error of this estimate were calculated using the difference method for systematic surveys outlined in Yates (1960; see also Kingsley and Hammill 1991), where the estimated number of whales seen within a stratum is calculated using the formula

$$Y = \left(\frac{W}{w}\right)\sum y_i$$

where Y is the estimated number of beluga at the surface, W is the

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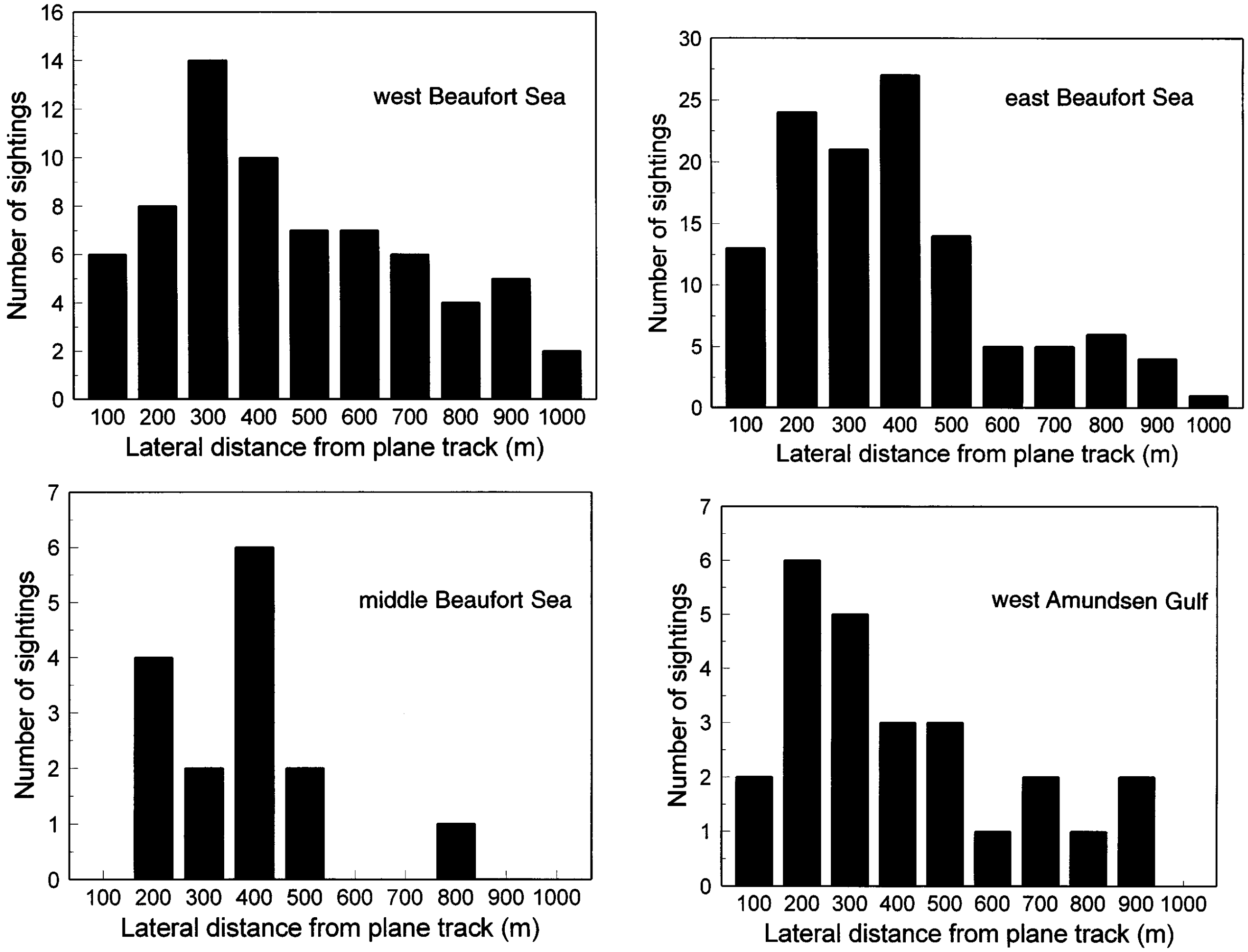
Fig. 2. Perpendicular distance from plane track of beluga whale sightings made during the 23–25 July 1992 aerial survey of the Beaufort Sea, Mackenzie estuary, and west Amundsen Gulf.



distance between transect lines, w is the width of the transect, and y_i is the number of beluga seen in the ith transect line. The approximate sampling standard error for the estimate of Y is given by the formula

$$SE(Y) = \left(\frac{W}{w}\right)\left(\frac{n}{2}\sum\frac{d_i^2}{(n-1)}\right)^{1/2}$$

where SE is the standard error of the estimate of Y and d_i is the difference between adjacent transects. The value $n - 1$ comes from Yates' (1960) n', which is the number of comparisons minus 1. Estimates and their variances for the strata and substrata were combined without applying any weighting criteria, such as corrections for sea state or glare (Yates 1960; Gasaway et al. 1986).

Using only line transect data collected by the primary observers in the offshore stratum, perpendicular distances were converted to the density and number of beluga visible at the surface, by the program DISTANCE (Laake et al. 1993). A distance truncation of 800 m from the aircraft track line was used in the analyses to avoid any biases associated with the inclusion of opportunistic sightings. Survey effort was concentrated in the area closest to the survey line to avoid missing any animals on, or close to, the track line.

