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Revised abundance estimates of humpback whales in West Greenland

M. P. Heide-Jørgensen, K.L. Laidre and R.G. Hansen
Greenland Institute of Natural Resources, Box 570, DK-3900 Nuuk, Greenland

M. Rasmussen
Húsavik Research Center, University of Iceland, Garðarsbraut 19, 640 Húsavik Iceland

M.L. Burt and D.L. Borchers
RUWPA, The Observatory, Buchanan Gardens, St Andrews, KY16 9LZ

R. Dietz and J. Teilmann
National Environmental Research Institute, University of Århus, Department of Arctic Environment, Frederiksborgvej 399, 4000 Roskilde, Denmark

Abstract

Aerial line transect surveys of humpback whales (*Megaptera novaeangliae*) conducted off West Greenland eight times between 1984 and 2007 were used to estimate the rate of increase on this summer feeding ground. The annual rate of increase was 9.4% yr^{-1} between 1987 and 2007 and a similar estimate was derived when including surveys in 1984 and 1985 with partial coverage of the summer feeding ground. This rate of increase is higher than the increase observed at the breeding grounds in the West Indies, but is in same magnitude as the observed rate of increase at other feeding grounds in the North Atlantic. The survey in 2007 was used to make a fully corrected abundance estimate including corrections for whales that were submerged during the passage of the survey plane. The line transect estimate for 2007 was 1,020 (cv=0.35). When the estimate was corrected for perception bias with mark-recapture distance sampling (MRDS) methods, the abundance increased to 1,528 (0.50). Correction for availability bias was developed based on time-depth-recorder information on the time spent at the surface (0-4 m). However, used directly this correction leads to a positively-biased abundance estimate and instead a correction was developed for the non-instantaneous visual sighting process in an aircraft. The resulting estimate for 2007 was 3,299 (cv=0.57). An alternative strip census estimate deploying a strip width of 300 m resulted in 995 (0.33) whales. Correction for perception bias with a simple Petersen estimator resulted in 1418 (0.36) whales and corrected for the same availability bias as for the MRDS method resulted in a fully corrected estimate of 3,039 (0.45) humpback whales in West Greenland in 2007.

Introduction

Humpback whales (*Megaptera novaeangliae*) divide their time between low latitude breeding grounds and high latitude feeding grounds. In the North Atlantic the main breeding grounds are located in the West Indies where the instantaneous rate of increase between 1979 and 1993 has been estimated at 0.031 (Stevick et al. 2003). The North

Atlantic feeding grounds are primarily located in northern Norway, around Iceland, in West Greenland, in eastern Canada, and in Gulf of Maine. Increases in abundance of humpback whales have also been detected at several of the these feeding grounds; 11% yr^{-1} around Iceland (Sigurjonsson and Gunnlaugsson 1990), 5.5% yr^{-1} in Gulf of Maine (Barlow and Clapham 1997), and 9.4% yr^{-1} in the Western North Atlantic (Katona and Beard 1990). Until now, no estimate of changes in abundance has been developed for the West Greenland feeding ground.

Aerial surveys for common minke (*Balaenoptera acutorostrata*) and fin whales (*Balaenoptera physalus*) have been conducted at regular intervals in West Greenland since 1984. Estimates of abundance of humpback whales from these surveys have only been presented for 2005 mostly due to the low number of sightings in the previous years.

In this study we reexamine the aerial survey data from 1984 through 1993 and develop a time series of the relative abundance of humpback whales using 8 surveys from 1984, 1985, 1987, 1988, 1989, 1993, 2005, and 2007. These estimates are then used together with recent abundance estimates to estimate the rate of increase of humpback whales on the West Greenland feeding ground since 1984.

Material and methods

Construction of abundance estimates for 1984 and 1985

Aerial surveys of the West Greenland banks north of 62^{o}N were conducted in June-July 1984 and 1985. East-west going transects separated by two nautical miles were chosen randomly and were flown in twin-engine high winged Partenavia Observer P68 at a target altitude and speed of 183 m and 160 km^{-h}, respectively. Three observers participated and the right front observer also acted as data recorder. Distance to sightings was estimated with inclinometers and the transect line was offset by 200 m due to the flat windows. The number of sightings from the surveys in 1984 and 1985 were too low to develop reliable detection functions. Instead the detection function from the surveys in 1987-1989 was used with a left truncation at 200 m to take into account the effects of the flat windows used in the 1984-85 surveys.

Construction of abundance estimates for 1987-89, 1993 and 2005

Aerial line transect surveys completed in July-August 1987-1989, 1993 and 2005 were used to estimate the summer abundance of humpback whales at surface in West Greenland. The surveys were conducted with a twin engine Partenavia Observer with two observers in rear seats with bubble windows and one observer in the right front seat with a flat window. Information on pod size of humpback whale groups and declination angle to sightings measured with inclinometers were recorded when possible.

Due to the low number of sightings a common detection function was developed for the surveys between 1987 and 1989. These surveys all used the same aircraft, the same target altitude (229 m), and same speed (160km^{-h}) and to some extent, the same observers. The surveys were also completed in weather conditions that were similar between years. An independent detection function was developed for the survey in 1993.

Details of the survey conducted in 2005 in West Greenland were presented in Heide-Jørgensen et al. (in press). The survey provided several sightings of large groups (>10 whales) which caused problems for the line transect estimation. Instead a line transect estimate for all groups $\leq$10 whales was derived and added to a strip census estimate of all groups >10 whales (discussed in detail in Heide-Jørgensen et al. in press).

Construction of abundance estimates for 2007

An aerial line transect survey of humpback whales in West Greenland was conducted between 25 August and 30 September 2007. The survey platform was a Twin Otter from Air Greenland, with long-range fuel tank and four independent observation platforms all with bubble windows. Sightings and a log of the cruise track (recorded from the aircrafts GPS) were recorded on a Redhen msDVRs system that also allowed for continuous video recording of the trackline as well as vertical digital photographic recordings. Declination angle to sightings was measured with Suunto inclinometers and the declination angles were converted to perpendicular distance of the animal to the trackline using an equation to adjust for earth curvature (Buckland et al. 2001). Target altitude and speed was 213 m and 167 km hr^{-1}, respectively.

Survey conditions were recorded at the start of the transect lines and whenever a change in 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 100 km) to the shelf break (i.e. the 200 m 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 11 strata plus several inshore strata (Fig. 1). The southern strata were planned to be covered first.

Conventional DS abundance estimator for the survey in 2007

Using conventional distance sampling (CDS) methods, animal abundance in each stratum was estimated by

$$\hat{N} = \frac{n}{2L\hat{\mu}}\hat{E}[s]A$$

where A is the area of the stratum, L is the total search effort in the stratum, n is the number of unique groups detected in the stratum by both observers and $\hat{\mu}$ was the estimated effective strip width of perpendicular distances to detected groups and $\hat{E}[s]$ was the estimated mean group size estimated using a regression of log group size against estimated detection probability.

Mark-Recapture distance sampling correction for perception bias for the survey in 2007

The search method used an independent observer configuration where observers 1 and 2 acted independently of each other. Detections of animals by observer 1 serve as a set of binary trials in which a success corresponds to a detection of the same group by observer 2. The converse is also true because the observers are acting independently; detections by observer 2 serve as trials for observer 1. Analysis of the detection histories using logistic regression allows the probability that an animal on the trackline is detected by an observer to be estimated, and thus, abundance can be estimated without assuming $g(0)$ is one. These methods combine aspects of both mark-recapture (MR) techniques and distance sampling (DS) techniques and so they are known as MRDS methods (Laake and Borchers, 2004).

Although observers were acting independently, dependence of detection probabilities on unmodelled variables can induce correlation in the detection probabilities. This is called unmodelled heterogeneity. Laake and Borchers (2004) and Borchers *et al*. (2006) developed estimators which assumed that detections were independent at zero perpendicular distance only – called point independence models - that are well suited for aerial surveys where no responsive movements are expected.

The effects of the correlation in detections can be reduced by modeling the effects of variables which cause the correlation. Variables, additional to perpendicular distance, can be included in the MRDS models with model selection criterion used to select the best model.

Group abundance was estimated in each stratum using:

$$\hat{N}_G = \frac{A}{2wL}\sum_{i=1}^{n}\frac{1}{\hat{p}_i}$$

where w is the truncation distance and $\hat{p}_i$ is the estimated probability of detecting group i obtained from the fitted MRDS model. Individual animal abundance is given by

$$\hat{N} = \frac{A}{2wL}\sum_{i=1}^{n}\frac{s_i}{\hat{p}_i}$$

where s_i is the size of the group i. The estimated group size in the stratum is given by

$$\hat{E}[s] = \frac{\hat{N}}{\hat{N}_G}$$

Strip census estimation of the survey in 2007

Most of the humpback whale sightings were made within 300 m from the trackline and at such relatively short distances it can be assumed that there is a constant probability of detecting a group of large whales like humpback whales. Thus in addition to the CDS estimates a strip census estimate was also developed with a simple arithmetic mean of the group size across all strata ($\hat{E}[a]$). To correct for perception bias ($\hat{p}'$) by the observers a Petersen estimate was used:

$$\hat{p}' = \frac{\sum n}{\frac{(S_1 + B + 1)(S_2 + B + 1)}{(B+1)}} - 1$$

where n is the total number of sightings, S_1 and S_2 are the sightings by observer platform 1 and 2 and B is the sightings by both platforms (Magnusson et al. 1978). The variance is estimated from:

$$Var(\hat{p}') = \frac{S_1 S_2 (S_1 + B + 1)(S_2 + B + 1)}{(B+1)^2 (B+2)}$$

Individual animal abundance was then developed from:

$$\hat{N}' = \frac{\left(\dfrac{n}{2 \cdot L \cdot 0.300} \hat{E}[a] \cdot A\right)}{\hat{p}'}$$

Correction for availability bias of the survey in 2007

Estimates of abundance from aerial surveys are negatively biased because some animals were underwater and hence undetectable during the passage of the plane. Satellite-linked time-depth-recorders deployed on five humpback whales off Central West Greenland (Fyllas Bank) in June-July 2000 have been used to show that this species spends between 20 and 68% of their time at the surface above 4 m, with an overall average of $\hat{a}'$. In order to account for this availability bias, corrected abundance (denoted by the subscript '*c*') was estimated by:

$$\hat{N}'_c = \frac{\hat{N}'}{\hat{a}'}$$

The parameter $\hat{a}'$ was the estimated from the satellite-linked time-depth-recorders that were deployed on humpback whales on Fyllas Bank and it was assumed that the whales were available for detection when within 4m of the surface.

