A note on the distribution and abundance of blue whales (*Balaenoptera musculus*) in the Central and Northeast North Atlantic

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ABSTRACT

The distribution and abundance of blue whales (*Balaenoptera musculus*) was assessed from ship surveys conducted in the Central and Northeast Atlantic in 1987, 1989, 1995 and 2001. Blue whales were most commonly sighted off western Iceland, and to a lesser extent northeast of Iceland. They were very rare or absent in the Northeast Atlantic. Sightings were combined over all surveys to estimate the detection function using standard line transect methodology, with the addition of a covariate to account for differences between surveys. Total abundance was highest in 1995 (979, 95% CI 137-2,542) and lowest in 1987 (222, 95% CI 115-440). Uncertainty in species identity had little effect on estimates of abundance. There was a significant positive trend in abundance northeast of Iceland and in the total survey area.

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INTRODUCTION

Co-ordinated international North Atlantic Cetacean Sighting Surveys (NASS) were initiated in 1987 (Sigurjónsson *et al.* 1989) and have been conducted 4 times (NASS-87, NASS-89, NASS-95 and NASS-2001). In these surveys large areas of the northern North Atlantic have been covered simultaneously by up to 15 vessels and 2 aircraft with participation of up to five countries (reviewed in Víkingsson *et al.* 2009).

Although blue whales (*Balaenoptera musculus*) have not been considered a primary target species of the NASS surveys, the coverage of the surveys is likely to have included a large part of the summer distribution area of the species in the northeast North Atlantic. Blue whale abundance estimates, based on the Icelandic part of the NASS-87 (Gunnlaugsson and Sigurjónsson 1990) and NASS-89 (Sigurjónsson and Víkingsson 1997) surveys have been published, but these estimates did not use standard line transect methodology (Buckland *et al.* 2001) and did not include estimates of variance. Here we present standardized estimates of blue whale abundance from all NASS.

METHODS

Field methodology

The sighting methodology used on Icelandic and Faroese (Sigurjónsson *et al.* 1989, 1991, Víkingsson *et al.* 2009) and Norwegian (Øien 1989, 1991) vessels has been described elsewhere. Too few sightings of blue whales (0 in 1987, 4 in 1989, 1 in 1995 and 8 in 1996-2001) were observed in the Norwegian surveys to warrant quantitative analysis of abundance; therefore, abundance estimation was limited to the Icelandic and Faroese sectors.

Post stratification

The surveys were originally stratified according to the expected density of the target species, but the stratification schemes were changed as experience was gained. Hence equivalent areas across surveys cannot be produced by simple combinations of the original blocks. Also, the original stratification scheme was not designed for blue whales. We used post-stratification to derive regions which were roughly equivalent in shape and size across surveys and encompassed important areas of blue whale distribution.

The original stratification scheme for the Icelandic and Faroese components of the surveys are given by Víkingsson *et al.* (2009). Because relative survey effort varied across blocks, we post-stratified only within the original blocks. The same post-stratification scheme used by Víkingsson *et al.* (2009) was employed. These post-blocks were then combined into "regions" that were roughly equivalent in size across surveys and tailored to the observed distribution of blue whales. Since blue whales tended to be concentrated to the west of Iceland in Denmark Strait in all surveys, this was defined as the "WEST" region (Fig. 1). In some years blue whales were observed to the north and east of Iceland: this was defined as the "NORTHEAST" region. No blue whales were observed in the Faroese survey area and very few were observed south of the West region. The "Total" region included WEST, NORTHEAST and the remainder of the Icelandic and Faroese survey areas.