Beluga close to the track line are missed more often than those on the middle or outer parts of the transect (Norton and Harwood 1985), owing to (*i*) the physical constraints of viewing beluga from an aircraft, (*ii*) the short time that an area of ocean near the aircraft is in view compared with areas farther from the aircraft, and (*iii*) instructions to concentrate on a swath beginning 50 m from the flight path during the line-transect portion of the flight. There was observer variability in each of the above factors that affected the detectability of beluga near the survey line. Rather than set individual offsets for each observer, the detectability curves for each substratum were plotted and examined, and the effect of offsetting the applied track line by 50, 100, 200, and 300 m was investigated by calculating and comparing estimates for each offset width.

To amass a suitable sample size of observations for line-transect analysis, the total number of observations was determined and the density and sampling standard error were determined, assuming the expected Poisson distribution (Burnham et al. 1980). As sighting curves were found to vary among substrata (Fig. 2), uniform, half-normal, and hazard models with cosine adjustments were fit to each substratum individually and the best-fit model was selected using the DISTANCE program algorithm based on the Akaike information criterion procedure (Laake et al. 1993).

Aerial surveys underestimate the number of whales present, because some whales may not surface during the observation period and some that surface may not be seen. On some flights, the secondary observers made observations that could be compared with those made by the primary observers. Using time of sighting, group size, and lateral distance, it was difficult to unequivocally determine which of the sightings made by the secondary observers were the same (i.e., duplicates) as those made by the primary observers. Many could only be assigned to the "possible" duplicate category, and an estimate of

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the number of duplicates was required for the formula to calculate the adjustment factor for missed-at-surface and about-to-surface beluga.

For this reason we established a process using six independent reviewers to determine which of the secondary observers' sightings were definitely not made by the primary observers (definite nonduplicates). The number of duplicates was entered into the calculations as the total number of sightings by the secondary observer minus the number of definite nonduplicates minus 1. With this approach, the possible duplicates were classified as duplicates, and thus we overmatched, which ultimately produced an adjustment factor that was an underestimate.

The six reviewers were provided with a listing of the survey data by transect, with all sightings in chronological order. The following information for each sighting was included: initials of observer, seat position, time of sighting, number of beluga in the group, clinometer reading, and, when available, comments (e.g., direction of movement, colour, and behaviour). Instructions to the reviewers stressed the need to err on the conservative side in determining definite nonduplicates. To be considered a definite nonduplicate, a sighting had to be identified as such by at least four of the six reviewers.

From the information provided, and with their own experience and judgement, the six reviewers established their own criteria on a sighting-by-sighting basis, with the most uniform predominating in the review process. At the conclusion of the process, we found that the most common criteria used by the reviewers were time of sighting and number of beluga in the group, although other criteria (e.g., clinometer reading, direction of movement, composition of group) were used in other cases when available and considered reliable by the reviewer.

For the estuary transects, an adjustment factor based on the definite nonduplicates was calculated using mark–recapture estimates for small sample sizes (Seber 1982), where the number of recaptures (m_2) was the number of groups seen by the secondary observer (n_2) minus the number of definite nonduplicates. The correction factor, N divided by n_1, where N is the actual number of groups present and n_1 is the number of groups seen by the primary observer, is

$$\frac{N}{n_1} = \frac{(n_1 + 1)(n_2 + 1) - (m_2 + 1)}{n_1(m_2 + 1)}$$

The SE of the adjustment factor is given by

$$SE = \frac{(n_1 + 1)(n_2 + 1)(n_1 - m_2) - (n_2 - m_2)}{(m_2 + 1)^2\,(m_2 + 2)}$$

Assumptions associated with this method are the same as for other mark–recapture estimates: that the population is closed, that all animals have an equal probability of being seen, that the observation of a beluga by the primary observer does not influence the chance that it will be seen by the secondary observer and vice versa, and that each beluga sighting can be categorized as either seen or not seen by the primary observer.

For the offshore stratum, the adjustment factor was calculated on the basis of Buckland and Turnock's (1992) mark–recapture procedure as it relates to line-transect methods and applied (by substratum) to the unadjusted estimates. The error estimate (Buckland and Turnock 1992) was simulated using the estimated probability densities of perpendicular distances at the track line and their error estimate, and resampling of the transects with replacement to establish the statistical error in the numbers of primary and resighted (secondary observer sightings that were definite nonduplicates) beluga groups. The process was replicated 1000 times and the standard error of the adjustment factor determined from these simulations. The procedure was simplified for the special case where there is no movement of beluga between the times when they are detected by the primary and secondary observers.

The assumptions of this method (Buckland and Turnock 1992) are (*i*) that no animals beyond the range of detectability by the secondary observer are able to move into the the range of detectability by the primary observer, (*ii*) that it is always possible to determine whether an animal detected by the secondary observer is also detected by the primary observer, (*iii*) that given an animal passes the secondary observer at lateral distance y, its probability of detection by the primary observer is independent of whether it was detected by the secondary observer, and, (*iv*) that the perpendicular distances for animals detected by the secondary observers are measured without bias.