However, direct correction with this availability correction factor will lead to a positive bias in the abundance estimate, because sightings of humpback whales from aerial surveys are not an instantaneous process as some whales may be seen ahead of the plane. The average observation time (i.e. the difference between first observation and time when the whales are passing abeam) for the 33 sightings (both observers) was estimated. McLaren (1961) and Barlow et al. (1988) provided a formula for estimating the average probability of detecting a whale at the surface:

Pr (being visible) =(s+t)/(s+d)

where s is the average time the whale is at the surface, d is the average time it is below the surface and t is the window of time the whale is within visual range of the observers. The probability of detecting a whale at the surface during a visual survey is used to correct the bias from an instantaneous sighting process:

Bias-correction of availability $\left(\hat{b}'\right) = \dfrac{s}{d} - \dfrac{1}{(t/d) + (s/d)}$

Using the delta method the coefficient of variation of $\hat{N}'_c$ was estimated by

$$cv\left(\hat{N}'_c\right) = \hat{N}'_c \sqrt{cv^2\left(\hat{\mu}\right) + cv^2(\hat{E}(s)) + cv^2(n/L) + cv^2(\hat{p}') + cv^2(\hat{a}') + cv^2\left(\hat{b}'\right)}$$

Construction of time series

A time series of indices of relative abundance of humpback whales was constructed from previous photo ID mark-recapture studies and from aerial and ship-based surveys presented previously (Larsen and Hammond 2004, Heide-Jørgensen et al. 2007) or re-analysed in this study (Larsen 1995, Larsen et al. 1989, Heide-Jørgensen et al. submitted) or presented for the first time here. The trend in abundance or instantaneous rate of increase ($N_t=N_o e^{rt}$) was estimated by weighted (weight=$1/cv(N)^2$) regression through the log transformed estimates of relative abundance (N).

Results

Construction of estimates of relative abundance

In all years the aerial surveys covered the coastal areas of West Greenland from 60°N (in 1984 and 1985 from 62°N) to 70°N with the maximum effort between 62° and 66°N (Fig. 1a-h). The total survey effort however ranged between 3260 and 8670 km (Table 1). The average ratio between survey effort and stratum area was 0.04 (SD=0.01) however this fluctuated in the first five years between 0.02 and 0.06, but remained constant around 0.04 after 1989. The seven abundance estimates were not significantly correlated with the survey effort (p=0.42). There was an increasing trend in sighting rate in the aerial surveys with r=0.06 (r^2=0.69) for the period 1984 through 2007.

The combined detection function for humpback whales for the surveys in 1987-89 was fitted with a half-normal function with a left truncation at 200m to construct a detection function for the surveys in 1984-85 that used flat windows. The sample size was 10 and the effective search width was 587 m (cv=0.37) (Fig. 2a). The distribution of perpendicular distances to the 15 humpback whale sightings were combined for the surveys in 1987-1989 and a half-normal model was selected to fit the sightings distance data (Fig. 2b). The effective search width was estimated at 708 m (cv=0.20). The survey in 1993 had 18 sightings that were fit to the half-normal model to derive an effective search width of 503 m (cv=0.43, Fig. 2c). A simple mean of the group sizes was used for each of the years.

In 2005 22 sightings within the truncation distance of 3 km were used for deriving a half-normal detection function model with an effective search width of 664m (cv=0.12), only slightly larger than what was found in previous years (see Heide-Jørgensen et al. in press). A regression of log group size against estimated detection probability was used to estimate mean group size across all strata.

In 2007 the distribution of perpendicular distances of sightings shows large number of sightings close to the trackline indicating the absence of a blind spot for observers beneath the plane. However, in the distributions for both observers there was a peak in sightings between 200-250 m after which detection declined substantially. Both hazard rate and half normal functional forms were considered but based on AIC the half-normal model was chosen. The survey region in the 2007 survey included an area of 213,996 km^2 with 8,670 km tracklines covered in Beaufort sea states less than 5 (Fig. 1 and Table 1). The pod sizes varied between 1 and 5 whales and all of the 21 sightings of humpback whales were seen in strata 4 to 11 with the exception of one sighting in stratum 14.

The uncorrected line transect estimates can be considered an index of the relative abundance of humpback whales from 1984 through 2007 (Table 2).

Trends in abundance

The uncorrected estimates from the aerial surveys are smaller than the estimates from the photo identification study except for 1993 where the survey abundance estimate was about twice the estimate from the photo ID study (Fig. 4). When comparing the estimates it should considered that the aerial surveys are not corrected for the time the whales were not available at the surface to be seen by the observers. The aerial survey estimates are similar to a ship-based line transect survey in 2005 (Fig. 4).

The time series of aerial line transect surveys provides an index of the changes in relative abundance (i.e. uncorrected for perception and availability bias) of humpback whales in West Greenland from 1984 through 2007 (Table 3). If it is assumed that the bias remains constant, the rate of increase of humpback whales on the feeding ground in West Greenland can be estimated. The abundance estimates from 1984-1985 and 1987-1989 used the same detection function and were therefore averaged for the purpose of estimating the rate of increase. The overall exponential rate of increase from 1984 to 2007 was 0.09 or 9.4% per year (SE=0.02, p=0.010). However, the 1984 survey did not survey south of 62°N and this could have caused an underestimation of the relative abundance. However, if the combined 1984-85 estimate is excluded, the exponential of increase is unchanged from the 0.09 or 9.4% per year (SE=0.02, p=0.044).

Current abundance

The CDS estimate for 2007 does not include animals that were submerged or missed by the observers (Table 3). Both the conventional DS model and the MRDS models were fitted to the data without truncation. The final MRDS model included a term for observer in the MR model (Table 4). This indicated that observer 2 had a much smaller probability of detection on the trackline than observer 1 (Table 5); 0.66 (cv=0.43) for observer 1 compared to 0.22 (cv=0.76) for observer 2 (Fig. 5). The estimate for both observers combined was 0.73 (cv=0.34). The abundance of humpback whales was 1,528 animals (cv=0.50; 95% CI 605 – 3,860) when using MRDS methods to correct for perception bias (Table 6).

If it is assumed that humpback whales can be seen at depths down to 4 m below the water surface (<4m) with an availability correction factor of 42% (cv=0.09, Table 7) then a corrected at surface abundance estimate for 2007 is 3,638 (cv=0.51) humpback whales in West Greenland.

Humpback whales are known to have long dive cycles with average dive times lasting several minutes and with average time spent at the surface (<4m) of >40 seconds for individuals (Winn and Reichley 1985). Both the dive time and the at-surface-time are considerably longer than the average time the whales are visible from an aircraft passing above. In this survey the time between first sighting of the whales and the time when the whales passed abeam was on average 3.21s (cv=0.38) and the average surface time (>4m) was estimated at 42% (cv=0.09) during daylight periods (09-21 hr) when the surveys were conducted (Table 7). If the probability of detecting a whale at the surface given the observation time of 3.21s (95% CI 1.56-6.59) and the ratio between dive and surface times is compared to an instantaneous correction of whales at the surface then the most severe positive bias can be expected for short durations of surfacings (and dives) (Fig. 6). For surface times >50s the positive bias from using an instantaneous correction of availability ranges between 5 and 20% for observation times between 1 and 6s, with a mean correction of 10% (cv=0.25) for an average 3.21s observation periods. When correcting for this positive bias in the availability factor the estimate of abundance of humpback whales in West Greenland is reduced to 3,299 (cv=0.57, 95% CI 1,170-9,301) in 2007.

The strip census estimate assuming 300 m strip width was 995 (0.33) which is not different from the CDS estimate (Table 8). The Petersen estimate of perception bias was 0.70 (cv=0.16) and correcting for this give an abundance of 1,418 whales (0.36). Further correction with the availability bias used above for the MRDS method gives an estimate of 3,377 (0.38) humpback whales corrected for whales that were submerged during the passage of the plane. Applying a correction for the time the whales are visible to be seen by the observers reduces the total abundance to 3,039 humpback whales (cv=0.45, 95%CI: 1,310-7,051) or slightly lower but more precise than the CDS estimate.

Discussion

Humpback whales have generally been protected in the North Atlantic since 1955 although a low level of exploitation (total catch 1955-85; 24) continued in West Greenland through 1985. After 1985 they were completely protected with the exception of a low number of whales taken as bycatch in fishery operations (total 1986-2001; 7). Considering this low level of exploitation and the fact that humpback whales have clearly increased on their breeding ground in other areas (i.e. the West Indies) it is not surprising that the abundance on the West Greenland feeding ground is also increasing. The detected increase is considerably larger than the increase of 3.2 % per year determined in the West Indies (Stevick et al. 2003) however is of the same magnitude as some of the estimates of increase from other North Atlantic feeding grounds.

The estimates of humpback whale abundance derived from the photo ID study in West Greenland in 1989-1993 (Larsen and Hammond 2004) may provide a correct magnitude of the occurrence of humpback whales in the areas where the photo ID work was concentrated at that time. However, it is obvious from the aerial survey series that only a fraction of the humpback whales are found in the areas where the photo ID work was conducted (see Fig. 7) and satellite tracking studies have demonstrated that some humpback whales do not spent time within the area used for the photo ID study (Heide-Jørgensen and Laidre 2007). With an increasing humpback whale population in West Greenland there are also good reasons to expect that the population will expand its distribution. In recent surveys humpback whales were found more widely in West Greenland than in previous surveys and there are now frequently records of observations far north in West Greenland (e.g. in Uummannaq 71°N, GINR unpubl. data). Thus the photo ID abundance estimates do not represent the complete abundance of humpback whales along the entire West Greenland coast and instead are only a fraction of the total abundance. If it is a constant number of humpback whales that use the photo ID area then the overall rate of increase along the entire West Greenland coast cannot be reliably detected with the past coverage of the photo ID study.

A fully corrected estimate of the abundance of humpback whales in 2007 was 3,820 whales, with a relatively large coefficient of variation (0.51). Even the lower bound of this estimate (1,489 whales) is substantially higher than any previous estimates. The estimate is based on a visual aerial line transect survey that covered a larger part of West Greenland than in previous surveys. However coverage was still partial with poor coverage west of Disko Bay and humpback whales were often observed at the westernmost point of the transects indicating that the West Greenland feeding ground may extend over deeper water (>200m) west of the shelf area into areas not covered in any of the surveys.

