Estimates of large whale abundance in West Greenland waters from an aerial survey in 2005

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ABSTRACT

An aerial line transect and cue counting survey of large whales in West Greenland was conducted in August and September 2005. The survey covered the area between Cape Farewell and Disko Island on the West Greenland coast out to the 200m depth contour. The surveyed area covered 163,574km² and a total of 246 sightings of 9 cetacean species were obtained. Abundance estimates were developed for humpback whales, *Megaptera novaeangliae* (21 sightings), fin whales, *Balaenoptera physalus* (78 sightings) and common minke whales, *B. acutorostrata* (42 sightings). The mean group size of humpback whales was 3.30 but groups as large as 95 animals were seen off effort. The mean group size of fin whales was 2.96 with groups as large as 50 seen. Common minke whale group size was 1.1 with only one sighting of a group of two whales. Humpback whales were found both in offshore and coastal areas of West Greenland with the exception of Store Hellefiske Bank and the Cape Farewell offshore area. The line transect abundance estimate of humpback whales was 1,218 (CV=0.56), uncorrected for submerged whales (availability bias) and whales that were available to be seen but were missed by the observers (perception bias). Fin whales were observed in all areas of the survey and the uncorrected line transect estimate was 1,660 (CV=0.38). When corrected for perception bias the estimates increases to 3,234 fin whales (CV=0.44). Common minke whales were found in almost equal densities in all strata except for the Cape Farewell offshore area, where none were seen. The cue-counting abundance estimate of common minke whales was 4,856 (CV=0.49) for West Greenland using a cue rate of 46.3 cues per hour (CV=0.11). If the estimate is corrected for perception bias the common minke whale abundance is estimated to be 10,792 whales (CV=0.59). Low coverage was attained in the northern area of West Greenland and this should cause an especially large negative bias for the estimates of fin whale and humpback whale abundance because this area is believed to have particularly large densities of these whales.

KEYWORDS: FIN WHALE; COMMON MINKE WHALE; HUMPBACK WHALE; SURVEY-AERIAL; SURVEY-VESSEL; NORTHERN HEMISPHERE; ABUNDANCE ESTIMATE; CUE COUNTING; DISTRIBUTION; *g*(0); SCHOOL SIZE

INTRODUCTION

Most estimates of abundance of large baleen whales, including common minke whales, *Balaenoptera acutorostrata*, fin whales, *B. physalus*, and humpback whales, *Megaptera novaeangliae*, in West Greenland waters are more than 10 years old. A series of aerial surveys of large baleen whales in West Greenland were conducted between 1983 and 1993 and abundance estimates were developed from cue counting techniques *(cf.* Hiby, 1985) in 1987/88 and in 1993 (Hiby *et al*., 1989; Larsen, 1995; Larsen *et al*., 1989). From these surveys, all conducted in July and August, fin whale abundance was estimated at 1,100 (95% confidence interval (CI) 520-2,100) in West Greenland in 1987/88 (IWC, 1992) and abundance of common minke whales was estimated at 3,266 in 1987/88 (95% CI 1,700-5,710 (IWC, 1990) and at 8,371 (95% CI 2,414-16,929) common minke whales in 1993 (Larsen, 1995).

Abundance of humpback whales in West Greenland was estimated from photo-ID surveys in July and August 1988-93, with a combined estimate over the five years of surveys of 360 humpback whales (95% CI 314-413) (Larsen and Hammond, 2004). A line transect analysis of the aerial survey in July and August 1993 resulted in an uncorrected estimate of 599 (95% CI 237-1,512) (Kingsley and Witting, 2001) and an aerial photographic survey in July through October 2002 and August through October 2004 provided an estimate of 400 humpback whales (CV=0.64) corrected for submergence about three quarter of the time.

In September 2005 a ship-based line transect survey was conducted in East and West Greenland covering the shelf areas out to the 200m depth contour (Heide-Jørgensen *et al*., 2007). Fin whales were most abundant in East Greenland with an estimate of 3,214 (95% CI 980-10,547) and a lower abundance of 1,980 (95% CI 913-4,296) was estimated for West Greenland. Humpback whales were found in both offshore and coastal areas of West Greenland and abundance was estimated at 1,306 (95% CI 570-2,989). They occurred in low numbers in East Greenland with abundance estimated at 347 (95% CI 48-2,515). Finally, common minke whale abundance was estimated at 1,848 (95% CI 197-17,348) for East Greenland and 4,479 (95% CI 1,760-11,394) for West Greenland. These abundance estimates are negatively biased due to incomplete survey coverage and lack of correction factors for availability and perception bias.

The lack of up-to-date information on the abundance of large cetaceans in West Greenland has made it difficult for the Scientific Committee of the International Whaling Committee (IWC) to provide advice on sustainable takes from especially common minke whales and fin whales in West Greenland (IWC, 2006). Given that the average annual removals during 1999-2004 of common minke whales and fin whales were 172 and 9, respectively, it seems prudent to update abundance estimates for these two species.

An aerial survey of large cetaceans was conducted in West Greenland in August-September 2005 and is reported on here. Abundance estimates were developed for fin whales, humpback whales and common minke whales and

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are presented here, with comparisons to the abundance estimates obtained during a ship based survey conducted simultaneously in 2005.

METHODS

Survey methods and design

The survey was conducted between 28 August and 23 September 2005. The survey platform was an Icelandic *Partenavia Observer P-68*, in which two observers were located in the rear seats each with bubble windows. An additional observer/flight leader was seated in the right front seat. Sightings and a log of the cruise track (recorded from the aircrafts GPS) were recorded on laptop computers. Declination angle to sightings was measured with Suunto inclinometers and lateral angle from the nose of the aircraft was estimated. No correction for the drift of the plane was applied. Sightings with time stamps were entered on dictaphones and on a computer-based voice recording system that also logged the positions of the plane. Target altitude and speed was 750 feet (229m) and 90kts (167km hr^{-1}), respectively. The survey was conducted in passing mode and large group sizes were only occasionally examined in closing mode. However, the initial group size was consistently used for the abundance estimations.

Cues were defined as the dorsal ridge breaking the surface for common minke whales and as a blow for fin and humpback whales. All cues were reported unless the group size was so large that reporting was impossible. Declination and lateral angles, as well as time for each cue, were recorded together with information on number of whales in the group and the visual cue of the sighting.

Survey conditions were recorded at the start of the transect lines and whenever a change in Beaufort sea state, horizontal visibility and glare occurred. The survey was designed to systematically cover the area between the coast of West Greenland and offshore (up to 100km) to the shelf break (i.e. the 200m depth contour). Transect lines were placed in an east-west direction except for south Greenland where they were placed in a north-south direction. The surveyed area was divided into six strata (Fig. 1) and southern strata were planned to be covered first.

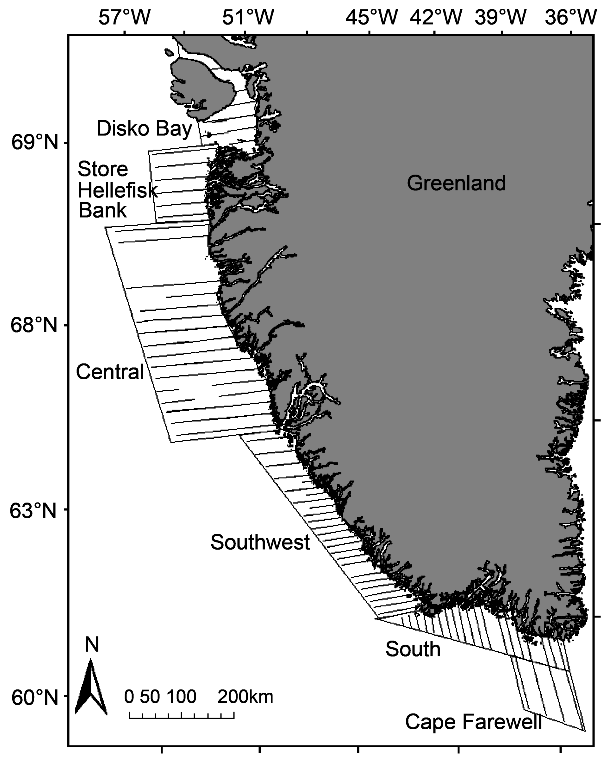

Fig. 1. Survey transect lines and delineation of strata for the aerial survey of large cetaceans in West Greenland in September 2005. The area of the strata was calculated as 12,312 km^2 for the Disko Bay strata, 15,669 km^2 for the Store Hellefiske Bank strata, 74,798km^2 for the central West Greenland strata, 29781 for the southwest Greenland strata, 11,523 km^2 for the Cape Farewell strata and 19,491km^2 for the South Greenland strata.