Results

Practice flights were conducted on 15–16 July 1992, and the survey was flown within the next favourable weather window, 23–25 July 1992. The Mackenzie estuary was ice free at the time of the survey (Fig. 3). The edge of the pack ice was located 100–150 km north of the Mackenzie estuary, 50–100 km north of the Tuktoyaktuk Peninsula, and 130 km north of Cape Dalhousie and Cape Bathurst (Fig. 4). There was a 15–90 km wide band of broken ice (2–6/10) between the consolidated ice edge far offshore and the ice-free nearshore area. This band extended from the western edge of the survey area east to Cape Bathurst (Fig. 4). Amundsen Gulf was essentially ice free during the survey, as was the area north of Cape Bathurst, at the approximate location where the Bathurst polynya usually occurs in winter. Waters off the Yukon coast (west of transect 7) could not be surveyed because of fog and low cloud (Fig. 4). Data obtained on portions of some offshore transects (see transects 15, 17, 23, 30, and 34 in Fig. 4) could not be used because of localized rough seas or patches of fog. Data collected by one of the primary observers for transects 11, 28, and 34 (7.7% of the total track line) could not be used, as strong forward glare essentially obliterated the search area on that side of the aircraft. For these transects, only data collected by the primary observer on the side of the aircraft with back glare were used in the analyses. Otherwise, conditions during the survey were favourable. The requisite survey conditions were met for 1183.9 km (100%) of the estuary stratum and 4130 km (97.6%) of the offshore stratum.

Estuary stratum

In the Mackenzie estuary, beluga were common in all substrata surveyed (Table 1, Fig. 3).The primary observers made a total of 253 sightings (404 beluga) in the estuary stratum, and the secondary observers functioning in two of the four substrata made a total of 37 sightings (69 beluga). In the estuary, 88% of the primary observers' on-transect sightings were of individuals or pairs.

The sightings were clumped in all substrata but Kugmallit Bay, and in some cases loose aggregations appeared to span several transect lines (Fig. 3). In the Shallow Bay and west Mackenzie Bay substrata, the aggregations were located immediately landward of the 2-m isobath (Fig. 3). When differences in survey coverage are accounted for, Kugmallit Bay appeared the most attractive to the beluga during late July 1992, having 35% of the sightings. West Mackenzie, east Mackenzie, and Shallow bays accounted for 17, 20, and 29% of the sightings, respectively.

Cows with calves were present in two of four substrata in the estuary, with a total of nine cow–calf pairs sighted in Kugmallit and east Mackenzie bays. This survey undoubtedly underestimated the number of calves present, because of the difficulty in detecting the small dark calves in the turbid estuary

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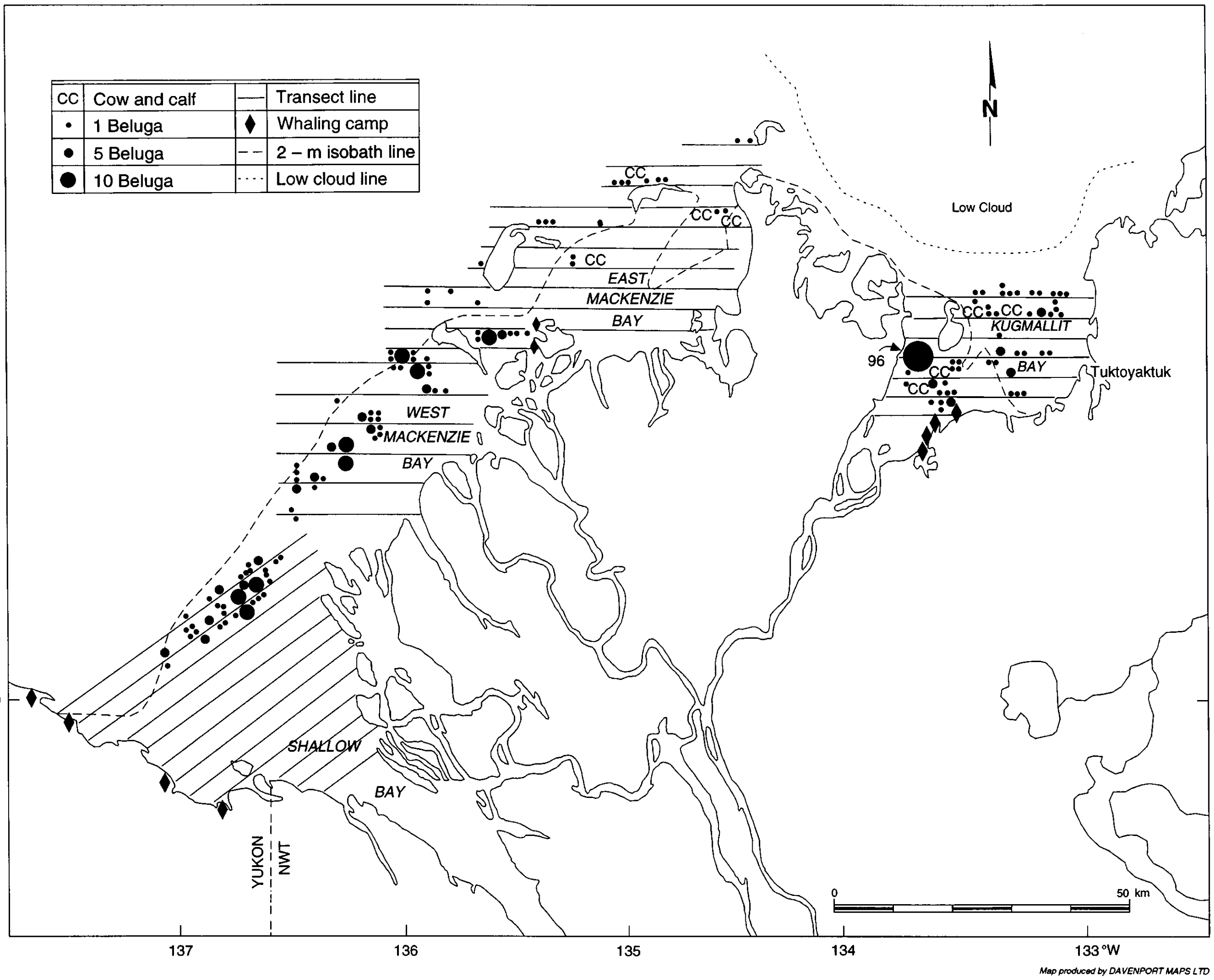
Fig. 3. Distribution of beluga whales observed in the Mackenzie estuary during an aerial survey on 23 July 1992.