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Table 1. Effort and sightings distributed by year and strata for the aerial surveys of West Greenland.

Year/strata	Effort (km)	Area (km^2)	Tran-sects	Effort/area	Sigh-tings	Mean pod size (se)	Sigh-ting rate
1984							
1: 71°20-70°N	491	24516	5	0.0200			
2: 70°-68°30'N	435	17872	3	0.0243			
3A: 68°30-67'N inshore	224	14913	3	0.0150			
3B: 68°30-67'N offshore	735	19305	7	0.0381			
4A: 67°-66'N inshore	442	9446	5	0.0468			
4B: 67°-66°N offshore	398	8311	6	0.0479			
5A: 66°-65°N inshore	174	6431	3	0.0271			
5B: 66°-65°N offshore	644	10900	7	0.0591			
6: 65-64°N	2145	17107	15	0.1254	3		
7: 64-63°N	699	11122	7	0.0628	1		
8: 63°-62°N	410	11748	4	0.0349	1		
Sum	6797	151671	65	0.0448	5	2.14 (0.27)	0.0007
1985							
1: 71°20-70°N	791	24516	7	0.0323			
2: 70°-68°30'N	321	17872	2	0.0180			
3A: 68°30-67'N inshore	337	14913	4	0.0226			
3B: 68°30-67'N offshore	424	19305	4	0.0220			
4A: 67°-66'N inshore	444	9446	5	0.0470	1		
4B: 67°-66°N offshore	462	8311	7	0.0556			
5A: 66°-65°N inshore	829	6431	9	0.1289	2		
5B: 66°-65°N offshore	1156	10900	12	0.1061	1		
6: 65-64°N	1007	17107	7	0.0589	3		
7: 64-63°N	298	11122	3	0.0268			
8: 63°-62°N	772	11748	6	0.0657			
Sum	6841	151671	66	0.0451	7	2.14 (0.27)	0.0007
1987							
1A: 71°30'-69°15'N	1915	14779	13	0.1296			
1B: Disko Bay and Vaigat	729	5358	11	0.1361			
2: 69°15'-67°N	1153	39883	7	0.0289			
3: 67°-64°15'N	1417	42400	8	0.0334	4		
4: 64°15'-60°40'N	1673	25165	9	0.0665	1		
5: 60°40'-58°45'°N	1118	16518	8	0.0677	2		
Sum	8005	144103	56	0.0556	7	1.9 (0.14)	0.0009
1988							
1A: 71°30'-69°45'N	703	24560	10	0.0286			
1B: Disko Bay and Vaigat	404	13876	12	0.0291			
2A: 69°45'-68°N	820	29228	5	0.0281			
2B: 68°-66°30'N	1077	19488	10	0.0553			
3: 66°30'-64°15'N	1399	41660	9	0.0336	7		
4: 64°15'-60°45'N	648	50742	6	0.0128	2		
5: 60°45'N-58°45'N	605	34283	8	0.0176			
Sum	5656	213837	60	0.0265	9	1.1 (0.14)	0.0012

Year/strata	Effort (km)	Area (km^2)	Tran-sects	Effort/area	Sigh-tings	Mean pod size (se)	Sigh-ting rate
1989							
2A: 69°45'-68°00'N	428	29228	4	0.0146			
2B: 68°-66°30'N	836	19488	5	0.0429			
3: 66°30'-64°15'N	706	41660	11	0.0169	1		
4: 64°15'-60°45'N	1218	50742	19	0.0240	2		
5: 60°45'-58°45'N	72	34283	2	0.0021			
Sum	3260	175401	41	0.0186	3	2.7 (0.7)	0.0009
1993							
1A: 71°30'-69°45'N	138	25130	5	0.0055			
1B: Disko Bay and Vaigat	392	13110	8	0.0299			
2A-C: 69°45'-68°00'N	1635	15160		0.1078			
2B-C: 68°-66°30'N	94	15700	5	0.0060			
3 offshore: 66°30'-64°15'N	185	26680	2	0.0069	1		
3 coast: 66°30'-64°15'N	828	23100	10	0.0358	6		
4 offshore: 64°15'-60°45'N	348	24320	4	0.0143			
4 coast: 64°15'-60°45'N	2341	27410	29	0.0854	9		
5 offshore: 60°45'-58°45'N	436	18450	6	0.0236	1		
5 coast: 60°45'-58°45'N	881	14920	11	0.0590	3		
Sum	7140	178850	75	0.0399	20	3.2 (0.60)	0.0025
2005							
CF: 59°-58°N	293	11523	4	0.0254			
CW: 67°30'-64°N	1958	74798	30	0.0262	4		
Disko Bay	556	12312	12	0.0452	1		
SG: 61°-59°N	1106	19491	19	0.0567	4		
SH: 68°30'-67°30'N	577	15669	7	0.0368			
SW: 64°-61°N	1968	29781	31	0.0661	13		
Sum	6458	163574	103	0.0395	22	8.3 (0.38)	0.0025
2007							
1: Uummannaq Fjord	191	8404	3	0.0227			
2: 71°30'-69°45'N	502	22631	5	0.0222			
3: Disko Bay and Vaigat	532	14653	9	0.0363			
4: 69°45'-68°N	545	34272	4	0.0159	1		
5: 68°-66°30'N offshore	862	16226	9	0.0531	3		
6: 68°-66°30'N inshore	973	14902	9	0.0653			
7: 66°30'-64°N offshore	551	22085	6	0.0249	2		
8: 66°30'-64°N inshore	1345	20264	12	0.0664	5		
9: 64°-62°N	998	20334	12	0.0491	4		
10: 62°-60°30'N	932	15951	10	0.0584	3		
11: 60°30-59°N	1194	24085	16	0.0496	2		
14: coastal 67-66°30'N	45	189	6	0.2381	1		
Sum	8670	213996	101	0.0405	21	1.5 (0.21)	0.0024

Table 2. Estimates of relative abundance of humpback whales in West Greenland. Numbers in parenthesis indicate the coefficient of the variation. Photo ID estimates from 1982 from Perkins et al. (1984 and 1985) and from 1988-1992 from Larsen and Hammond (2004). Aerial line transect estimates from 1984-85 and 1987-1993 from this study, from 2005 from Heide-Jørgensen et al. (in press) and from 2007 from this study. The ship-based line transect estimate is from Heide-Jørgensen et al. (2007).

Year	Aerial line transect abundance	Ship-based line transect abundance	Photo ID
1982			271 (0.13)
1984	99 (0.46) *)		
1985	177 (0.44) *)		
1987	220 (0.62)		
1988	200 (0.74)		
1989	272 (0.75)		357 (0.16)
1990			355 (0.12)
1991			376 (0.19)
1992			566 (0.42)
1993	873 (0.53)		348 (0.12)
2005	1158 (0.35)	829 (0.36)**)/1306 (0.42)	
2007	1020 (0.35)		

*) Partial coverage

Table 3. Humpback whale abundance estimates in 2007 using DS methodology showing the encounter rate (n/L), effective strip width (esw) and estimates for pod size $E[s]$, pod density D_G, pod abundance N_G , animal density D and animal abundance N. Strata without sightings are not shown although the total densities take all strata into account. Percentage cv are given in parentheses.

Stratum	n/L (pods/km)	(km)	$E[s]$	D_G (pods/km^2)	N_G (pods)	D (whales/km^2)	N (whales)	*Variance* $\hat{\mu}$ *:n/L:G*
4	0.0018 (80.9)			0.0030 (83.2)	101 (83.1)	0.0041 (84.0)	141 (84.0)	5.2/92.9/1.9
5	0.0035 (76.7)			0.0056 (79.1)	91 (79.1)	0.0078 (79.9)	127 (79.9)	5.7/92.2/2.1
7	0.0036 (95.5)			0.0058 (97.4)	129 (97.4)	0.0081 (98.0)	180 (98.0)	3.8/94.8/1.4
8	0.0037 (60.6)			0.0060 (63.5)	121 (63.5)	0.0083 (64.6)	169 (64.6)	8.7/88.1/3.2
9	0.0050 (38.1)	0.311 (19.1)	1.394 (11.5)	0.0081 (42.6)	164 (42.6)	0.0112 (44.1)	228 (44.1)	18.7/74.5/6.8
10	0.0021 (68.2)			0.0035 (70.8)	55 (70.8)	0.0048 (71.8)	77 (71.8)	7.1/90.3/2.6
11	0.0017 (60.1)			0.0027 (63.1)	65 (63.1)	0.0038 (64.1)	90 (64.1)	8.9/87.9/3.2
14	0.0223 (84.9)			0.0358 (87.0)	7 (87.0)	0.0500 (87.8)	9 (87.8)	4.7/93.5/1.7
Total	**0.0022 (20.0)**			**0.0033 (33.0)**	**732 (33.0)**	**0.0046 (35.0)**	**1 020 (35.0)**	**7.9/89.3/2.9**

Table 4. MRDS point independence model fitted to the data from 2007 survey.

DS model	MR model	AIC	ΔAIC
Uniform	Petersen	205.34	0
HN: D	D	296.03	90.69
HZ: D	D	296.55	91.21
HN: D	D + O	292.97	87.63
HZ: D	D + O	293.49	88.15

Table 5. Number of sightings seen by each observer and the number of duplicates (seen by both) during the 2007 survey. The total column shows the number of sightings seen by observer 1 plus observer 2 minus sightings seen by both.

Pod size	Observer 1	Observer 2	Seen by both	Total
1	14	11	10	15
2	4	1	1	4
3	1	1	1	1
5	1	1	1	1
Total	**20**	**14**	**13**	**21**

Table 6. Humpback whale abundance estimates in 2007 using MRDS methodology showing the encounter rate (n/L), estimates for pod size $E[s]$, pod density D_G, pod abundance N_G , whale density D and whale abundance N. Strata without sightings are not shown although the total densities take all strata into account. Percentage cv are given in parentheses.