Analytical methods

Humpback whales

Animal abundance was estimated by

$$\hat{N} = \frac{n}{2L}\hat{f}(0)\hat{E}[s]A$$

where n was the number of groups detected, L was the transect line length, $\hat{f}(0)$ was the intercept of the estimated probability density function of distances to detected groups, $\hat{E}[s]$ was estimated mean group size, and A was stratum area (see Buckland *et al*., 2001, for further details of estimation methods). Only effort and detections in sea states 4 and below were used in the analyses.

A regression of log group size against estimated detection probability was used to estimate mean group size and because of the small sample size, a single mean group size was estimated over all strata.

In addition alternative abundance estimates were calculated where small groups (<11 whales) were estimated using the above described line transect analysis and large groups (>10 whales) were estimated using a fixed strip width.

Fin whales

Fin whale abundance was also estimated using line transect methods. Only effort and detections in sea states 4 and below were used in the analyses. To reduce the influence of errors in the distance measurements the estimations were based on grouped distance data, using a regression of log school size on estimated detection probability to estimate mean group size. Because of small sample size, a single mean group size was estimated over all strata. Duplicates between right front and right rear observers of sightings were determined based on coincidence in timing, lateral angle and perpendicular distance.

Common minke whales

Standard cue-counting methods (assuming probability of detection at zero radial distance is 1) were used to estimate the abundance of common minke whales, as follows:

$$\hat{N} = \frac{n}{\varphi T\hat{\eta}}\hat{h}(0)\hat{E}[s]A$$

Here A is the survey area; n is the number of detected cues; T is the total time spent searching; $\varphi/(2\pi)$ is the fraction of a full circle searched (taken to be 0.5 here since the region ahead of abeam on both sides of the aircraft was searched); $\hat{h}(0)$ is the estimated slope of the probability density function of radial distances to detections, evaluated at distance zero; $\hat{\eta}$ is the estimated cue rate of animals (see Buckland *et al*., 2001, pp. 191-193 for further details). Only effort and detections in sea states 3 and below were used in the analysis.

Substantial random errors in measuring distance can lead to substantial positive bias (see Borchers *et al*., 2003), thus the data were examined for evidence of measurement error, and methods which take account of measurement errors were considered.

Although the sample size is small (only 4 duplicates from 32 sightings), the probability of detecting a cue at the closest distance was estimated and abundance was estimated using a 'point independence' method (Borchers *et al*., 2006) that does not assume certain detection at distance zero.

RESULTS

The survey covered the coast of West Greenland between northern Disko Island (70°45'N) south to Cape Farewell (60°N). Six strata were covered: Disko Bay, Store Hellefiske Bank, Central West Greenland, South West Greenland, South Greenland and an offshore Cape Farewell stratum (Fig. 1). All survey effort in Disko Bay and on Store Hellefiske Bank was completed before 12 September. After this, between 11 and 20 September, the survey was primarily concentrated in the southwest and south Greenland and after this effort was concentrated in the two strata in south Greenland. A total of 246 sightings were made during the survey. Species could not be determined for 54 sightings, but most of these were of unidentified dolphins (Table 1).

Distribution of sightings

Large baleen whale sightings were made in all strata (Figs 2a-d). Sightings of fin whales were heavily concentrated in the Central West Greenland strata in an offshore area at approximately 66°N 56°W, although additional sightings were made all along the West Greenland coast generally around the 200m depth contour (Fig. 2a). Sightings of humpback whales were also found at a high concentration off Central West Greenland, yet sightings of humpback whales in both the South West and South strata were made closer to the coast at depths of <100m (Fig. 2b). Common minke whale sightings were distributed along the entire coast and no apparent concentration areas were detected (Fig. 2c). Minke sightings were generally made at <200m depths. Sei whales were also mainly found in the same area where fin and humpback whales were found in large concentrations, although a few sei whales were seen outside of the high density region in Central West Greenland (Fig. 2d).

Large to medium sized toothed whales were also detected (Fig. 2d). Pilot whales (*Globicephala* spp.) were seen in all strata and sightings were generally far offshore beyond 400-600m depths. Two sightings of sperm whales occurred south of Cape Farewell in offshore waters. Several sightings of smaller toothed whales, particularly white-beaked dolphins (*Lagenorhynchus albirostris*) and Atlantic white-sided dolphins (*L. acutus*), were made. All sightings of these dolphins were concentrated in the South West and South strata and none were seen north of Nuuk (64°N). The many sightings of unidentified delphinoids (*n*=44) were in the same areas where the sightings of white-beaked dolphin and white-sided dolphins were made. Two unidentified small dolphins were seen in Disko Bay and these sightings were

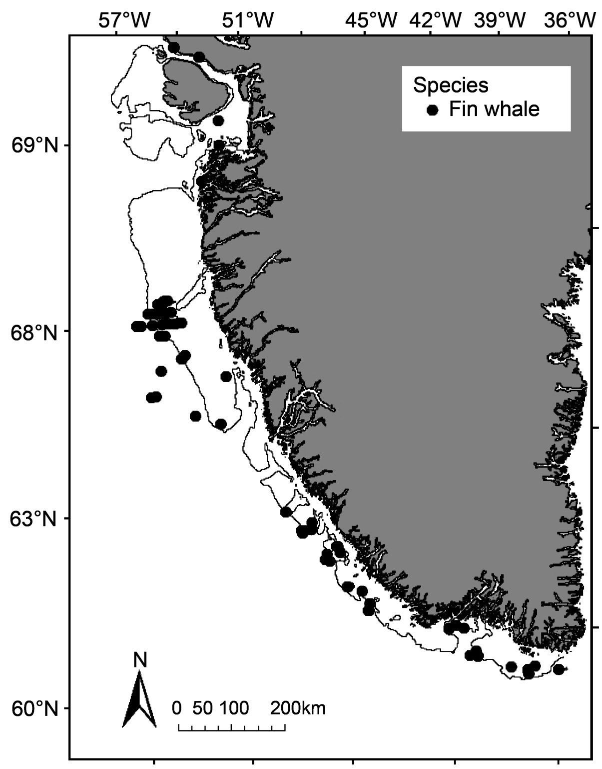

Fig. 2a. Sightings of fin whales during the aerial survey off West Greenland September 2005.

Table 1

The total numbers of observations of each of the different species of marine mammals observed during the survey. Observations are included from sea states and areas that are not included in the abundance estimations. Coefficients of variation are in brackets.