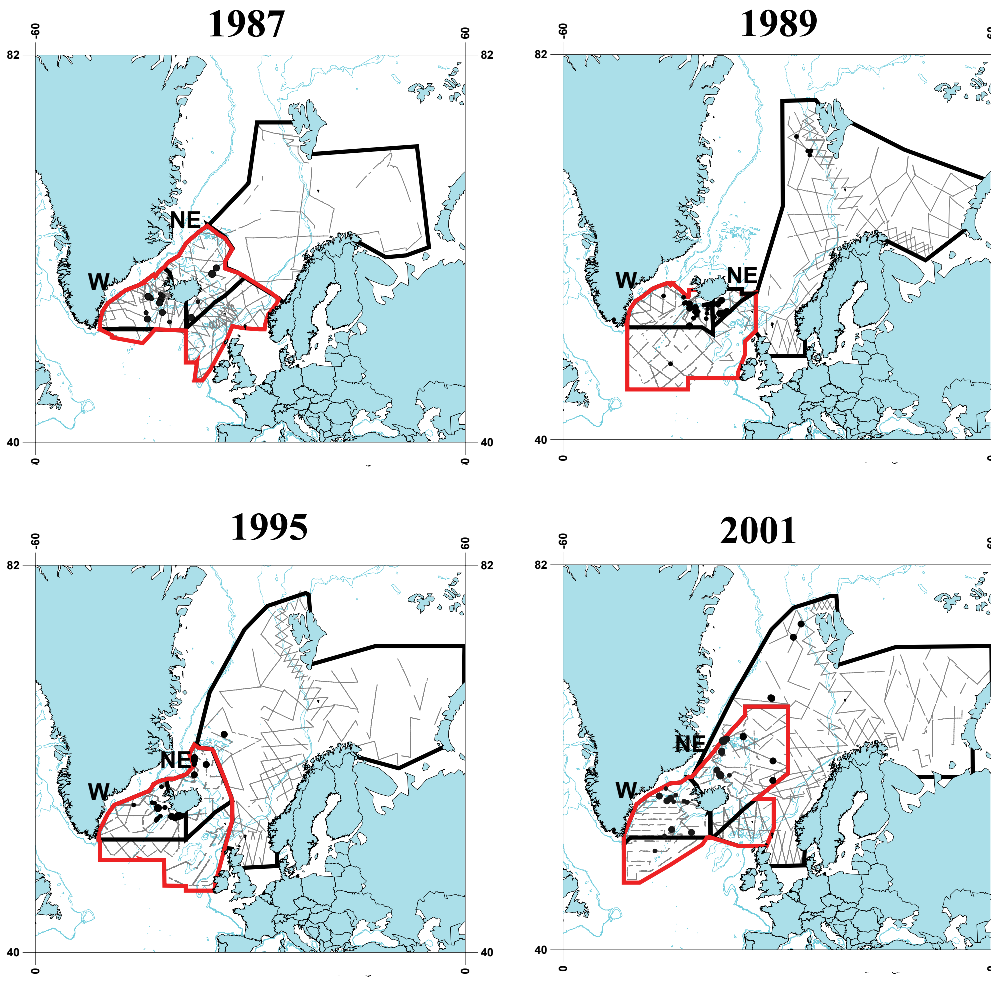

Fig. 1. Realized survey effort and sightings of blue whales in NASS ship surveys, 1987 to 2001. Symbol size is proportional to group size from 1 to 4+. The Norwegian sector of the 2001 survey was surveyed from 1996-2001. Regions identified are WEST (W) and NORTHEAST (NE), and the total area used in abundance estimates is outlined in red.

Data treatment and analysis

Blue whales were not a target species of the NASS. It was often difficult to discriminate between fin whales (*Balaenoptera physalus*) and blue whales at sea, and fin whales are overwhelmingly more abundant in the survey area. Blue whale sightings were recorded as follows, in decreasing order of certainty of identification:
BM - blue whale;
BM? - likely blue whale;
BM?BP - like blue like fin;
BP?BM - like fin like blue.

The distribution of these sighting types among surveys and blocks is shown in Table 1. Sightings of BM?BP were rarely recorded, while sightings of BP?BM were common in all surveys. An unknown and likely decreasing proportion of the last three categories (<100%) were in fact sightings of blue whale groups. Including all sightings in the abundance estimate would therefore result in positive bias, while including none of the uncertain sightings would result in negative bias. We performed a base analysis including BM+BM?, which is the standard practice for analyses of NASS data (Pike *et al.* 2009a, Víkingsson *et al.* 2009). We assessed the sensitivity of the estimates to uncertainty in species identification by calculating additional estimates including 1) BM+BM?+BM?BP (base+) and 2) BM+BM?+BM?BP+BP?BM (base++).