Stratum	n/L (pods/km)	D_G (pods/km^2)	N_G (pods)	D (whales/km^2)	N (whales)	$E[s]$
4	0.0018 (80.9)	0.0040 (90.0)	138 (90.0)	0.0040 (90.0)	138 (84.0)	1.00 (00.0)
5	0.0035 (76.7)	0.0076 (86.2)	124 (86.2)	0.0127 (95.9)	207 (79.9)	1.67 (20.9)
7	0.0036 (95.5)	0.0080 (103.2)	176 (103.2)	0.0159 (103.2)	352 (98.0)	2.00 (00.0)
8	0.0037 (60.6)	0.0082 (72.2)	166 (72.2)	0.0082 (72.2)	166 (64.6)	1.00 (00.0)
9	0.0050 (38.1)	0.0110 (54.7)	224 (54.7)	0.0242 (60.5)	492 (44.1)	2.20 (33.8)
10	0.0021 (68.2)	0.0047 (78.7)	75 (78.7)	0.0047 (78.7)	75 (71.8)	1.00 (24.1)
11	0.0017 (60.1)	0.0037 (71.8)	89 (71.8)	0.0037 (71.8)	89 (64.1)	1.00 (00.0)
14	0.0223 (84.9)	0.0489 (93.5)	9 (93.5)	0.0489 (93.5)	9 (87.8)	1.00 (00.0)
Total	**0.0022 (20.0)**	**0.0045 (47.6)**	**1 001 (47.6)**	**0.0069 (50.1)**	**1 528 (50.1)**	**1.53 (13.7)**

Table 7. Proportion of time spent at surface (0-4 m) for four humpback whales instrumented on Fyllas Bank in June 2006.

Whale	Date	6 hr period	Percentage time at 0-4 m
21809	8/6/2000	03-09	47.92
20158	7/6/2000	03-09	19.80
20158	8/6/2000	03-09	25.59
			31.10
21801	10/6/2000	09-15	37.17
21801	20/06/2000	09-15	42.51
21802	10/6/2000	09-15	34.35
21802	17/6/2000	09-15	68.42
21802	18/6/2000	09-15	71.75
21802	22/6/2000	09-15	32.04
			47.71
21801	10/6/2000	15-21	33.52
21801	14/6/2000	15-21	26.57
21801	15/6/2000	15-21	40.67
21801	16/7/2000	15-21	34.94
20160	9/6/2000	15-21	26.53
21802	14/6/2000	15-21	37.73
21802	17/6/2000	15-21	57.77
21802	19/6/2000	15-21	39.58
			37.16
21801	9/6/2000	21-03	31.79
21801	11/6/2000	21-03	26.35
21801	14/7/2000	21-03	44.44
21801	18/7/2000	21-03	42.62
20158	5/6/2000	21-03	48.89
20158	7/6/2000	21-03	30.72
21802	16/6/2000	21-03	57.64
21802	23/6/2000	21-03	35.30
			39.72
Average	All days all whales	09-21	41.68
SD			14.24
n			14.00
SE			3.81
cv			0.09

Table 8. Humpback whale estimates in 2007 using strip census methodology with esw=300m showing the encounter rate (*n*/*L*) and simple estimate of pod size *E*[*s*], pod density D_G, pod abundance N_G , animal density *D*, animal abundance *N* component percentagesof var(D) where *n/L* is encounter rate and *G* is group size. Strata without sightings are not shown although the total densities take all strata into account. Percentage cv are given in parentheses.

Stratum	*n*/*L* (pods/km)	*E*[*s*]	D_G (pods/km^2)	N_G (pods)	*D* (animals/km^2)	*N* (animals)	*Variance n/L:G*
4	0.0018 (80.9)	1.42 (15.6)	0.0031 (80.9)	105 (80.9)	0.0044 (82.4)	149 (82.4)	96.5/3.5
5	0.0035 (76.7)		0.0058 (76.7)	94 (76.7)	0.0082 (74.1)	134 (78.3)	96.1/3.9
7	0.0036 (95.5)		0.0061 (95.5)	134 (95.5)	0.0086 (96.8)	190 (96.8)	97.4/2.6
8	0.0030 (75.0)		0.0050 (75.0)	101 (75.0)	0.0071 (76.6)	143 (76.6)	95.1/4.9
9	0.0040 (46.5)		0.0067 (46.5)	114 (46.5)	0.0095 (49.0)	193 (49.0)	90.0/10.0
10	0.0017 (60.1)		0.0031 (69.9)	57 (69.9)	0.0051 (70.0)	81 (70.0)	95.1/4.9
11	0.0017 (60.1)		0.0028 (60.1)	66 (60.1)	0.0040 (62.1)	96 (59.6)	93.8/6.2
14	0.0223 (84.9)		0.0371 (84.9)	7 (84.9)	0.0528 (86.3)	10 (86.3)	96.8/3.2
Total	**0.0024 (20.0)**		**0.0032 (29.1)**	**701 (29.5)**	**0.0045 (33.0)**	**995 (33.0)**	**95.1/4.9**

Fig. 1a. Survey lines and sightings of humpback whales in 1984.

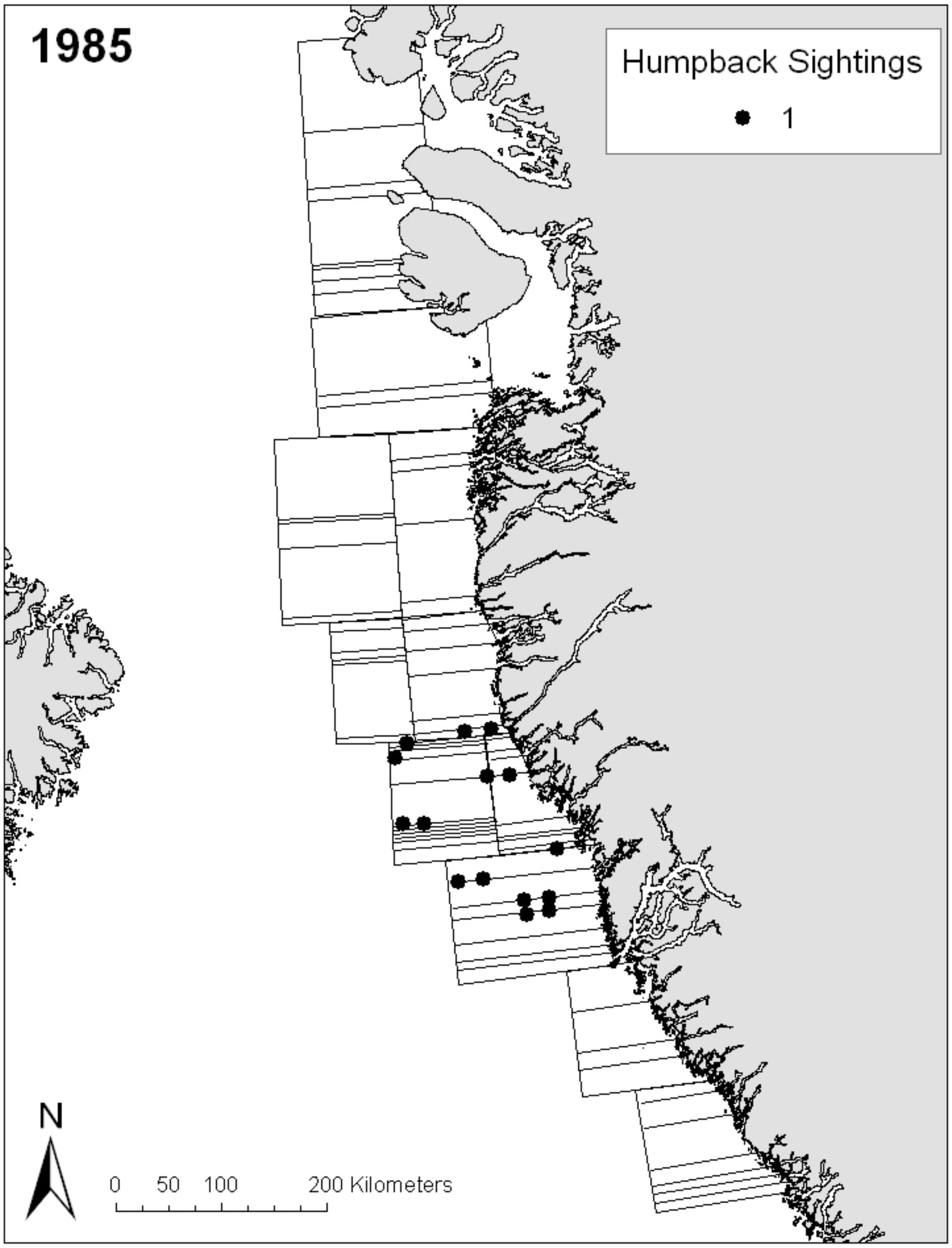

Fig. 1b. Survey lines and sightings of humpback whales in 1985.