waters, and because most sightings in this stratum were rapid and partial.

Using a strip-transect method and data collected by the primary observers, we estimate that 1998 (95% CI 1630–2366) beluga were visible at the surface in the four bays of the Mackenzie estuary on 23 July 1992 (Table 2). The calculated standard errors of the estimates for each bay ranged from 10 to 22% (Table 2). As most (88%) groups consisted of one or two beluga (Fig. 5), an adjustment for group size was not warranted. Kugmallit Bay had the highest density of beluga visible at the surface (1.137 beluga/km^2), while the average density for the estuary stratum was 0.56 beluga/km^2.

Offshore stratum

Offshore, beluga were sighted on each of the 20 transect lines flown (Fig. 4). The primary observers saw a total of 251 groups (414 beluga), while the secondary observers saw 108 groups (232 beluga; Table 1). Clinometer readings were obtained for 93.6% of all beluga sightings made in the offshore stratum by the primary observers.

The largest group of beluga seen during the survey consisted of 22 animals (off-transect owing to sea state, southern end of transect 34), while the mean group size for on-transect sightings in the offshore was 1.65 (standard deviation 1.43, range 1–12; Fig. 5). Offshore, 87% of the primary observers' on-transect beluga sightings were of individuals or pairs. Sightings of cow–calf pairs were made by the primary observers in each substratum, and in total, 28 cow–calf pairs (11.1% of sightings) were seen at the surface in the offshore (Fig. 4). While it is more likely that observers will detect calves in the clearer offshore waters than in the turbid estuary, the detectability of calves is still expected to be less than that of the larger white or gray animals.

When differences in survey coverage were accounted for, it was apparent that the east Beaufort substratum was the most attractive to beluga during late July 1992. Approximately 50% of the on-transect sightings in the offshore were made in this substratum (Table 2). The majority of beluga seen in the east Beaufort and west Amundsen substrata were moving in an easterly direction at the time of sighting, while no particular direction predominated in other areas of aggregation, including the estuary (Figs. 3 and 4).

It was expected that the line-transect method would produce an estimate of the number of beluga visible at the surface that would maximize at an offset between 0 and 300 m from the flight path, as the influence of the lower probability of

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Fig. 4. Distribution of beluga whales observed in the offshore Beaufort Sea and west Amundsen Gulf during an aerial survey, 24–25 July 1992.