Species	Number of sightings	Number of individuals	Mean group size	Maximum group size	Minimum group size
Fin whale	78	231	2.96 (0.23)	50	1
Sei whale	4	13	3.30 (0.69)	10	1
Humpback whale	21	350	16.70 (0.35)	95	1
Sperm whale	2	2	1.00 (0)	1	1
Unidentified large whale	12	15	1.25 (0.14)	3	1
Minke whale	42	43	1.10 (0.02)	2	1
Pilot whale	10	181	18.20 (0.33)	50	1
Unidentified small whale	10	16	1.60 (0.27)	5	1
White-beaked dolphin	12	62	5.20 (0.25)	13	1
White-sided dolphin	3	27	9.00 (0.61)	20	3
Harbour porpoise	8	19	2.40 (0.26)	6	1
Unidentified dolphin	44	406	9.20 (0.15)	45	1

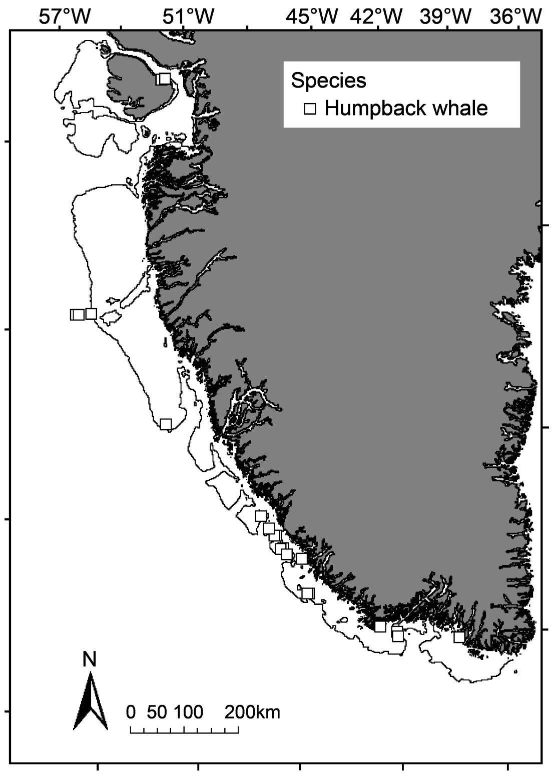

Fig. 2b. Sightings of humpback whales during the aerial survey off West Greenland September 2005.

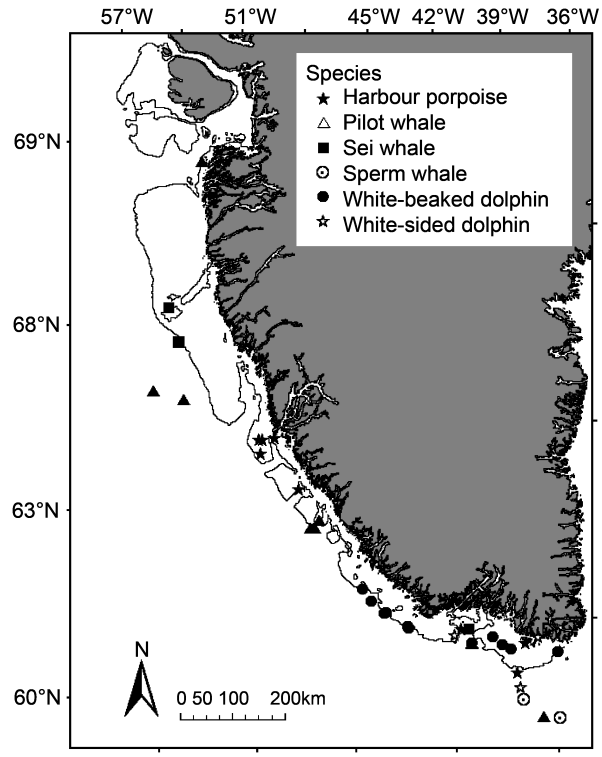

Fig. 2d. Sightings of sei whales, pilot whales, sperm whales, harbour porpoises, white-beaked and white-sided dolphin during the aerial survey off West Greenland September 2005.

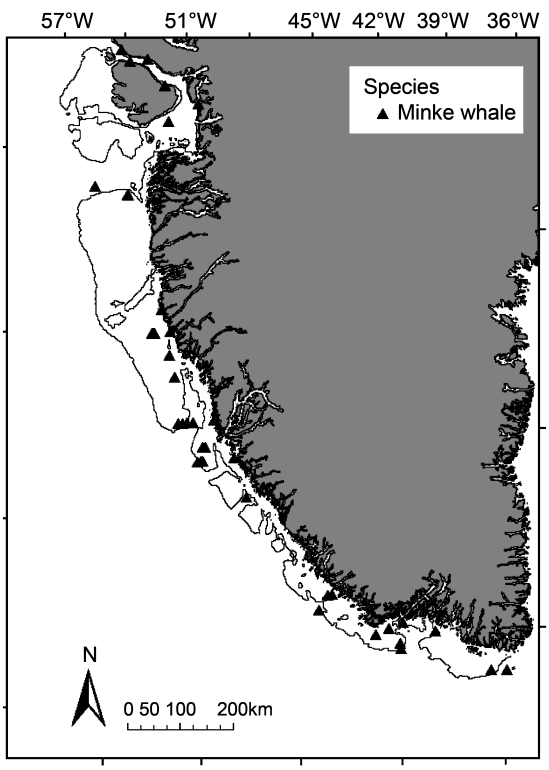

Fig. 2c. Sightings of common minke whales during the aerial survey off West Greenland September 2005.

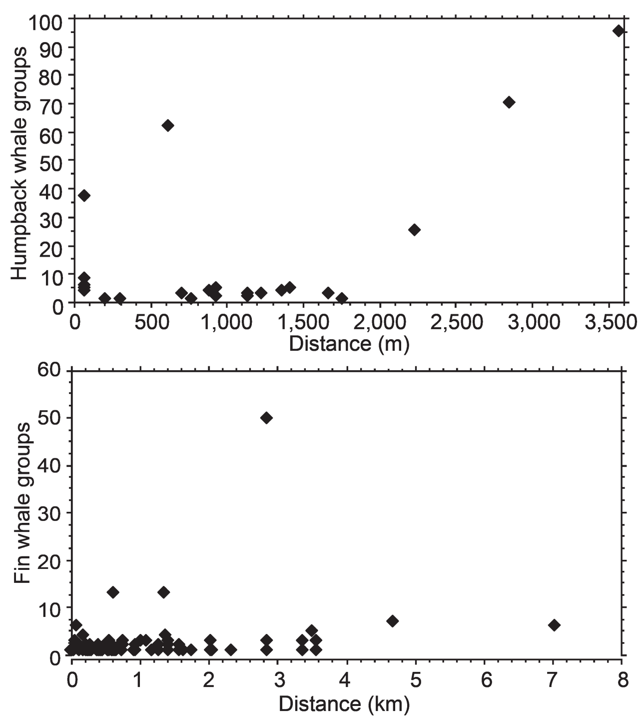

Fig. 3. Distribution of humpback whale (upper panel) and fin whale (lower panel) group sizes in relation to distance from trackline.

likely of harbour porpoises (*Phocoena phocoena*); additional sightings of this species were made south of Nuuk Fjord.

Humpback whale abundance estimates

Humpback whales were found predominantly in groups, and the size of the groups was often large; only 17% of detections were of single animals and 43% were of groups larger than five (Fig. 3). The frequent occurrence of humpback whales in large groups prevented the use of cue counting methods for abundance estimation, instead the abundance of humpback whales was analysed using standard line transect methods, assuming probability of detection on the line to be 1. There were no duplicate sightings of humpback whales so perception bias and measurement error could not be estimated.

Detection function and abundance estimates

Half-normal and hazard-rate detection functions were fitted to the grouped data. Sample size was lower than desirable for line transect surveys (only 22 groups out of 23 were within the truncation distance of 3km); this precluded stratifying for estimation of the detection function and *f*(0) and it precluded use of covariates in this estimation. Based on Akaike's Information Criterion (AIC), a half-normal detection function model with no adjustment terms was chosen (Fig. 4). The associated χ^2 goodness-of-fit statistic was not significant (p=0.63), indicating an adequate fit to the data.

Estimates of the key components of the line transect estimator are shown in Table 2, together with summaries of stratum areas, effort and estimated density and abundance. Total abundance was estimate to be 1,218 humpback whales (CV=0.57) with log-based 95% confidence interval (423; 3,508) and log-based 90% confidence interval (501; 2,960).