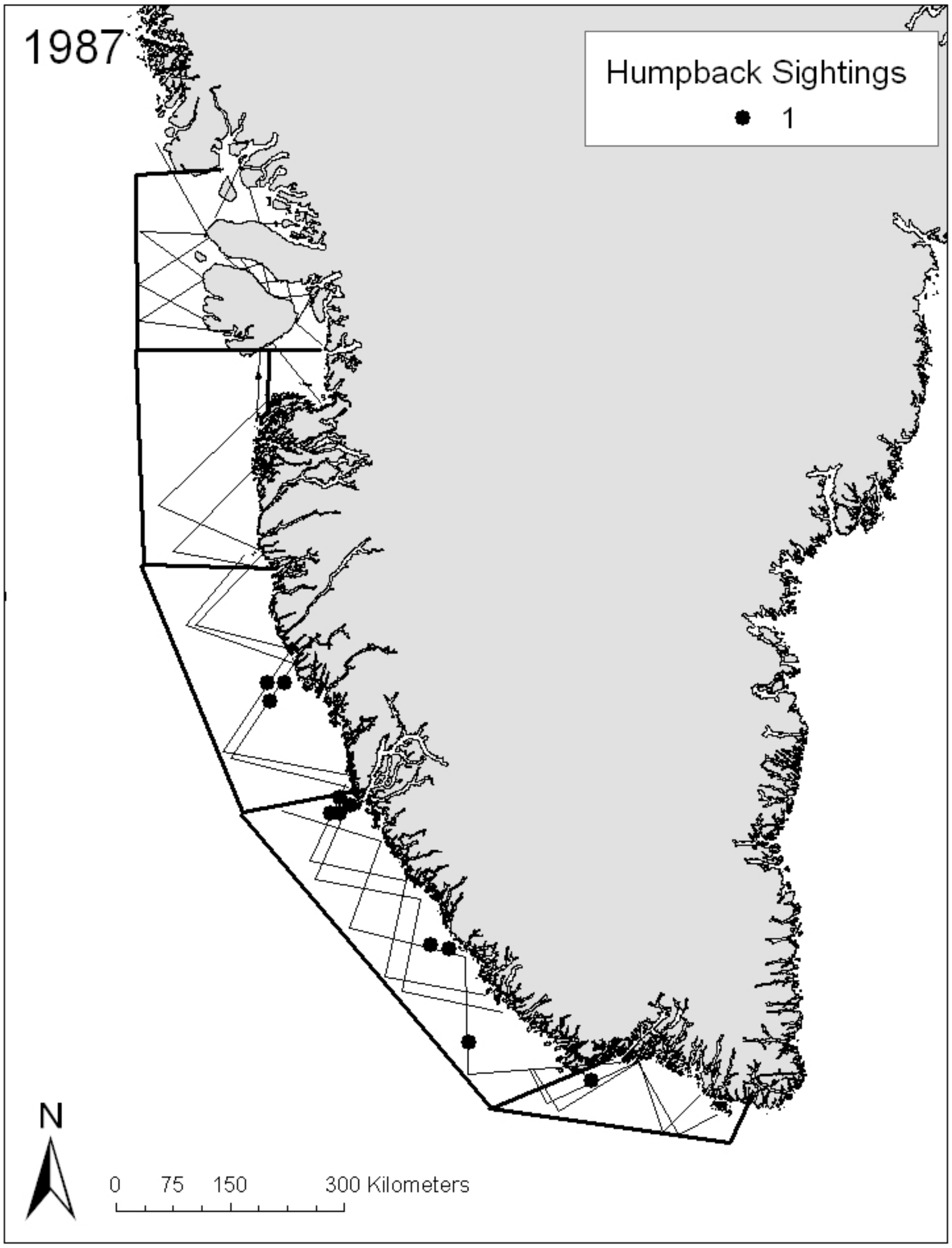

Fig. 1c. Survey lines and sightings of humpback whales in 1987.

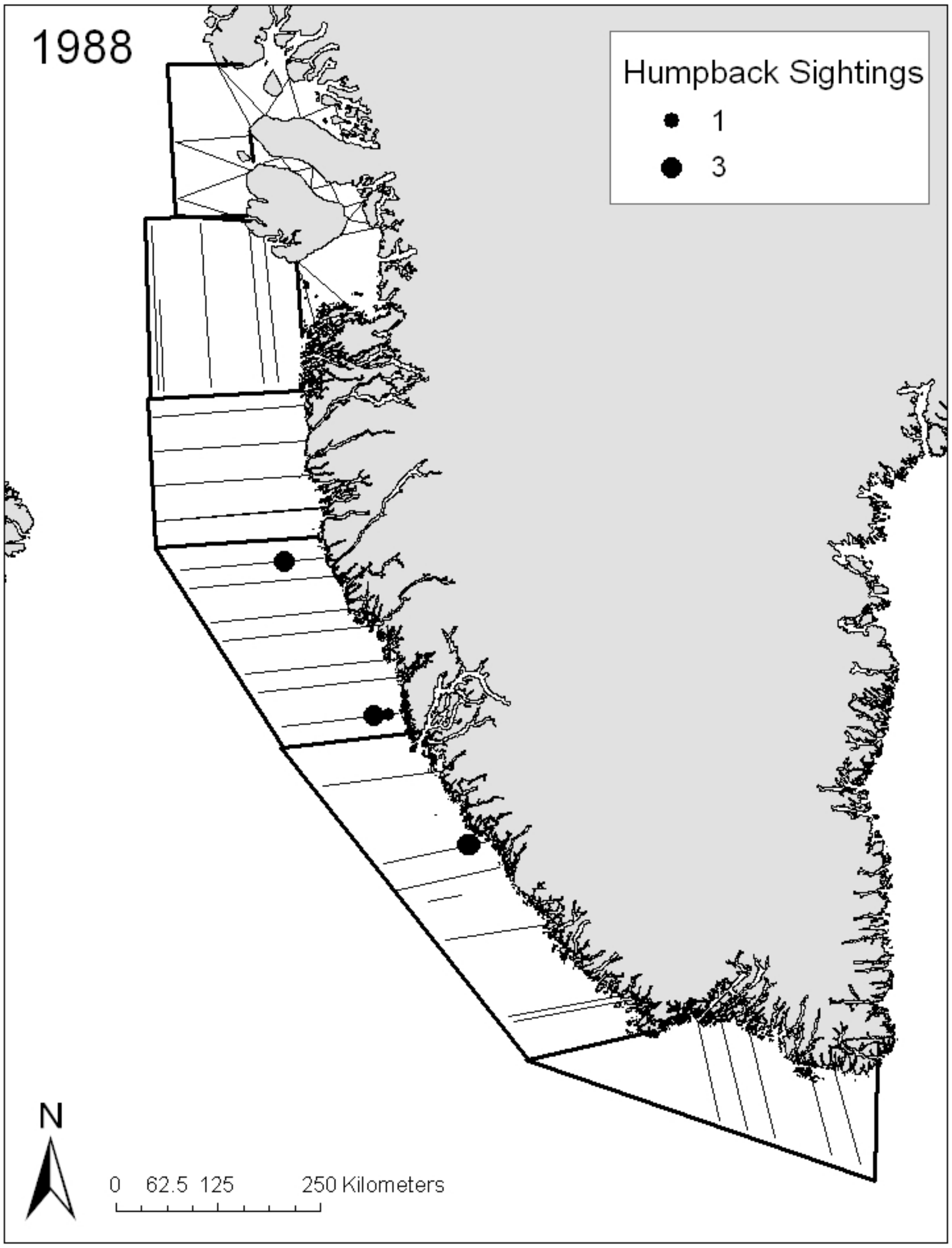

Fig. 1d. Survey lines and sightings of humpback whales in 1988.

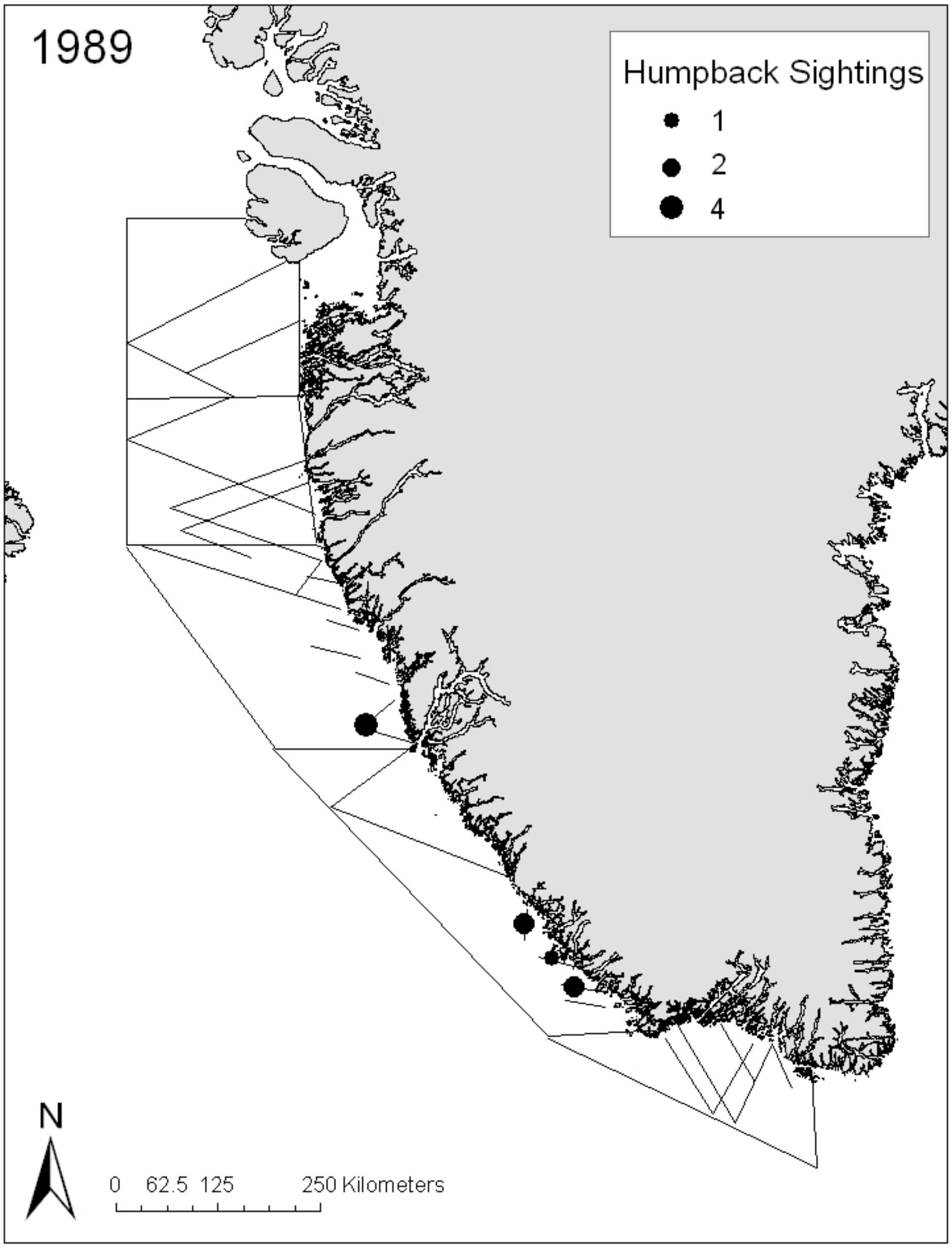

Fig. 1e. Survey lines and sightings of humpback whales in 1989.