All observations and search effort done at Beaufort sea state (BSS) >5 were discarded before analysis, to reduce the proportion of effort conducted under poor sighting conditions. This resulted in a loss of 2% of effort and 0 sightings in 1987, 9% and 0 in 1989, 6% and 8 in 1995, and 4% and 2 in 2001.

Data analyses were carried out using the DISTANCE 5.0 (Thomas *et al.* 2005) software package and stratified line transect methods (Buckland *et al.* 2001). There were not enough sightings in any individual survey to reliably estimate the detection function, as this normally requires a minimum of about 40 sightings (Buckland *et al.* 2001). Therefore sightings from all surveys were combined for the purpose of estimating detection functions. This was considered reasonable because the same basic field method, and some of the same vessels and observers were used on all surveys. Line transect analysis has been shown to be reasonably robust to this type of pooling (Buckland *et al.* 2001). In addition the use of multiple covariates distance sampling (MCDS, Thomas *et al.* 2005) enabled us to include a covariate for survey year, which should account for differences in strip width attributable to survey when present. Calculation of model parameter effective strip width (*esw*) was therefore pooled over surveys and geographical strata. Estimation of group size (*s*) was estimated separately over geographical strata within surveys. Mean, rather than adjusted group size (Buckland *et al.* 2001) was used as there was no evidence of size bias in group detectability. Encounter rate (n/L) was calculated separately for each stratum within surveys.

A variety of models for the detection function $f(x)$ were initially considered, and the final model was chosen by minimisation of Akaike's information criterion (AIC) (Buckland *et al.* 2001), goodness of fit statistics and visual inspection of model fits. Effective strip width was estimated at the stratum level and could therefore vary between strata depending on covariate levels. This necessitates estimation of total variance by bootstrap methods as variance estimates at the stratum level are not independent (Buckland *et al.* 2001, Thomas *et al.* 2005). Exploratory analyses indicated that the inclusion of more than a single covariate in the models precluded the reliable estimation of variance by bootstrap re-sampling, probably due to the sparseness of the data matrix. Therefore only the covariate for survey year was included.

Regional and total rates of increase in blue whale density were calculated using log linear regression, and confidence intervals for the rates of increase were estimated using a parametric bootstrapping procedure, assuming a log normal distribution for the abundance estimates with the estimated coefficient of variation, using the 2.5 and 97.5 percentiles of the distribution of log-linear slopes from 1,000 re-samplings.

RESULTS

The distribution of blue whale sightings is shown in Fig. 1. Blue whales were most common to the west and south of Iceland in all surveys, and had a relatively coastal distribution in most years. In 2001 the distribution appeared more offshore but there was very little effort in inshore areas. Blue whales were also sighted northeast of Iceland, as far north as Jan Mayen island. Almost no blue whales were sighted in the Norwegian sector, except for a few west of Svalbard in 1989 and 2001.

The greatest number of blue whale sightings were made in 1995 and the fewest in 1987 (Table 1). The percentage of sightings positively identified as blue whales as opposed to the less certain blue whale categories (BM? and BM?BP) ranged from 68% in 1989 to 93% in 1987. In 1995 there was a higher number of BP?BM than in other years.

Abundance

The half normal model provided the best fit for the base case detection function, and the inclusion of the covariates for survey year improved the fit substantially (Fig. 2). Survey year changed the *esw* as follows: 1995<2001<1989<1987 (Table 2). The same models were used for the base+ and base++ detection functions, which resulted in slightly greater effective strip widths for base+ and substantially greater for base++ (Table 2).

The abundance estimates by survey and region are shown in Table 2. For the base case analysis abundance was highest in the WEST region in all years except 2001, when it was higher in the NORTHEAST. Total abundance was lowest in 1987 and highest in 2001, but there were no significant differences in between-year comparisons of regional or total abundance. There was little relative difference in the total estimates for the base and base+/base++ analyses, with the largest difference seen in 1987 when base++ was 34% higher than base. None of these differences were statistically significant.

The WEST region was similarly covered by all surveys, but otherwise the 1989 survey covered a substantially different area than the others (Fig. 1). We therefore excluded it from estimation of the rate of increase (*R*) in regions other than WEST (Table 3). Rate of increase was positive in the NORTHEAST and WEST regions and the total survey area. However the bootstrap confidence interval overlapped with 0 for the WEST region. The point estimate of *R* was highest for the NORTHEAST region. The rate of increase for the total survey area was 9% per year (95% CI 2% to 17%) for the base case estimation.