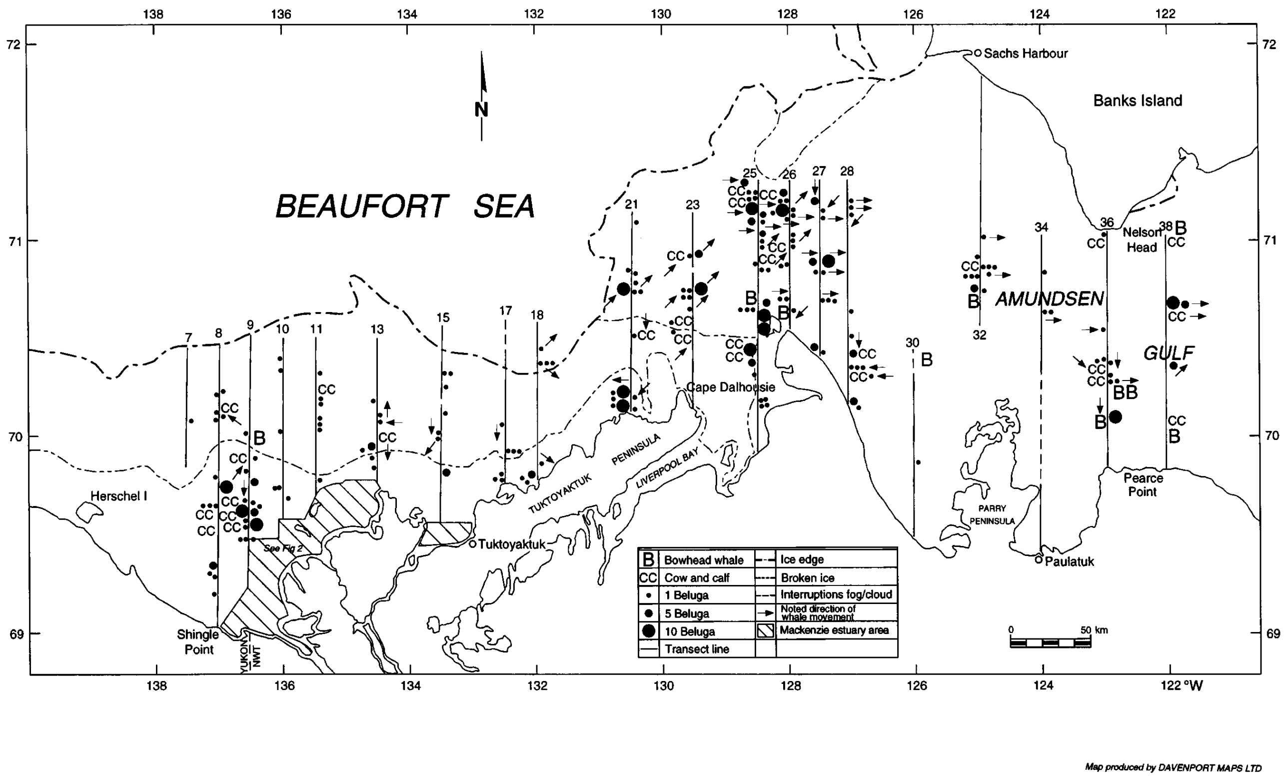

Table 1. Size of the strata, substrata, and surveyed area and counts of beluga sighted at the surface by primary and secondary observers in the Beaufort Sea, Mackenzie estuary, and Amundsen Gulf aerial survey, 23–25 July 1992.

Stratum	Substratum	Size of substratum (km^2)	No. of transects	Approximate survey coverage (%)	Survey distance under requisite survey conditions (km)	Primary observers: No. of sightings	Primary observers: No. of beluga	Secondary observers: No. of sightings	Secondary observers: No. of beluga
				Strip transect					
Estuary	Kugmallit Bay	619	7	25	191.3	120	176	—	—
	Shallow Bay	1 056	12	29	380.9	39	84	19	37
	East Mackenzie Bay[a]	1 104	11	15	423.6	41	49	—	—
	West Mackenzie Bay	791	6	19	188.1	53	95	18	32
	Total	3 571[b]	36		1183.9	253	404	37	69
				Line transect					
Offshore	West Beaufort Sea	12 461	6	6.3	975.5	76	95	31	38
	Middle Beaufort Sea	12 391	4	4.5	746.0	16	33	9	20
	East Beaufort Sea	21 977	6	4.6	1276.2	127	227	52	132
	West Amundsen Gulf	27 590	5	2.9	1132.3	32	59	16	42
	Total	74 419	20		4130.0	251	414	108	232
Total		77 990	56			504	818	145	301

Note: Offshore data are based on line-transect method only; sampling fraction = 0.5.

[a]Data from only one primary observer were used for analyses.

[b]Determined by adding substratum estimates calculated to 0.01, then rounding to a whole number.

detecting beluga close to the aircraft track line was removed. Our analysis comparing estimates derived using different offset widths (50, 100, 200, and 300 m) confirmed this, although there were few differences among the estimates and all of the estimates fell within each other's confidence regions (Table 3). Since plots of the numbers of on-transect sightings against lateral sighting distances for three of our four substrata (incorporating 85% of the offshore on-transect sightings) showed reduced detectability in the 0- to 100-m interval and peak detectability in the 100- to 200-m interval (Fig. 2), and on the basis of previous beluga surveys in the Beaufort region that used or recommended an offset of 100 m (Davis and Evans 1982; Norton and Harwood 1986), a 100-m offset was selected. In addition, from the offset comparisons (Table 3), choosing 100 m represents the best compromise between selecting the offsets that produced the largest estimate (e.g.,

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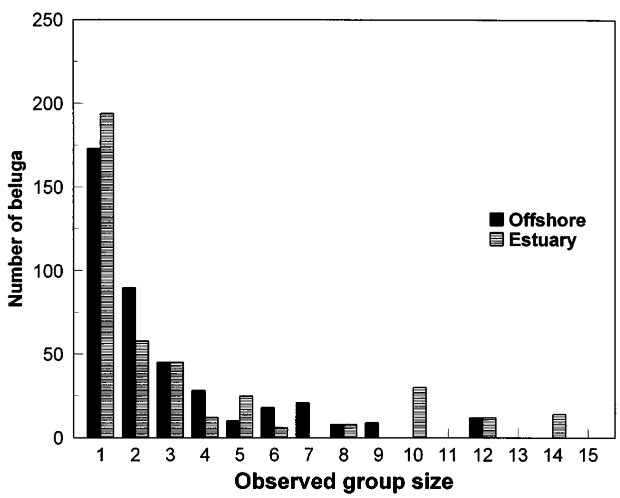
Table 2. Estimated density of beluga (number/km^2) and standard error (SE), applied adjustment for missed clinometer readings (AF), and estimated number, standard error (SE), and 95% confidence interval (CI) of surfaced, visible beluga, based on observations by the primary observers in the 23–25 July 1992 aerial survey of the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf.