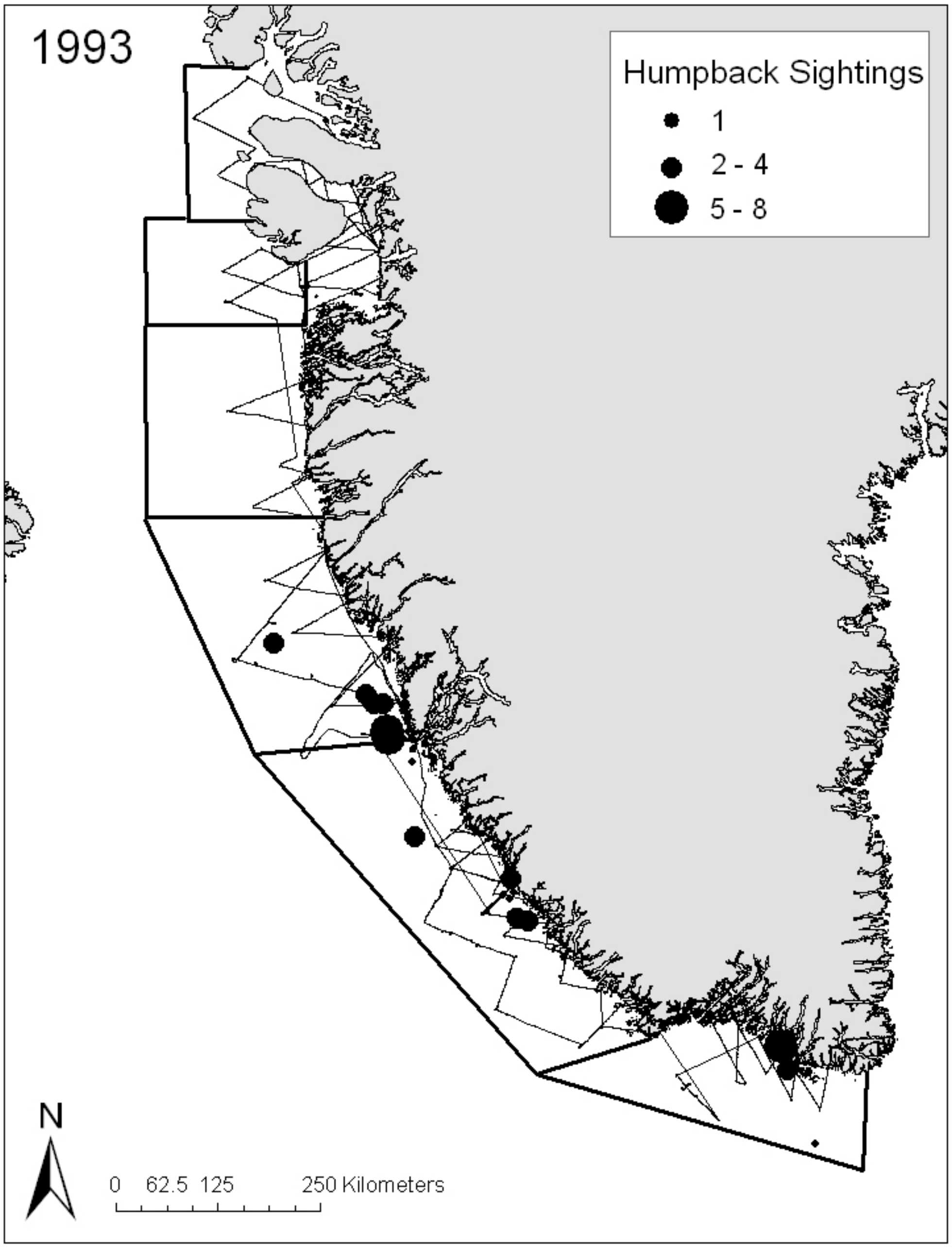

Fig. 1f. Survey lines and sightings of humpback whales in 1993.

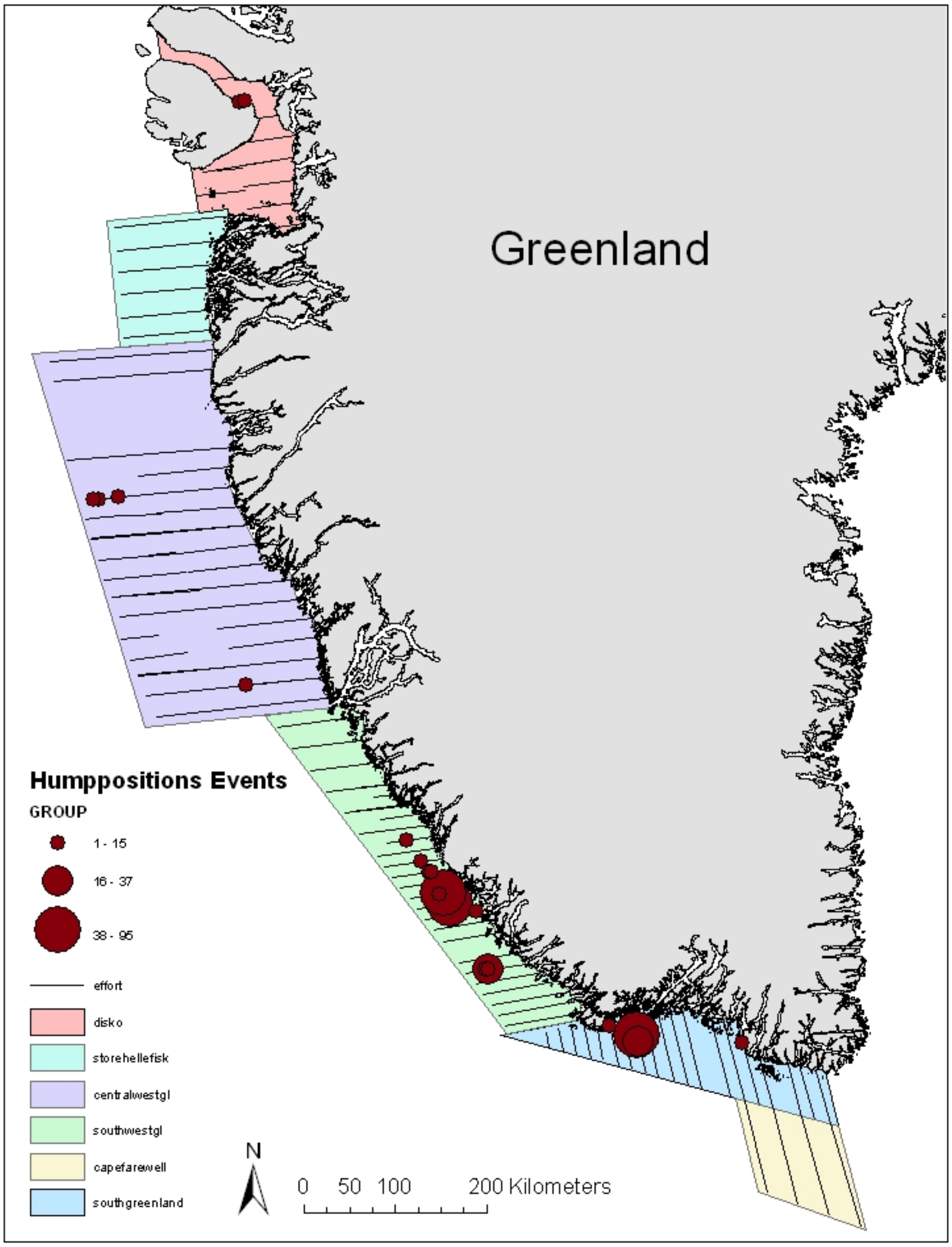

Fig. 1g. Strata, transect lines and sightings of humpback whales during the 2005 aerial survey.

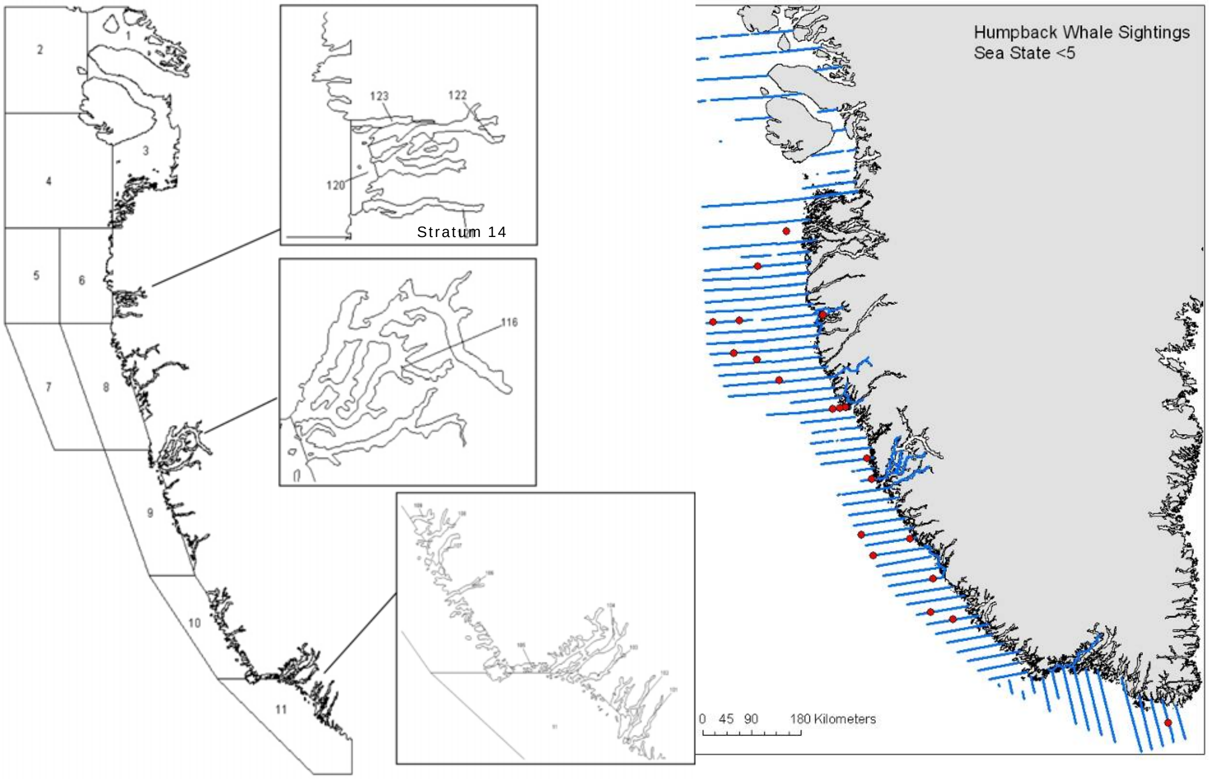

Fig. 1h. Strata (left) and transect lines and sightings of humpback whales (right) during the 2007 aerial survey.