One problem with the humpback whale abundance analysis was the combination of both solitary whales and whales in large groups (>10) that could bias both the estimates of mean group size and the detection function in line transect analysis (Fig. 3). An alternative approach was to estimate the abundance based on small groups (<11 whales) and using the same line transect technique described above with a right truncation at 2.0km. Abundance based on large groups (>10 whales) was then estimated separately using strip census analyses with a fixed strip width of 3.6km. The combined estimate of the line transect and strip census analyses was 1,158 (CV=0.35) humpback whales (Table 3) and was thus not different from the results obtained from the line transect analysis of all group sizes.

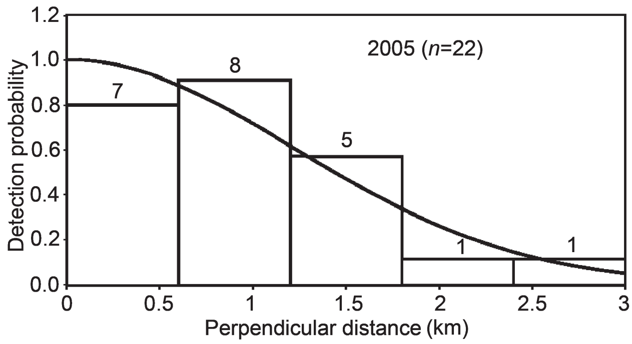

Fig. 4. Perpendicular distance histogram and fitted half-normal probability density function for humpback whale line transect data.

Fin whale abundance estimates

Fin whale group sizes were not as variable and large as for humpback whales; 61% of detections were of single whales, 17% were in groups of two and 9% were in groups of 5 or more (Fig. 3).

Measurement errors

Although the sample size was small, there appears to be little difference between the estimates of perpendicular distances from the two platforms at distances less than about 1.5km (Fig. 5). The level of distance 'binning' used in analysis (see Fig. 6) should make the line transect estimates of fin whale abundance insensitive to both the small errors at distances less than 1.5km and the more substantial errors at larger distances. The apparent lack of substantial errors at smaller distances (Figs 5 and 7) indicates that little, if anything, would be gained by incorporating a measurement error model in estimation. Estimating the measurement error process parameters from such a small sample size may add substantially to the variance of the resulting density and abundance estimates. Measurement errors were therefore dealt with only by using binned distance data in estimation.

Probability of detection at distance zero

Sightings from only the right side of the plane (where there were two independent observers) were used to estimate *g*(0). Conditional detection functions for each observer

Table 2

Humpback whale data summary and estimates. K is number of transects; a is area (km^2); L is transect length (km); n is number of groups detected within 3km; n/L is encounter rate (groups per 1,000km); $\hat{f}(0)$ is the intercept of the probability density function; $\hat{E}[s]$ is estimated mean group size; $\hat{D}$ is estimated animal density (animals per 1,000 km^2); $\hat{N}$ is estimated animal abundance. Coefficients of variation are in brackets.

Stratum	Area (km^2)	K	L (km)	n	n/L	$\hat{f}(0)$	$\hat{E}[s]$	$\hat{D}$	$\hat{N}$
Cape Farewell	11,523	4	293	0	0.0			0	0
Central West	74,798	30	1,958	4	2.04 (0.91)			5.63 (1.00)	421 (1.00)
Disko Bay	12,312	12	556	1	1.80 (1.78)	0.664	8.3	4.95 (1.82)	61 (1.82)
South Greenland	19,491	19	1,106	4	3.62 (0.46)	(0.12)	(0.38)	9.97 (0.62)	194 (0.62)
Store Hellefiske Bank	15,669	7	577	0	0			0	0
South West	29,781	31	1,968	12	6.61 (0.42)			18.2 (0.60)	542 (0.60)
Total	**163,574**							**19.1 (0.57)**	**1,218 (0.57)**

Table 3

Estimates of humpback whale abundance based on line transect analyses of groups <10 and strip census estimates of groups >10.

	Right truncation	n	N	CV	Mean group size	Expected group size
Strip census estimate of groups >10	3.6km	5	647	0.48	57.8	
Line transect abundance of groups < 10	2.0km	18	511	0.53	3.39	4.06
			N (sum)	CV	lower 95% CI	upper 95% CI
Combined estimate			1,158	0.35	595	2,255

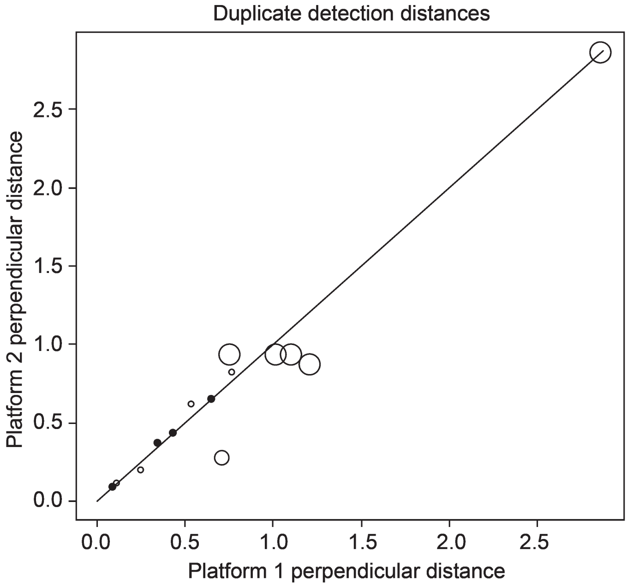

Fig. 5. Perpendicular distance estimates (in km) from duplicates (minke=solid dots, fin=circles; dots are proportional to group size (1, 2 or 3)). The line corresponds to platform 1 (front observer) and platform 2 (rear observer) estimated distances being equal.

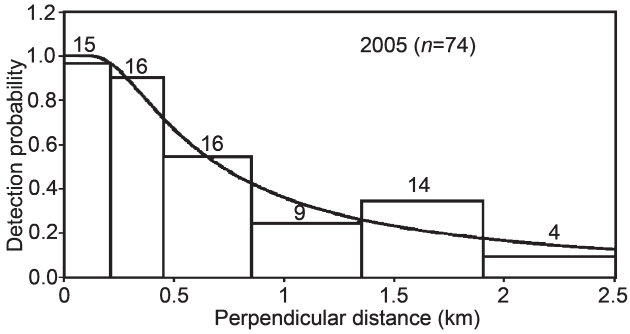

Fig. 6. Perpendicular distance histogram and fitted hazard rate probability density function for fin whale line transect data.

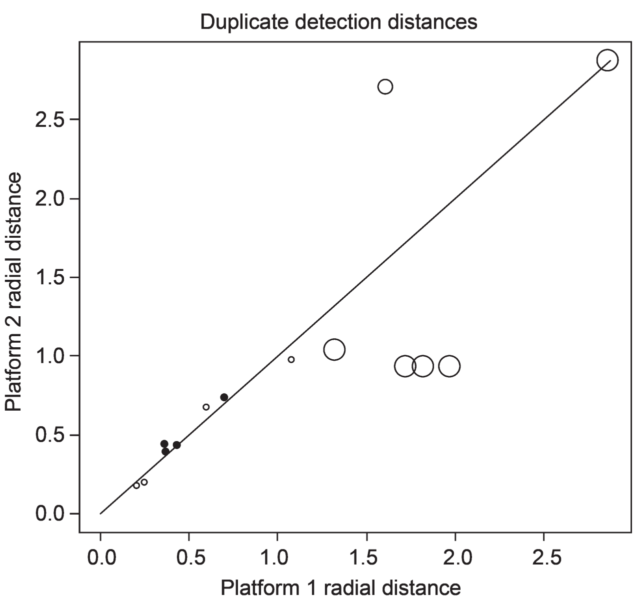

Fig. 7. Radial distance (in km) estimates from duplicates (minke=solid dots, fin=circles; dots are proportional to group size (1, 2 or 3)). The line corresponds to platform 1 (front observer) and platform 2 (rear observer) estimated distances being equal.