		Density			No. of beluga[a]		
Stratum	Substratum	Mean	SE	AF	Mean	SE	95% CI
Estuary	Kugmallit	1.137	0.225	na	704	155	394 – 1 014
	Shallow	0.314	0.051	na	332	62	208 – 456
	East Mackenzie Bay	0.355	0.033	na	392	51	290 – 493
	West Mackenzie Bay	0.721	0.060	na	570	57	456 – 684
	Total				1 998	184	1 630 – 2 366
Offshore	West Beaufort Sea	0.166	0.0314	1.085	2 065	391	1 419 – 3 004
	Middle Beaufort Sea	0.135	0.0490	1.000	1 675	607	808 – 3 471
	East Beaufort Sea	0.311	0.0465	1.023	6 832	1023	5 101 – 9 149
	West Amundsen Gulf	0.099	0.0286	1.300	2 738	807	1 526 – 4 911
	Total				13 309[b]	1490	10 330 –16 289
Total					15 307	1501	12 305 – 18 309

Note: na, not applicable.
[a]Estimated number of surfaced, visible beluga as determined by a strip-transect method (estuary stratum) and line-transect method (offshore stratum).
[b]Determined by adding substratum estimates calculated to 0.01, then rounding to a whole number.

Fig. 5. Frequency distribution of group sizes of beluga observed on transect by primary observers during the 23–25 July 1992 aerial survey of the Beaufort Sea, Mackenzie estuary, and west Amundsen Gulf.



300 m) and the estimate that used the greatest proportion of the observations (e.g., 100 m, $n = 193$).

The DISTANCE program was then allowed to select the most appropriate detection model on the basis of the Akaike information criterion procedure (Laake et al. 1993). This procedure also had little influence on the estimated number of beluga visible at the surface in the offshore stratum (Table 4). Like the selection of the offset, the estimates based on the uniform, half-normal, and hazard models all fell within each other's confidence intervals (Table 4). The residuals associated with group size did not indicate that a blocking by group size was warranted, probably because 87% of the primary observers' on-transect groups consisted of only one or two whales. Using a 100-m offset and correcting (by substratum) for the proportion of observations without clinometer readings (16 of 251 sightings), the number of visible, surfaced beluga was estimated to be 13 309 (95% CI 10 330 – 16 289; Table 2).

One assumption of the line-transect method is that perpendicular distances are recorded for all sightings. However, when the density of beluga increases, sightings may occur too fast for the perpendicular distances of all beluga groups to be determined. During the present survey, in 6.4% of the sightings, perpendicular distances were missing. In correcting our estimates to include sightings with no clinometer readings, we assumed that these observations have the same perpendicular distance distribution as the observations for which distances were recorded. We believe that this is valid, since observers, when questioned, said that distances were missed in situations where beluga were encountered quickly and repeatedly, when time was insufficient to take a reading before having to move on to the next sighting (e.g., related to the density of beluga and not to the lateral distance of the beluga on the transect).

Adjusted estimate

In two of the four estuary substrata, usable data were obtained from the secondary observers to calculate an adjustment factor for beluga missed by the primary observers. Forty and 36 beluga sightings were made by primary and secondary observers, respectively, during surveys of the Shallow and west Mackenzie substrata. Three of the 36 groups seen by the secondary observers were interpreted as definite nonduplicates. Thus, the primary observers missed 3.62 (SE = 0.89) beluga groups. The adjustment factor for beluga groups that were visible but not seen by the primary observers was 1.085 (SE = 0.022) and the adjusted estimate was 2168 beluga (SE = 204).

In the offshore stratum, usable data from the secondary observers were obtained in all four substrata. Eighty-five beluga groups were seen by the secondary observers between 100 and 800 m from the flight path, of which 18 groups were determined by four or more of the six reviewers to be definite nonduplicate observations. Using the mark–recapture method applied to line-transect methods (Buckland and Turnock 1992), the adjustment factor for the offshore stratum was determined to be 1.312 (SE = 0.139). Applying this factor to the unadjusted

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Table 3. Line-transect survey estimates for offsets of 0, 50, 100, 200, and 300 m from the aircraft track line.