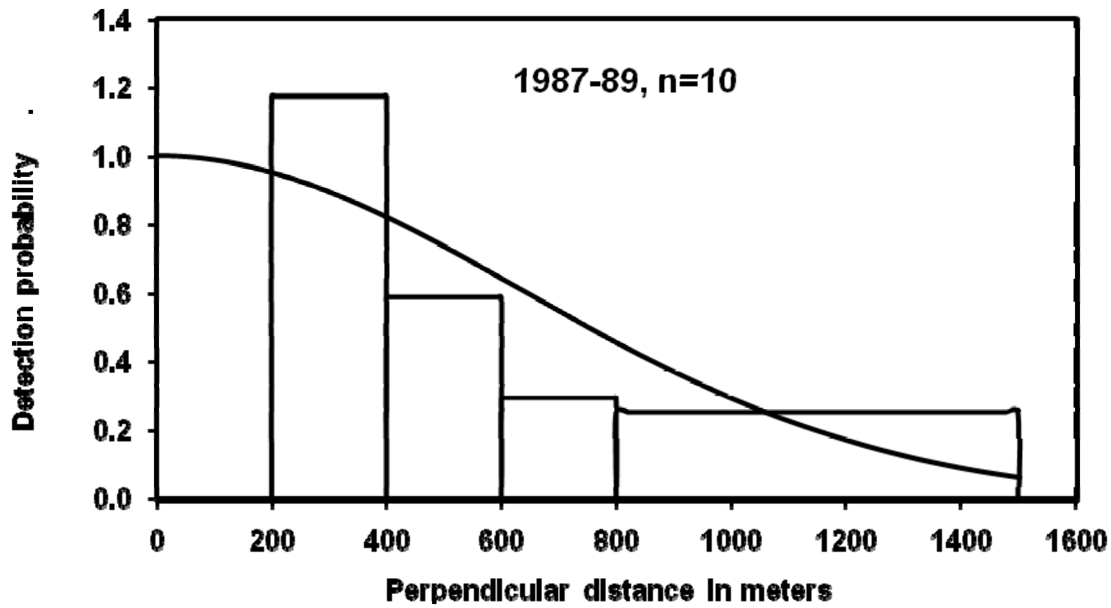

Fig. 2a. Distribution of sightings of humpback whales at various distances from the trackline during the surveys in 1987-89 with a left a truncation at 200 m to allow the detection function to be applied to the surveys in 1984 and 1985 that used flat windows instead of the bubble windows that were used in subsequent surveys. Data has been fitted to the half-normal model and the fitted curve shows the expected number of sightings. The sightings were truncated at 1500 m and the effective search width was 587 m (cv=0.37).

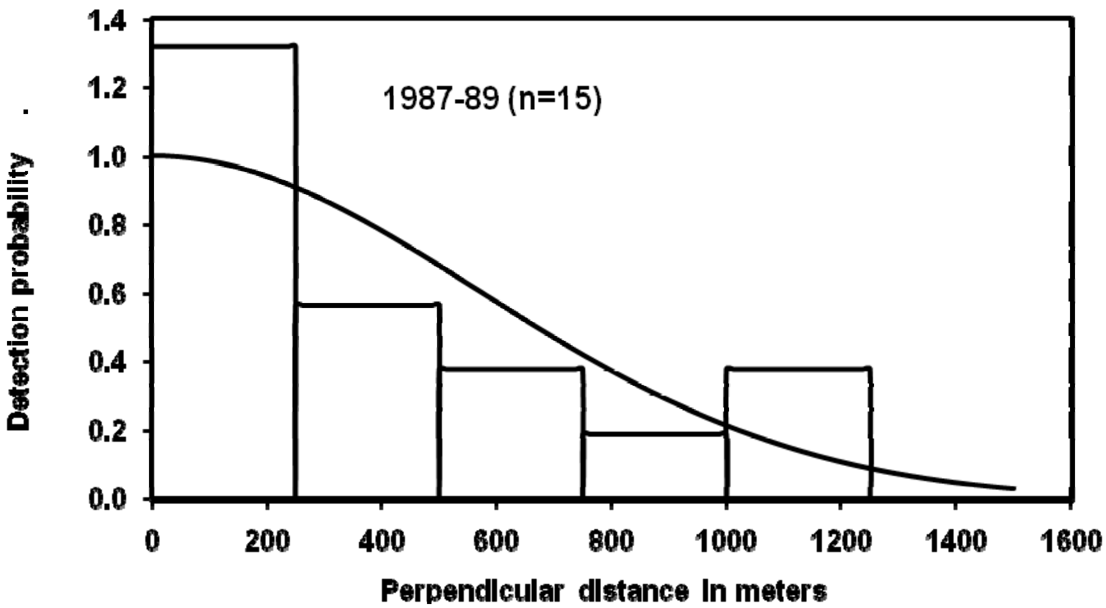

Fig. 2b. Distribution of sightings of humpback whales at various distances from the trackline during the surveys in 1987-89. Data has been fitted to the half-normal model and the fitted curve shows the expected number of sightings. The sightings were truncated at 1500 m and the effective search width was 708 m (cv=0.20).

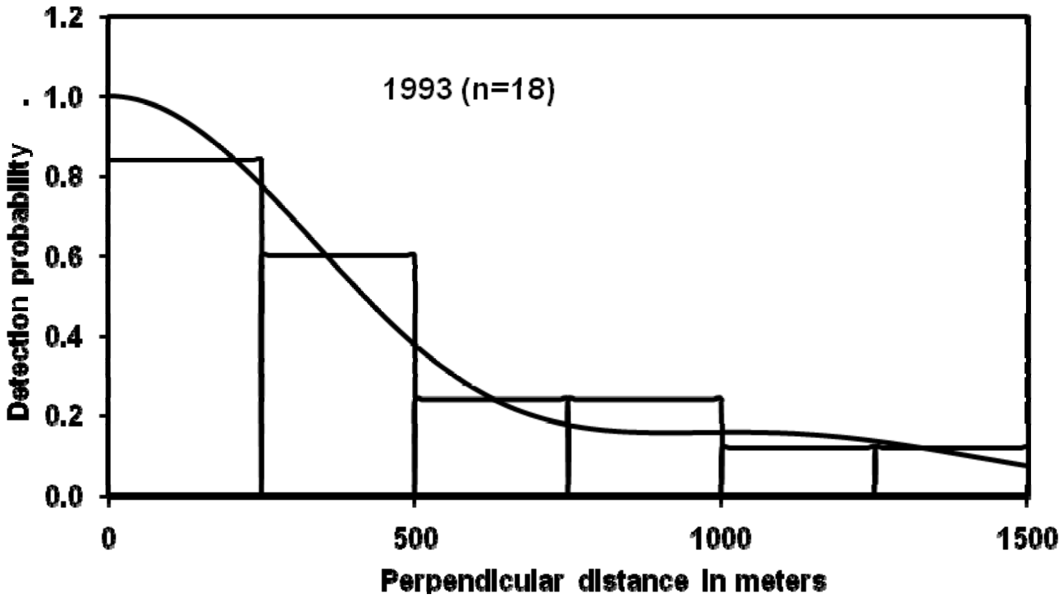

Fig. 2c. Distribution of sightings of humpback whales at various distances from the trackline during the survey in 1993. Data has been fitted to the half-normal model and the fitted curve shows the expected number of sightings. The sightings were truncated at 1500 m and the effective search width was 503 m (cv=0.43).

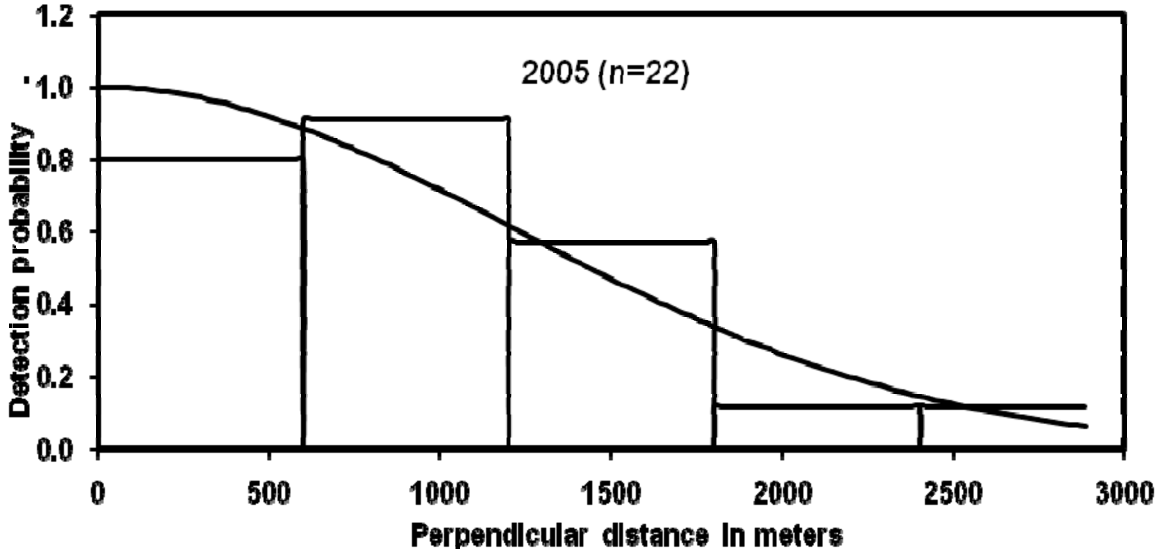

Fig. 2d. Distribution of sightings of humpback whales at various distances from the trackline during the survey in 2007. Data has been fitted to the hazard rate function and the fitted curve shows the expected number of sightings. The effective search width was 1506 m (cv=0.17) (see also Heide-Jørgensen et al. in press).

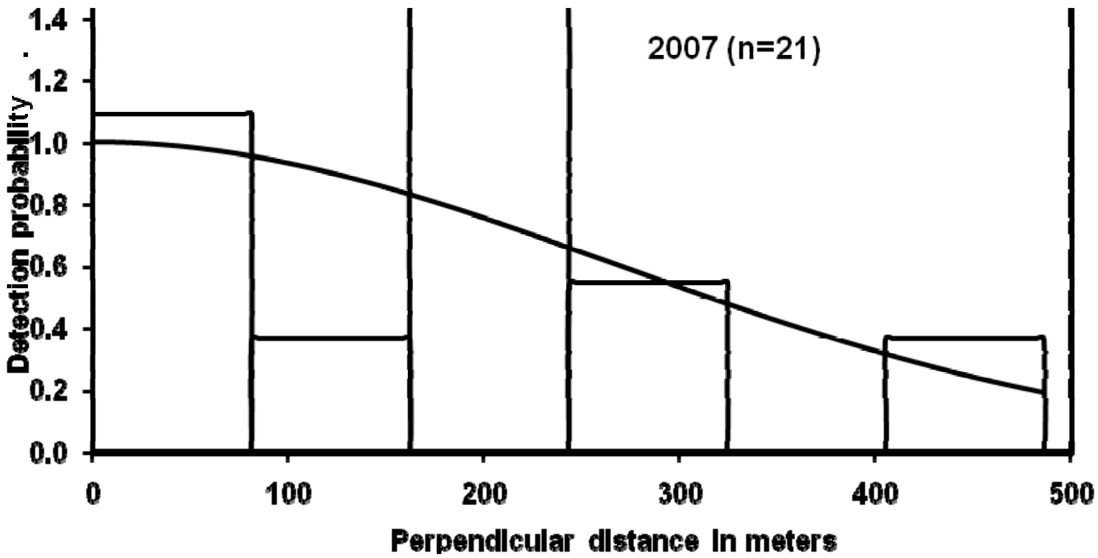

Fig. 2e. Distribution of sightings of humpback whales at various distances from the trackline during the survey in 2007. Data has been fitted to the hazard rate function and the fitted curve shows the expected number of sightings. The effective search width was 311 m (cv=0.19).