Table 1. Numbers of sightings by region for NASS, 1987-2001. L – effort; A – area.

SURVEY	REGION	L (*nm*)	A (nm^2)	BM	BM?	BM?BP	BP?BM	TOTAL
1987	NE	2,993	128,336	3	0	0	3	6
1987	OUT	7,929	345,666	1	0	0	1	2
1987	WEST	5,434	192,302	10	1	0	11	22
1987	TOTAL	16,356	666,304	14	1	0	15	30
1989	NE	1,107	34,945	6	2	0	3	11
1989	OUT	5,061	667,777	1	0	0	5	6
1989	WEST	3,604	175,185	16	2	7	9	34
1989	TOTAL	9,772	877,907	23	4	7	17	51
1995	NE	1,406	91,821	7	0	0	3	10
1995	OUT	3,094	437,545	0	0	0	0	0
1995	WEST	2,888	178,763	18	9	0	43	70
1995	TOTAL	7,388	708,129	25	9	0	46	80
2001	NE	3,529	254,076	11	1	2	1	15
2001	OUT	2,921	349,960	0	1	0	0	1
2001	WEST	2,997	191,434	11	1	0	27	39
2001	TOTAL	9,447	795,470	22	3	2	28	55
ALL				84	17	9	106	216

Table 2. Characteristics of abundance estimates for blue whales from the NASS. *esw* – effective strip half-width, averaged over all covariates; *s* – mean group size; *n* – number of sightings; *D* – density (no. per 1,000 nm^2); *N* – abundance.

SURVEY	REGION	*esw* (m)	*s*		*n*	*D*	*N*		95% CI L	95% CI R
1987	NE	3,182	2.00	(0.50)	3	0.444	57	(0.597)	0	135
1987	OUT	3,182	2.00	(0.00)	1	0.049	17	(0.893)	0	55
1987	WEST	3,182	1.45	(0.36)	11	0.770	148	(0.423)	56	266
1987	TOTAL	3,182	1.60	(0.40)	15	0.333	222	(0.352)	115	440
1987	TOTAL+	3,182	1.60	(0.40)	15	0.374	249	(0.362)	114	492
1987	TOTAL++	4,139	1.50	(0.42)	30	0.447	298	(0.254)	166	462
1989	NE	2,572	1.75	(0.40)	8	3.892	136	(0.438)	29	255
1989	OUT	2,572	1.00	(0.00)	1	0.055	37	(0.820)	0	72
1989	WEST	2,572	1.39	(0.70)	18	2.044	358	(0.303)	165	576
1989	TOTAL	2,572	1.48	(0.60)	27	0.605	531	(0.238)	288	759
1989	TOTAL+	2,700	1.44	(0.57)	34	0.685	601	(0.273)	315	903
1989	TOTAL++	3,445	1.39	(0.52)	51	0.703	617	(0.234)	376	941
1995	NE	1,679	1.57	(0.34)	7	2.494	229	(0.625)	0	530
1995	OUT	1,679		(0.00)		0.000	0			
1995	WEST	1,679	1.56	(0.51)	27	4.000	715	(0.650)	58	2,136
1995	TOTAL	1,679	1.56	(0.48)	34	1.383	979	(0.641)	137	2,542
1995	TOTAL+	1,679	1.56	(0.48)	34	1.383	979	(0.620)	200	2,996
1995	TOTAL++	3,321	1.30	(0.46)	80	1.703	1,206	(0.337)	593	2,180
2001	NE	2,556	2.08	(0.43)	12	2.236	568	(0.506)	79	1,305
2001	OUT	2,556	1.00	(0.00)	1	0.000	0			
2001	WEST	2,556	1.33	(0.37)	12	1.504	288	(0.415)	150	529
2001	TOTAL	2,556	1.68	(0.48)	25	1.075	855	(0.353)	358	1,419
2001	TOTAL+	2,556	1.67	(0.47)	27	1.075	855	(0.371)	351	1,589
2001	TOTAL++	3,655	1.53	(0.47)	55	1.272	1,012	(0.231)	581	1,485