			Estimate			Model selected by			
Offset	Substratum	*n*	Mean	SE	df	DISTANCE	χ^2	df	*p*
0	West Beaufort Sea	62	1 845	332	74	Half-normal	4.27	6	>0.64
	Middle Beaufort Sea	15	1 486	545	22	Uniform + 1[a]	3.48	4	>0.48
	West Amundsen Gulf	24	1 863	548	43	Uniform + 1[a]	1.77	5	>0.88
	Total	215	11 075	1236	217				
50	West Beaufort Sea	57	2 022	356	71	Uniform + 1[a]	4.42	5	>0.49
	Middle Beaufort Sea	15	1 788	706	27	Half-normal	2.68	2	>0.26
	West Amundsen Gulf	23	1 900	564	42	Uniform + 1[a]	2.81	5	>0.73
	Total	206	12 195	1329	203				
100	West Beaufort Sea	56	1 903	360	66	Half-normal	2.27	5	>0.81
	Middle Beaufort Sea	15	1 675	607	22	Uniform + 1[a]	4.89	3	>0.18
	East Beaufort Sea	101	6 678	1008	174	Hazard	3.24	4	>0.52
	West Amundsen Gulf	21	2 106	621	39	Uniform + 1[a]	1.18	4	>0.88
	Total	193	12 363	1374	222				
200	West Beaufort Sea	48	2 257	411	59	Uniform + 1[a]	1.04	4	>0.90
	Middle Beaufort Sea	11	1 477	668	19	Half-normal	4.18	2	>0.12
	East Beaufort Sea	76	6 844	1306	118	Hazard + 1[a]	2.82	3	>0.42
	West Amundsen Gulf	15	1 412	503	26	Uniform + 1[a]	1.07	3	>0.78
	Total	150	11 990	1613	177				
300	West Beaufort Sea	34	1 579	388	39	Half-normal + 1[a]	0.35	3	>0.95
	Middle Beaufort Sea	9	3 168	1535	14	Half-normal + 2[a]	3.11	2	>0.21
	East Beaufort Sea	55	9 648	2064	92	Half-normal + 2[a]	0.19	2	>0.91
	West Amundsen Gulf	10	780	322	9	Uniform + 1[a]	2.00	4	>0.74
	Total	105	15 174	2621	79				

[a]Number of cosine adjustments entered into the fit.

Table 4. Difference in estimates of number of beluga, owing to the selection of model for line-transect analysis in the offshore stratum.

		No. of beluga[a]		
Substratum	Model	Mean	SE	95% CI
West Beaufort Sea	Uniform + 1[b]	1 990	372	1 375 – 2 880
	Half-normal	1 903	360	1 308 – 2 769
	Hazard	2 063	531	1 243 – 3 425
Middle Beaufort Sea	Uniform + 1[b]	1 675	607	808 – 3 471
	Half-normal	1 901	756	869 – 4 160
	Hazard	1 562	608	721 – 3 382
East Beaufort Sea	Uniform + 1[b]	6 991	903	5 433 – 8 997
	Half-normal	7 193	1031	5 444 – 9 517
	Hazard	6 678	1000	4 987 – 8 943
West Amundsen Gulf	Uniform + 1[b]	2 106	621	1 174 – 3 778
	Half-normal	2 149	683	1 146 – 4 030
	Hazard	2 119	844	963 – 4 662
All	Uniform	12 762	1306	10 446 – 15 592
	Half-normal	13 151	1491	10 537 – 16 413
	Hazard	12 422	1538	9 755 – 15 818

Note: A 100-m offset from the aircraft track line was used.
[a]Estimated number of surfaced, visible beluga.
[b]Number of cosine adjustments.

substratum estimates (Table 2) yielded an overall adjusted estimate for the offshore stratum of 17 462 visible beluga (SE = 2238). Adding the adjusted estimates for the estuary and offshore strata, the overall adjusted estimate for the survey was 19 629 (95% CI 15 134 – 24 125) surfaced, visible beluga.

The assumptions associated with the application of the mark–recapture method to the estuary (strip transect) and offshore (line transect) data were not violated in most cases. The first assumption, that the population is closed, was not expected to be violated, since the primary and secondary observers were watching essentially the same water at the same time (e.g., <0.2 s between observers). Another assumption, that all animals have an equal probability of being seen by an observer, was not expected to be violated for this same reason, and because whale behaviour would not be expected to change within the short period of time separating the observers. The assumption that the observation of a beluga by the primary observer does not influence the chance that it will be seen by the secondary observer and vice versa was not violated, as the primary and secondary observer pairs could not see or hear each other during the survey. For the line-transect application, the assumption that secondary observers recorded lateral distances without bias was met, as the full range of lateral distances was recorded (Fig. 2).

One assumption, which applied to both the strip- and line-transect approaches for calculating the adjustment factors, was that all beluga sightings could be categorized as either seen or not seen by the primary observer. This assumption was not met in either case, as a large number of the primary observers' sightings were difficult or impossible to unequivocally match or not match with the secondary observers' data. However, with our process of first identifying the definite nonduplicates, and setting the number of duplicates as 1 minus this value, we were, in effect, overmatching, and this had the effect of producing adjustment factors that were ultimately underestimates.

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Discussion

The distribution of beluga found in this survey was similar to that from the July 1984 survey (Norton and Harwood 1985) in which it was determined that large numbers (thousands) of beluga were widely distributed throughout the offshore at the same time that others remained aggregated in the Mackenzie estuary. Females with calves were found in the estuary as well as widely distributed throughout the offshore in both the 1984 and 1992 surveys.

In this study, we found that beluga were aggregated in several offshore areas, including (*i*) 10–30 km to the northwest of west Mackenzie Bay, (*ii*) within 5–10 km of shore off the Tuktoyaktuk Peninsula, Baillie Islands, and the mouth of the Horton River, (*iii*) 50–80 km off Cape Bathurst in the approximate area where the Bathurst polynya often recurs in winter, and (*iv*) in central Amundsen Gulf, approximately 50 km north of Pearce Point. The area off Cape Bathurst appeared particularly attractive to beluga in July 1992, when the aggregation encompassed more than 2500 km^2.