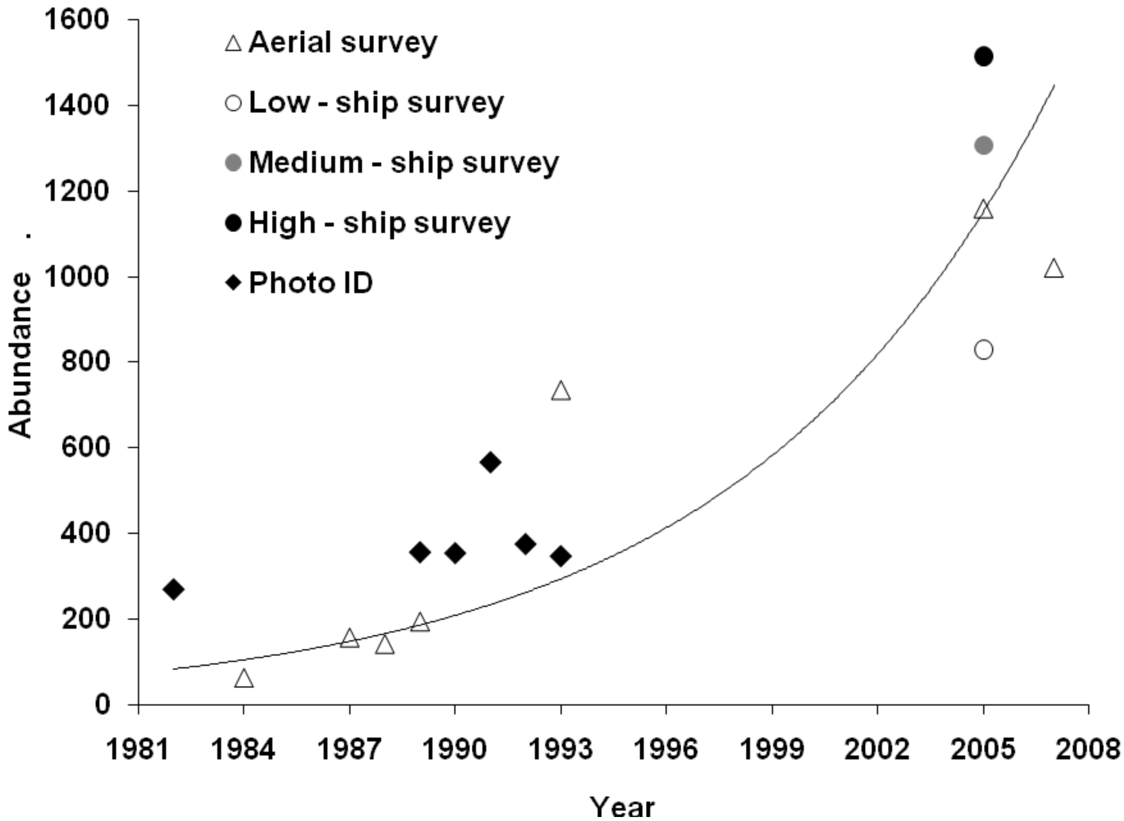

Fig. 3. Trends in relative abundance of humpback whales in West Greenland 1982-2007. The exponential growth model is fitted to the estimates from the aerial surveys. Details of the three abundance options from the ship-based survey in 2005 are given in Heide-Jørgensen et al. (2007).

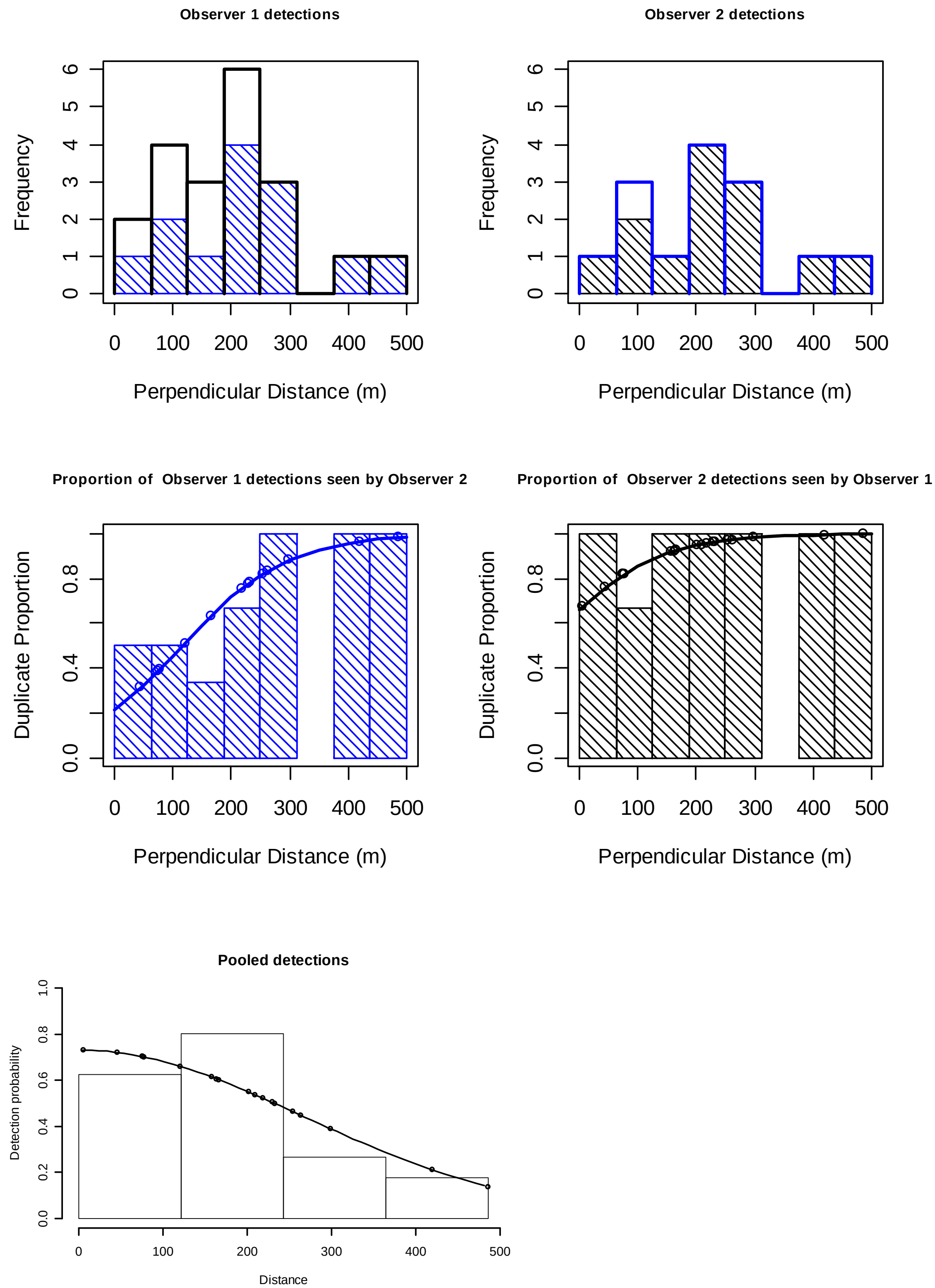

Fig. 4 Detection function plots for the MRDS analyses. Duplicate detections are indicated in the shaded areas; as a number in the top plots and as a proportion in the middle plots. The points are the probability of detection for each sighting given its perpendicular distance. The lines are the fitted models (in the pooled detection plot, the line is a smooth function fitted to the points).

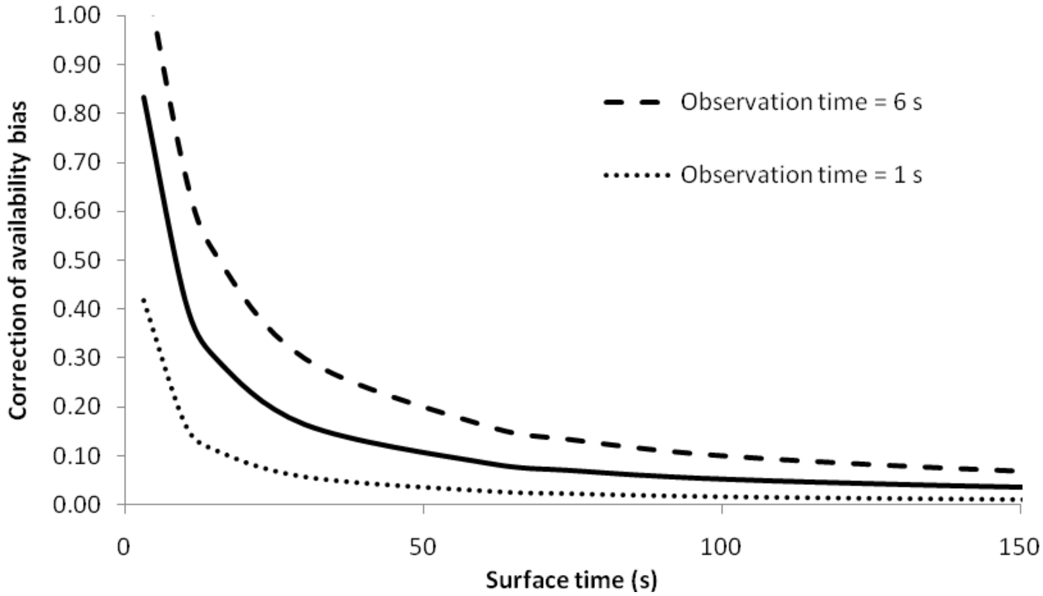

Fig. 5. Estimation of the positive bias in instantaneous availability correction factors compared to correction based on the probability of detecting a whale given surface-dive patterns with 36% of time at surface and average observation times of 1, 3 and 6 seconds.