DISCUSSION AND CONCLUSIONS

Blue whales are relatively rare in the area surveyed by the NASS, and each individual survey produces too few sightings for reliable estimation of a detection function and hence abundance. We therefore first had to combine sightings from all 4 surveys to estimate a common detection function, then estimate abundance at the survey and regional level. The use of a covariate for survey year in the detection function makes this approach defensible, in that it allows variation in effective strip width between surveys even though the detection function is estimated using pooled data. Nevertheless it would be preferable to estimate the detection functions at the survey level, as the functional form of the detection function might also vary between surveys, as has been observed with fin whales (Víkingsson *et al.* 2009).

The greatest problem in counting blue whales in this area is the difficulty in discriminating between sightings of the blue whale and of the vastly more abundant fin whale. We approached this problem here by including less certain blue whale sightings in the base+ and base++ estimates to assess the magnitude of the potential bias. In practice the problem was less serious than anticipated because of the difference in the detection functions between the analyses. Most of the uncertain blue whale sightings are animals that were seen at great distance and were not closed upon for species identification. Their addition to the detection function results in a wider *esw* and hence an abundance estimate lower than might be expected given the greater number of sightings. Therefore we feel that the base case analysis is likely the best balance be-

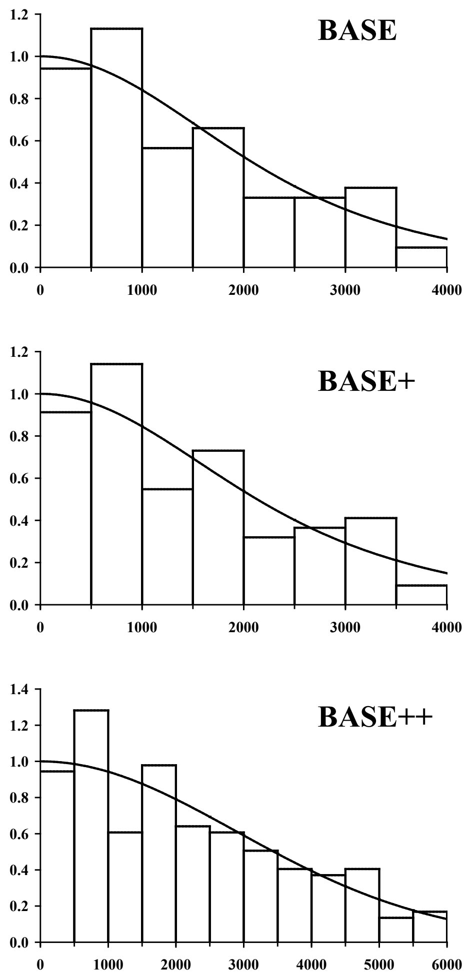

Fig. 2. *Detection functions for the base, base+ and base++ analyses. Distances in meters.*

tween the potential for positive bias through inclusion of uncertain sightings, and negative bias through their exclusion. The problem of uncertain species identification could be addressed by closing on a larger proportion of sightings, or perhaps by using very high-powered binoculars as aids. However these measures would be costly in terms of ship time and observer effort, and this analysis suggests that such effort may not be worthwhile in terms of increased precision or accuracy of the resulting estimates.

The estimates reported here have a negative bias because they are not corrected for a) visible whales that were missed by observers (perception bias), and b) whales that were diving and not visible to the observers (availability bias). Double platform data to correct for perception bias was collected in 2001 but too few trials for blue whales were available to estimate perception bias. Pike *et al.* (MS 2006) found that perception bias was very small for fin whales in NASS 2001, and we would expect the same to be true for blue whales. Perception bias may also have varied between surveys but we have no way to assess this. Assessment of availability bias requires information on the proportion of time the animals spend at the surface visible to observers. These data are not available for blue whales in this area. However, we would expect this bias to be relatively small, as blue whales are not a long-diving species (Croll *et al.* 2001) and they are visible from a great distance. Therefore they are available for sighting within the search area of the observers for a relatively long time as the survey vessel passes.