(conditional on detection by the other observer) were estimated using the iterative logistic regression, as implemented in *Distance* 5.0, release 2 (Thomas *et al*., 2006). After truncating at 2.5km to remove an influential observation at 3km which led to conditional detection functions which increased slightly with distance, there remained 27 detections by the rear observer, 20 by the front observer and 6 duplicates. Fig. 8 shows the distribution of detections and duplicate proportions (proportion of each observer's detections which were seen by the other observer) as a function of distance, together with each observer's estimated conditional detection function (conditional on detection by the other observer). Models were selected using AIC and a model with radial distance and observer as explanatory variables was found to be best on this basis.

The probability of detecting a fin whale group on the trackline was estimated to be 0.34 (CV=0.29) for the rear observer, 0.26 (CV=0.32) for the front observer and 0.51 (CV=0.21) for both observers combined assuming that their probabilities are independent.

Detection function and abundance estimates

Truncation of perpendicular distances at 2.5km excluded 12% of detections (*n*= 84). Half-normal and hazard rate detection function forms were considered and a hazard rate function with no adjustment parameters was selected on the basis of AIC (Fig. 6). The associated χ^2 goodness-of-fit statistic was not significant (p=0.15), indicating an adequate fit to the data.

Estimates of the key components of the line transect estimator are shown in Table 4, together with summaries of stratum areas, effort and estimated density and abundance. Total fin whale abundance was estimated to be 1,660 animals (CV=0.38) and log-based 95% confidence interval (799; 3,450) and log-based 90% confidence interval (899; 3,066). The estimate corrected for $g(0)<1$, for both observers combined, was 3,234 animals (95% CI 1,412; 7,406, Table 4). This point estimate of abundance is likely negatively biased because $g(0)$ for the left side of the aircraft is likely to be lower than the combined $g(0)$ for the right side because the left side had only one observer.

An alternative approach that takes into account diving whales is the cue counting technique. Cue-counting methods were applied to estimate the abundance of solitary fin whales and to compare with line transect abundance of solitary fin whales. Using a cue rate of 50 cues per hour (Heide-Jørgensen and Simon, 2007), a cue counting abundance estimate of 8,889 (*n*=50, CV=0.68) solitary fin whales was achieved. This estimate is ~10 times bigger than a line transect estimate calculated solely for solitary fin whales (719, CV=0.40). The reason for this large difference is unclear; however, the detection function fitted to the observed radial distance distribution in the cue counting estimate showed a somewhat unrealistic rapid drop off close to the origin and cue counting estimates were not developed any further for fin whales.

Common minke whale abundance estimates

With the exception of one group of two whales, all common minke whale detections were of solitary animals and cue counting methods could be used for estimating abundance.

Measurement errors

The sample size of four common minke whale cues detected by both front and rear observers (minke duplicates) in the right side of plane was too small to estimate the distance

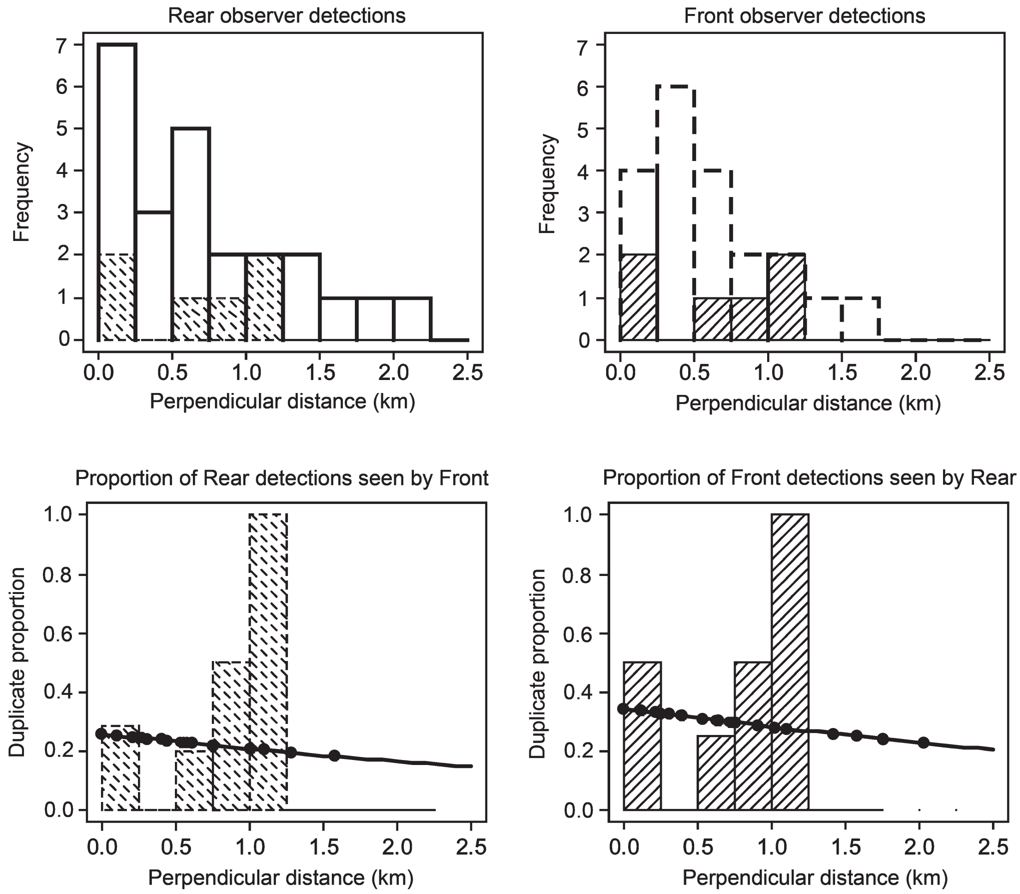

Fig. 8. Duplicate proportions and estimated conditional detection functions for fin whales. All data and estimates are for the right hand side of the aircraft only. The top row of plots shows the number of detections by each observer, with the numbers of these that were detected by the other observer (the duplicates) shaded. Bars with solid lines correspond to rear observer detections, bars with dashed lines correspond to front observer detections. The bottom row of plots shows the duplicate proportions, together with fitted detection function (smooth curve) and estimated detection probability for individual detections made by the observer in question.

Table 4

Fin whale data summary and estimates. K is number of transects; a is area (km^2); L is transect length (km); n is number of groups detected within 3km; n/L is encounter rate (groups per 1,000km); $\hat{f}(0)$ is the intercept of the probability density function; $\hat{E}[s]$ is estimated mean group size; $\hat{D}$ is estimated animal density (animals per 1,000 km^2); $\hat{N}$ is estimated animal abundance. Coefficients of variation are in brackets.

Stratum	Area (km^2)	K	L (km)	n	n/L	$\hat{f}(0)$	$\hat{E}[s]$	$\hat{D}$	$\hat{N}$
Cape Farewell	11,523	4	293	2	6.8 (2.09)			5.21 (2.10)	60 (2.10)
Central West	74,798	30	1,958	38	19.4 (0.41)			14.87 (0.47)	1,112 (0.47)
Disko Bay	12,312	12	556	1	1.80 (0.67)			1.38 (0.71)	17 (0.71)
South Greenland	19,491	19	1,106	17	15.4 (0.29)	0.997 (0.22)	1.54 (0.12)	11.78 (0.37)	230 (0.37)
Store Hellefiske Bank	15,669	6	577	6	10.4 (1.14)			7.96 (1.17)	125 (1.17)
Southwest Greenland	29,781	31	1,968	10	5.1 (0.28)			3.89 (0.37)	116 (0.37)
Total	163,574							10.15 (0.38)	1,660 (0.38)
Corrected for $g(0)<1$									3,234 (0.44)

measurement error process reliably. However, comparison of measurement of cues from both minke and fin whales suggest that the difference in measurement error between the two platforms within about 1.5km is negligible (Fig. 7) and no attempt was made to incorporate distance measurement error into the abundance estimation. It is not possible to estimate bias in estimating distance by either platform from these data.