There is some evidence that these offshore locations may be associated with feeding. For example, the area off Cape Bathurst is characterized by nutrient-rich waters that may be more productive than elsewhere in the Beaufort Sea. This area was found to be particularly attractive to bowhead whales (LGL Ltd. 1988) and ringed seals (Harwood 1989) during the open-water period. Inuvialuit hunters have reported occasionally landing whales with full stomachs from the nearshore Tuktoyaktuk Peninsula area, unlike the majority of the whales landed in the estuary (e.g., >99%), which have nothing in their stomach (L. Harwood, DFO, Inuvik, NT X0E 0T0, Canada, unpublished data).

Aerial survey observers in this and previous surveys have reported that beluga in these offshore areas are frequently associated with seabirds and commonly exhibit darting behaviour thought to be associated with feeding (Norton and Harwood 1985, 1986). Beluga were observed aggregated in these same areas in the beluga survey of 21–23 July 1984 (Norton and Harwood 1985), and in bowhead whale surveys flown in mid-August 1981 (Davis and Evans 1982), late August 1982 (Harwood and Ford 1983), late August 1984 (Norton and Harwood 1985), and August–September 1985 (Duval 1986).

The distribution of beluga in all substrata of the estuary in 1992 showed a pattern typical of earlier surveys of the estuary, with the exception of Kugmallit Bay, where the whales were less clumped than in past surveys (e.g., Fraker and Fraker 1979, 1981). There was no hunting activity coincident with the 1992 survey, and either this or weather, food, or reductions in the level of industrial activity may have caused or contributed to the apparent differences in distribution. The occurrence of beluga along the 2-m isobath in Shallow and west Mackenzie bays is similar to that seen in previous years (Fraker and Fraker 1981; Norton and Harwood 1986), and may be related to the availability of food (Norton and Harwood 1986) or suitable substrate for rubbing, although this has not been documented for this area as it has for other areas (e.g., Smith et al. 1992). Beluga are thought to aggregate in estuaries to facilitate the annual moult, because low salinity levels and high temperatures promote this process (St. Aubin et al. 1990).

Using only data collected by the primary observers, the present survey yielded an overall, uncorrected estimate of 15 307 (95% CI 12 305 – 18 309) visible beluga whales in the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf. This estimate is considerably larger than those published previously for this stock, based on surveys in either the offshore (estimate 11 500, Davis and Evans 1982; initial estimate 7081 (Norton and Harwood 1985), revised estimate 10 519, based on reanalysis using the line-transect method (P. Norton and L.A. Harwood, unpublished data, cited in Duval 1993) or the estuary (estimates ranged from a low of 3500 in 1981 to a high of 7000 in 1982; see Table 7 in Norton and Harwood 1986). However, none of the earlier estimates is strictly comparable to that from the 1992 survey, as the latter involved a larger offshore area and the Mackenzie estuary in the same survey, and used a line-transect method in the offshore. The 15 307 estimate is itself considered an underestimate because calves were under-represented in the sample of surfaced whales, and because no adjustment was made for whales that were missed by observers, were below the surface at the time of the survey, or were outside of the study area.

Incorporating data collected by the secondary observers, we adjusted our estimate for the study area to 19 629 (95% CI 15 134 – 24 125) surfaced, visible beluga. This estimate includes an adjustment for missed-at-surface whales (missed by the primary observer but detected at the surface by the secondary observer) and for about-to-surface whales (i.e., those that surface during the short time separating the observation periods of the primary and secondary observers). The amount of correction owing to missed-at-surface whales compared with the amount of correction owing to about-to-surface whales is not known. However, the latter is expected to be very small because the secondary observer essentially doubles the surveillance period by a known amount of time (e.g., range 4–17 s), and this is huge compared with the time interval between two observers at opposite ends of a Twin Otter (e.g., <0.2 s).

Two other negative biases on this estimate for which we could not account are (*i*) beluga far below the surface and therefore not available for sighting by either the primary or secondary observer and (*ii*) beluga outside of the study area at the time of the survey. Studies in the Beaufort region and elsewhere suggest that these aspects are very consequential to the estimate. The preliminary results of a satellite telemetry study involving 20 beluga tagged in the Mackenzie estuary in July of 1993 and 1995 suggest that the range of the Beaufort beluga stock extends far beyond the eastern-, western-, and northernmost areas surveyed in 1992 (P. Richard, DFO, Winnipeg, MB R3T 2N6, Canada, personal communication).

In regard to time below the surface, results from beluga tagged with satellite-linked transmitters in Cunningham Inlet, Northwest Territories, indicate that beluga may spend up to 42% of their time at depths below 8 m (Martin and Smith 1992). Although these results cannot be directly applied to those from Beaufort Sea beluga, owing to differences in stock composition, whale behaviour, and habitat, it is probable that Beaufort Sea beluga spend a considerable amount of their time below the surface, as do beluga studied elsewhere (e.g., Frost et al. 1985; Martin and Smith 1992). To obtain an actual estimate of the size of the Beaufort Sea beluga stock, correction factors for both the relative amount of time spent in view and the animals outside of the study area are necessary, but would be difficult to determine.

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