Blue whales were not the target species of the NASS, and the surveys were not optimised to obtain precise estimates for the species. Better estimates could be obtained in future surveys by stratifying such that effort was concentrated in areas where blue whales are most common, especially to the west of Iceland. Alternatively, a model based analysis might produce more precise estimates from the present data (*e.g.* Paxton *et al.* 2009), although the reliability of the variance estimates from this type of analysis is questionable. An approach using mark recapture techniques, possibly through photo-ID and/ or biopsy sampling (Smith *et al.* 1999), might also be effective for this species. This has been attempted in the Western Atlantic, but it was concluded that the whales in this area did not constitute a closed population and that their distribution varied between years, violating the assumptions of mark-recapture models (Hammond *et al.* 1990). Such a programme would require sampling in all summering areas and probably in the breeding areas as well, as has been done for humpback whales (*Megaptera novaeangliae*) in the North Atlantic (Smith *et al.* 1999).

Blue whales were concentrated off western Iceland in most years, mainly on or just off the Icelandic shelf (Fig. 1). Blue whales are known to occur regularly off the Snæfellsnes peninsula in western Iceland and support a whale watching

Table 3. Rate of increase (*R*) for blue whales.

REGION	*R*	cv	95% CI L	95% CI R
NE	0.13	0.434	0.03	0.25
WEST	0.04	0.982	-0.03	0.11
TOTAL	0.09	0.397	0.02	0.17
TOTAL+	0.08	0.456	0.01	0.16
TOTAL++	0.09	0.310	0.03	0.14

enterprise in the area. Whales were seen farther offshore in 2001 but there was little effort on the shelf in that year. Nine sightings of blue whales were recorded on the shelf off western Iceland in the aerial survey that occurred concurrently with the ship survey in 2001 (Pike *et al.* 2009b). It is therefore likely that a major part of the blue whale concentration was missed by the ship survey in 2001. A secondary concentration of blue whale sightings occurred northeast of Iceland in most surveys. Blue whales sightings were not recorded in surveyed areas off the British Isles, around the Faroe Islands, off Norway and in the eastern Barents Sea, indicating that densities are extremely low in these areas.

There were no significant differences between any of the estimates, however abundance was lowest in 1987 and highest in 1995. For the reasons mentioned above we consider the 2001 estimate to be negatively biased because the main part of the blue whale concentration off western Iceland was likely missed during the survey. Therefore, our best and most recent estimate of blue whale abundance comes from the 1995 survey (979, 95% CI 137-2,542). Gunnlaugsson and Sigurjónsson (1990) reported an estimate of 442 blue whales (no cv given) from NASS-1987, and Sigurjónsson and Víkingsson (1997) reported an estimate of 878 (no cv given) blue whales from NASS-1989. Both these estimates used an assumed esw of 1 nm, which is similar to that estimated here. Unsurprisingly our estimates for 1987 and 1989 are similar to those previously reported, but ours are estimated using standard methods and give an estimate of uncertainty.

Mean annual rate of increase (R) was strongly positive in all regions, and significantly so in the NORTHEAST region and the total survey area. Sigurjónsson and Gunnlaugsson (1990) reported that the sighting rate of blue whales off western Iceland was increasing at a rate of 5.2% (cv 0.22) per year between 1969 and 1988 based on observations onboard whaling vessels. This is very similar to the point estimate of R we detect for the WEST region (4%), which includes the former whaling grounds of western Iceland. Estimation of R would be affected by differences in bias between surveys. Given that we consider the 2001 survey estimate to be negatively biased because of lack of coverage of an area of known blue whale concentration off west Iceland, our estimates for R may be conservative. Taken together with the findings of Sigurjónsson and Gunnlaugsson (1990), our results suggest that the blue whale population around Iceland is recovering.

The stock structure of blue whales in the North Atlantic is almost completely unknown. It has been suggested that there are 2 stocks, one in the east and one in the west (Ingebrigtsen 1929, Gambell 1979). Satellite tracking of a single blue whale during 26. July – 16 August 1999 showed a south-westerly movement of around 1,500 km towards the Denmark Strait indicative of a migration route between Iceland and West Greenland (Heide-Jørgensen *et al.* 2001). A comparison of an Icelandic photo-id catalogue of 89 blue whales with a Canadian east coast collection of nearly 400 animals and 24 blue whales from the Azores has not revealed any movements between these areas. Recently, the first long-range photographic match was made for blue whales in the North Atlantic. This was an animal photographed off Mauritania in 2005, that had previously been photographed off Iceland some 5,200 km away (Sears *et al.* 2005).