Probability of detection at distance zero

Independent observer data were available only for the right side of the aircraft. These were used to estimate probability of detection at the closest radial distance used in analysis. As the front observer did not have a clear view of distance zero (because there was no bubble window in this position), and no detections were made within 0.2km of the aircraft, data were left-truncated at 0.2km before analysis. Fig. 9 shows

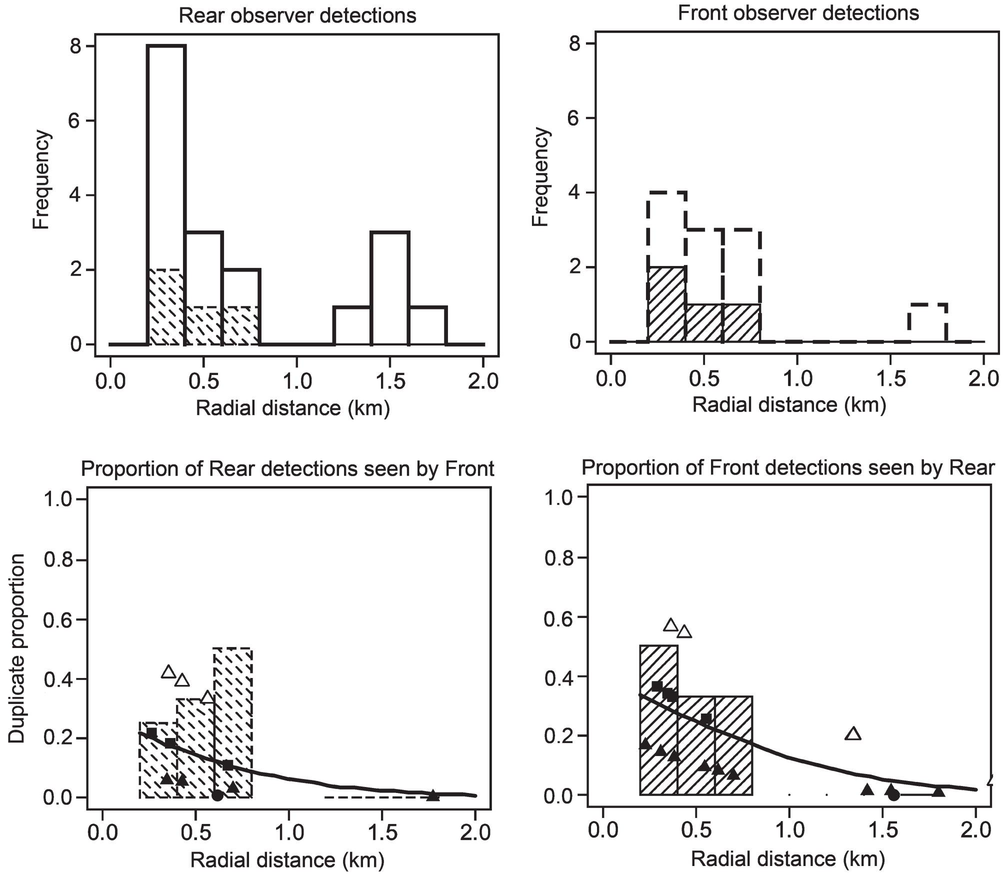

Fig. 9. Duplicate proportions and estimated conditional detection functions for common minke whales. All data and estimates are for the right hand side of the aircraft only. The top row of plots shows the number of detections by each observer, with the numbers of these that were detected by the other observer (the duplicates) shaded. Bars with solid lines correspond to rear observer detections, bars with dashed lines correspond to front observer detections. The bottom row of plots shows the duplicate proportions, together with fitted detection function (smooth curve) and estimated detection probability for individual detections made by the observer in question. Different Beaufort sea state for individual detections is indicated using different symbols: 0, 1, 2, and 3 are plotted using , , and respectively.

the duplicate proportions (proportion of each observer's detections which were seen by the other observer) as a function of distance, together with each observer's estimated conditional detection function (conditional on detection by the other observer). Conditional detection functions were estimated using the iterative logistic regression, as implemented in *Distance* 5.0, release 2 (Thomas *et al*., 2006). Models were selected using AIC and a model with radial distance, observer and Beaufort sea state as explanatory variables was found to be best on this basis.

The probability of detecting a cue at distance 0.2 km was estimated to be 0.36 (CV=0.39) for the rear observer, 0.22 (CV=0.42) for the front observer and 0.45 (CV=0.33) for both observers combined. As noted above, the sample size for this analysis was small (21 detections by the rear observer, 11 by the front observer, with 4 duplicates) and as a result, the reliability of these estimates is somewhat uncertain.

Detection function and abundance estimates

The slope of the probability density function $h(0)$ was estimated by fitting half-normal and hazard-rate functional forms to grouped radial distance data truncated at 1.6km. This led to seven detections (17% of the distances) being discarded. A hazard-rate detection function form with no adjustment terms was selected on the basis of AIC. The resulting detection function and fit of the pdf of radial distances to the observed radial distance distribution are shown in Figs 10 and 11. The associated χ^2 goodness-of-fit statistic was not significant (p=0.47), indicating an adequate fit to the data.

Estimates of the key components of the cue-counting estimator are shown in Table 5, together with summaries of stratum areas, effort and estimated density and abundance. Cue densities were converted to animal densities by dividing by an estimated cue rate of 46.3 cues per hour (CV=0.11) (Heide-Jørgensen and Simon, 2007). If detection

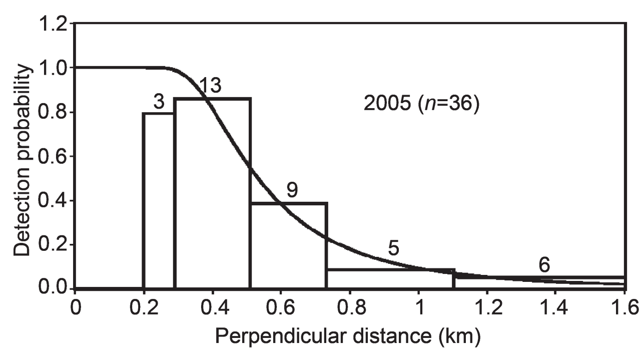

Fig. 10. Radial distance histogram and fitted hazard-rate detection function for common minke whale cue-counting data. (Note that the histogram bar heights have been scaled in inverse proportion to their mean radial distance, in order to place them on a comparable scale to the detection function curve.)

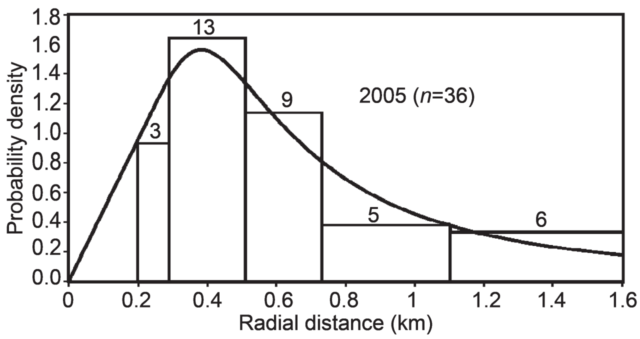

Fig. 11. Fit of the hazard-rate probability density function of radial distances to the observed radial distance distribution for common minke whale cue-counting data.

at distance 0.2km (called '$g(0)$' in the table) is assumed to be certain, total common minke whale abundance is estimated to be 4,856 animals (CV=0.49), log-based 95% CI=1,910-12,348 and log-based 90% CI=2,219-10,628. If detection at distance 0.2km is estimated as above, total common minke whale abundance is estimated to be 10,792 animals (CV=0.59), log-based 95% CI=3,594-32,407 and log-based 90% CI=4,289-27,156. In obtaining these estimates it is assumed that the observer on the left side of the aircraft has the same probability of detecting a cue at 0.2km as the two observers on the right side of the plane.