Blue whales are usually present in northern areas only during the summer months. The differential timing of depletions of feeding stocks off Norway, Iceland and the western Atlantic does suggest that discrete feeding aggregations exist, with limited mixing between areas.

Blue whales were heavily hunted in all areas of the North Atlantic in the late 19th and early 20th century. Modern whaling began off north Norway in the 1860's and initially concentrated nearly exclusively on blue whales (Tønnessen and Johnsen 1982). Whaling subsequently spread to other areas including Iceland, the Faroes, the Shetland Islands, the Hebrides, Ireland, Bear Island and Svalbard. In all cases the outcome was the same, with whalers initially taking blue whales, then switching to other species as they became depleted. Blue whale catches peaked in north Norway around 1880 and again in 1904 when whaling was banned temporarily, by which time about 3,500 blue whales had been taken (Rørvik and Jonsgård 1981, Christensen *et al.* 1992). It appears that this take was sufficient to heavily deplete the stock, as whalers had for the most part switched to fin whales by the end of this period (Ingebrigtsen 1929). Indeed, when whaling resumed off Norway in 1918, of 1,764 whales taken between 1918 and 1920, only 3 were blue whales. Blue whales were taken in Norway and other locations in the Northeast Atlantic after 1904 and until they were protected in 1955. A total of 1,405 blue whales were taken in areas other than Svalbard during this period, in addition to 98 taken in the Faroes between 1894 and 1903 (Bloch and Allison MS 2006). A total of 2,180 whales were taken near Svalbard in the period 1903 – 1914, of which more than 973 were certainly blue whales (Tønnessen and Johnsen 1982). Therefore the total take of blue whales after 1904 certainly exceeded 2,378 whales. This continued hunting may have prevented the stock from recovering. Our surveys suggest that blue whales continue to be very rare in the Northeast, where they were once common, particularly in the area around Svalbard and along the coast of northern Norway.

A similar pattern was observed in Iceland, with only relatively less devastating effects. Modern whaling there began in 1883 and ended temporarily in 1915 when whaling was banned. Over this period the catch totalled about 6,000 blue whales (Sigurjónsson and Gunnlaugsson 1990). Subsequently fewer than 200 blue whales were taken off Iceland before the species was protected there in 1959. Given that substantial numbers of fin whales were taken in the same period by whalers who would have taken blue whales given the opportunity, it seems clear that the species was heavily depleted. Results from the NASS series as well as systematic observations collected from whalers (Sigurjónsson and Gunnlaugsson 1990) indicate that the blue whale stock off western Iceland has recovered somewhat since whaling for this species ceased. However, it appears that a large proportion of the historical catch of blue whales was taken off eastern and northern Iceland, especially in coastal waters, areas where they are seldom encountered today (Sigurjónsson and Gunnlaugsson MS 2006). Blue whales may have changed their distribution pattern, or the stock component that previously occupied these areas may not have recovered from overharvesting.

The only other areas where blue whales occur in significant numbers during the summer in the North Atlantic are off eastern Canada and in the Gulf of St Lawrence, and off West Greenland (COSEWIC 2002). Numbers off eastern Canada appear to be in the low hundreds (COSEWIC 2002). Estimates for West Greenland are not available but densities must be very low given the low number of sightings from recent aerial (Larsen *et al.* 1989, Larsen 1995) and ship (Heide-Jørgensen *et al.* MS 2006) surveys. The concentration of blue whales around Iceland is therefore likely the largest remaining in the North Atlantic and therefore central to the recovery of this species.

We conclude that the results from the NASS are consistent with a population of blue whales in the Central and Northeast Atlantic numbering probably around 1,000 animals, based on the 1995 and 2001 surveys. Blue whale distribution is centred off west Iceland with lesser concentrations between Iceland and Jan Mayen. Very few blue whales occur off East Iceland, the Faroes or in the Northeast Atlantic, areas where they were abundant before modern whaling began. There is evidence that the numbers of blue whales around Iceland are increasing.

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