DISCUSSION

Due to inclement weather conditions the survey failed to cover areas west of Disko Island, the western part of the northern edge of Store Hellefiske Bank and a large part of the Central West Greenland strata. This lack of coverage, especially in the latter area, may cause a negative bias in the estimate of fin whale abundance in West Greenland, since large concentrations of fin whales are known to occur in this region. Supporting evidence for a negative bias is that the ship-based survey in September 2005 found large numbers of fin whales around 67°N, 57°W, the area not covered in the present survey. Furthermore locations from fin whales tracked by satellite as well as observations from Norwegian minke whalers indicate that fin whales occur in this area in conspicuous numbers (Heide-Jørgensen *et al*., 2007; Heide-Jørgensen *et al*., 2003). No survey coverage was attained in offshore areas (i.e. west of the 200m depth contour) south of 64°N and this may cause additional negative bias to the estimates of fin and common minke whale abundance in West Greenland.

The line transect estimate of humpback whale abundance in this study (1,218; 95% CI-423-3,508) was very similar to the estimate from a simultaneous ship-based survey (1,306; 95% CI-570-2,989) (Heide-Jørgensen *et al*., 2007). However, the estimate from the aerial survey is negatively biased because some animals will have been underwater and hence undetectable during passage of the plane and no corrections were made for whales missed by the observers. If estimates of the percentage of time humpback whales are visible from the air were available, this bias might be reduced substantially. Bannister and Hedley (2001) estimated the surface detection probabilities for aerial surveys of Southern Hemisphere humpback whales to range between 0.25 and 0.41. Satellite-linked time-depth recorders deployed on five humpback whales off Central West Greenland (Fyllas Bank) in June-July 2000 has shown that these whales spend between 29.7 and 43.6% of their time at the surface above 4m with an average of 36% (Dietz *et al*., 2002). If it is assumed that humpback whales can be seen at depths down to 4m the estimates will need to be multiplied by approximately three to account for the time the whales are visible (above a certain depth) to be seen by the observers. This would lead to a substantially larger abundance estimate of humpback whales in West Greenland.

Previously the abundance of humpback whales in West Greenland has been estimated to about 360 humpback whales (95% CI 314-413) for 1988-93 (Larsen and Hammond, 2004), 599 (95% CI=237-1,512) in 1993 (Kingsley and Witting, 2001) and 400 (CV=0.64) in 2002 and 2004 (Witting and Kingsley, 2005). The uncorrected aerial and the ship based surveys in 2005 both confirm that the current abundance of humpback whales in West Greenland is substantially larger than what was estimated in the surveys in the 1990s. This may be due to both a severe underestimation of abundance in previous surveys, growth in population size and/or increased affinity to the West Greenland feeding ground. The timing of the surveys in 2005 was one month later than the surveys conducted in the 1990s. Humpback whales arriving late on the West Greenland feeding ground could have contributed to the larger abundance estimates in 2005. The unprecedented observations of large groups of humpback whales (up to 95 individuals), often with a reddish defecation trailing behind, could be interpreted as an autumn feeding migration to West

Table 5

Minke whale data summary and estimates. K is number of transects; a is area (km^2); T is time spent searching (hours); n is number of cues detected within 1.6 km; n/T is encounter rate (cues per hour); $\hat{h}(0)$ is the slope of the density function; $\hat{D}$ is estimated animal density (animals per 10^6 km^2); $\hat{N}$ is estimated animal abundance. Coefficients of variation are in brackets. Estimated cue rate of $\hat{\eta}$ =46.3 cues per hour (CV=0.11) was used to convert cue density to whale density. Estimates in columns headed 'estimated $g(0)$' are those in columns headed '$g(0)$=1' divided by the estimated $g(0)$ of 0.45 (CV=0.33).

Stratum	Area (km^2)	K	T hour	n	n/T	$\hat{h}(0)$	$\hat{D}$	$\hat{N}$
Cape Farewell	11,523	3	1.26	0	0		0	0
Central West	74,798	27	11.47	12	1.047 (0.45)		34.35 (0.61)	2,569 (0.61)
Disko Bay	12,312	11	3.02	2	0.663 (0.45)	4.77 (0.40)	21.76 (0.61)	268 (0.61)
South Greenland	19,491	19	7.09	8	1.129 (0.38)		37.04 (0.56)	722 (0.56)
Store Hellefiske Bank	15,669	6	3.52	3	0.853 (0.55)		28.00 (0.69)	439 (0.69)
Southwest Greenland	29,781	29	11.38	10	0.879 (0.47)		28.84 (0.62)	859 (0.62)
Total	163,574						29.69 (0.49)	4,856 (0.49)
Corrected for $g(0)$<1							65.97 (0.59)	10,792 (0.59)

Greenland, but could also be the result of an aggregation of whales before the autumn migration out of Greenlandic waters.

Comparison of cue counting and line transect estimates for solitary fin whales resulted in a cue counting estimate that was ~10 times the line transect estimate. This suggests that the availability bias in line transect estimates may be large and that the fin whale abundance estimate presented here (based on a line transect analysis of all schools) may be substantially negatively biased. Circumstances made the cue counting estimate less attractive: the direction of the bias, if any, is unknown; the cue counting method can not deal with large group sizes; and the detection function showed an implausible drop near the origin.

The line transect estimate of fin whale abundance (1,660; 95% CI 799-3,450) was similar to the estimate obtained from a simultaneous ship-based survey (1,980; 95% CI 913-4,296). Both estimates are negatively biased to an unknown degree by incomplete coverage, lack of correction for submerged whales and especially for the aerial survey, by the lack of correction for whales missed by the observers. Correcting the aerial survey for perception bias increases the abundance estimate to 3,234 whales (95% CI 1,412-7,406). However, all three estimates confirm that the likely magnitude of the fin whale abundance off West Greenland in September is in the low thousands. The 1987/88 estimate of 1,100 (95% CI 520-2,100) fin whales in West Greenland (IWC, 1992) was a cue counting estimate and is therefore not directly comparable to the current abundance estimates. However, considering that the current but uncorrected estimates are larger than the earlier estimates corrected for availability bias (by the cue counting technique) it seems likely that the abundance of fin whales in West Greenland has increased. Additional evidence that fin whale abundance has increased in West Greenland comes from a simple comparison of encounter rates. About three times as many whales were seen (per unit effort) in the 2005 survey than in the 1987 survey. The later timing of the aerial survey in 2005 could be partially responsible by including fin whales arriving late on the West Greenland feeding ground. However, like humpback whales, fin whales were also seen in large groups of up to 50 whales. These group sizes were not seen on previous surveys, and could be interpreted as an autumn aggregation before the initiation of the southward migration.

The cue counting estimate of common minke whale abundance (4,856; 95% CI 1,910-12,348) was close to the estimate obtained from the simultaneous ship-based survey (4,479, 95% CI 1,760-11,394). The two estimates are however not directly comparable since the aerial survey estimate corrects for availability bias (cue counting technique) and the ship based survey estimate assumes that all common minke whales are at the surface to be seen during the passage of the survey platform. The cue counting common minke whale abundance estimate from this survey is also not significantly different from previous estimates from West Greenland, but when corrected for perception bias or $g(0)$ it is considerably larger than previous estimates, although not statistically different. The data that were used for estimating the perception bias were based on a small sample size from just one side of the plane and the estimate of $g(0)$ is similarly imprecise (CV=0.59). However, the few duplicate sightings between the front and rear observer indicate that a considerable number of common minke whales were not detected. In comparison with perception bias of other species of marine mammals in aerial surveys, common minke whales are clearly among the most difficult animals to detect and the low estimate of $g(0)$, i.e. the high estimated perception bias, determined in this study is not unexpected (Table 6). The $g(0)$ for the fin whales was unexpectedly low given their conspicuous large blows and body size. A possible explanation for the low fin whale detection is the fact that the survey was a multispecies survey where the detection might by negatively affected by the simultaneous recording of several species. Common minke whales are hard to detect because they are inconspicuous and spend a short time at the surface, but it could also be because of the rather demanding data collection from each cue of a whale. Finally the fact that the survey targets whales close to the plane (i.e. common minke whales) as well as those farther away (fin and humpback whales) might add to perception bias for common minke whales.

This study demonstrates the amount of data that can be obtained from an aerial survey effort of the shelf area off West Greenland in a year with reasonably good weather conditions. Other years in which surveys were attempted have had much more severe weather conditions and the timing of the present survey (late August and September) may have improved the likelihood of experiencing fair weather. The trade off is that the southward migration of baleen whales out of the Greenland shelf areas might already have started which also negatively affects the abundance estimates. Víkingsson and Heide-Jørgensen (2005) showed that some common minke whales tagged with satellite transmitters left the Icelandic shelf areas in mid September when they initiated their southbound migration.

This study has also brought to light the difficulties of applying the cue counting method to other species besides solitary common minke whales. Fin whales and humpback whales occur in groups and some of these groups are of up to 50 fin whales and 95 humpback whales. It is not a simple or practical task to count cues from tens of animals simultaneously and it becomes increasingly complicated with increasing whale pod size. Also, because there is a

Table 6

Estimates of fraction detected on the transect line for multispecies aerial surveys of marine mammals in West Greenland and characterization of the main features of the sighting process. GINR=Greenland Institute of Natural Resources.

Species	Survey platform	Mean pod size	Detection of cues	Perception bias	Estimation method	Ref.
Narwhal	Twin Otter	1.7	Dark but mostly in leads	0.86 (0.13)	Mark-recapture, full conditional independence	GINR
Beluga	Twin Otter	3.0	White moving groups	0.77 (0.10)	Mark-recapture, full conditional independence	GINR
Bowhead whale	Twin Otter	1	Big black body, blows, in leads	0.62 (0.19)	Mark-recapture, full conditional independence	GINR
Walrus	Twin Otter	1-2	Small brown body	0.51 (0.25)	Mark-recapture, full conditional independence	GINR
Fin whale	Partenavia	3.0	Large blows	0.51 (0.21)	Line transect, point conditional independence	This survey
Minke whale	Partenavia	1.1	Inconspicuous blows	0.45 (0.33)	Cue counting, point conditional independence	This survey

considerable range in fin whale group sizes, some of them large, the fin whale cue counting estimates will be fairly sensitive to whether or not animals in groups cue at the same rate as the observed individuals from which cue rate estimates were obtained.

The question remains if the cue counting method is the most efficient and accurate way to obtain abundance estimates of large cetaceans in West Greenland. Alternative methods include sight-resight methods applied to aerial line-transect survey (e.g. Innes *et al*., 2002) with correction for perception bias from double platform experiments and telemetry data on species specific surface times to correct for availability bias.

In summary, we believe that the abundance estimates presented in this study are definitely underestimates of the actual abundance of large whales in West Greenland because of incomplete coverage in presumed high density areas, no correction for perception bias in the case of humpback whales, lack of correction for availability bias for fin whales and humpback whales and sightings of unidentified large whales that were not included. Some whales may also have started their southbound autumn migration out of Greenland and were therefore not available to be counted during the survey.

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REFERENCES

Bannister, J.L. and Hedley, S.L. 2001. Southern Hemisphere group IV humpback whales: their status from recent aerial survey. *Mem. Queensl. Mus*. 47(2): 587-98.

Borchers, D.L., Lake, J.L., Southwell, C. and Paxton, C.G.M. 2006. Accommodating unmodelled heterogeneity in double-observer distance sampling surveys. *Biometrics* 62: 372-78.

Borchers, D.L., Pike, D., Gunnlaugsson, T. and Víkingsson, G.A. 2003. Analyses of the NASS 1987 and 2001 minke whale cue counting surveys taking account of distance estimation errors. Paper SC/55/NAM3 presented to the IWC Scientific Committee, May 2003, Berlin (unpublished). 33pp. [Paper available from the Office of this Journal].

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, L. 2001. *Introduction to Distance Sampling: Estimating Abundance of Biological Populations*. Oxford University Press, Oxford, UK. vi+xv+432pp.

Dietz, R., Teilmann, J., Heide-Jørgensen, M.P. and Jensen, M.V. 2002. Satellite tracking of humpback whales in West Greenland. *NERI Technical Report* 411(2002): 1-40. [Published by National Environmental Research Institute, Ministry of the Environment, Denmark].

Heide-Jørgensen, M.P. and Simon, M. 2007. A note on cue rates for common minke, fin and humpback whales off West Greenland. *J. Cetacean Res. Manage*. 9(3): 211-14.

Heide-Jørgensen, M.P., Simon, M.J. and Laidre, K.L. 2007. Estimates of large whale abundance in Greenland waters from a ship-based survey in 2005. *J. Cetacean Res. Manage* 9(2): 95-104.

Heide-Jørgensen, M.P., Witting, L. and Jensen, M.V. 2003. Inshore-offshore movements of two fin whales *Balaenoptera physalus* tracked by satellite off West Greenland. *J. Cetacean Res. Manage*. 5(3): 214-45.

Hiby, A.R. 1985. An approach to estimating population densities of great whales from sighting surveys. *IMA (Inst. Math. Appl.) J. Math. Appl. Med. Biol*. 2: 201-20.

Hiby, A.R., Ward, A. and Lovell, P. 1989. Analysis of the North Atlantic Sightings Survey 1987: aerial survey results. *Rep. int. Whal. Commn* 39: 447-55.

Innes, S., Heide-Jørgensen, M.P., Laake, J., Laidre, K.L., Cleator, H., Richard, P. and Stewart, R.E.A. 2002. Surveys of belugas and narwhals in the Canadian high Arctic in 1996. *NAMMCO Sci. Publ*. 4: 169-90.

International Whaling Commission. 1990. Report of the Scientific Committee. *Rep. int. Whal. Commn* 40:39-79.

International Whaling Commission. 1992. Report of the Comprehensive Assessment Special Meeting on North Atlantic Fin Whales, Reykjavík, 25 February-1 March 1991. *Rep. int. Whal. Commn* 42:595-644.

International Whaling Commission. 2006. Report of the Scientific Committee. Annex E. Report of the Standing Working Group (SWG) on the Development of an Aboriginal Whaling Management Procedure (AWMP). *J. Cetacean Res. Manage. (Suppl.)* 8:91-109.

Kingsley, M.C.S. and Witting, L. 2001. A preliminary analysis of aerial survey observations of humpback whales in Greenland waters. Paper SC/53/NAH23 presented to the IWC Scientific Committee, July 2001, London (unpublished). 51pp. [Paper available from the Office of this Journal].

Larsen, F. 1995. Abundance of minke and fin whales off West Greenland, 1993. *Rep. int. Whal. Commn* 45: 365-70.

Larsen, F. and Hammond, P.S. 2004. Distribution and abundance of West Greenland humpback whales *Megaptera novaeangliae*. *J. Zool., London*. 263: 343-58.

Larsen, F., Martin, A.R. and Nielsen, P.B. 1989. North Atlantic Sightings Survey 1987: report of the West Greenland aerial survey. *Rep. int. Whal. Commn* 39: 443-46.

Thomas, L., Laake, J.L., Strindberg, S., Marques, F.F.C., Buckland, S.T., Borchers, D.L., Anderson, D.R., Burnham, K.P., Hedley, S.L., Pollard, J.H., Bishop, J.R.B. and Marques, T.A. 2006. Distance 5.0. Release 1. Research Unit for Wildlife Population Assessment, University of St Andrews, UK. [Available from: *http://www.ruwpa.st-and.ac.uk/distance/*].

Víkingsson, G.A. and Heide-Jørgensen, M.P. 2005. A note on the movements of minke whales tracked by satellite in Icelandic waters in 2001-2004. Paper SC/57/O9 presented to the IWC Scientific Committee, June 2005, Ulsan, Korea (unpublished). 3pp. [Paper available from the Office of this Journal].

Witting, L. and Kingsley, M. 2005. Abundance of marine mammals off West Greenland, 2002-2004. Paper SC/57/AWMP3 presented to the IWC Scientific Committee, June 2005, Ulsan, Korea (unpublished). 13pp. [Paper available from the Office of this Journal].

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