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ESTIMATES OF THE ABUNDANCE OF CETACEANS IN THE CENTRAL NORTH ATLANTIC BASED ON THE NASS ICELANDIC AND FAROESE SHIPBOARD SURVEYS CONDUCTED IN 2015

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ABSTRACT

The North Atlantic Sightings Survey (NASS), the sixth in a series of surveys done between 1987 and 2015, was conducted in June/July 2015 and covered a large area of the northern North Atlantic. The Icelandic and Faroese ship survey component of the NASS covered the area between the Faroe Islands and East Greenland from latitude 52° to 72° N. The survey used 3 vessels and an independent double-platform configuration with each platform staffed by a minimum of 2 observers. Here we present both uncorrected abundance estimates derived using Multiple Covariates Distance Sampling, and corrected abundance estimates derived using Mark-Recapture Distance Sampling, for the following species: fin (*Balaenoptera physalus*), common minke (*B. acutorstrata*), humpback (*Megaptera novaeangliae*), blue (*B. musculus*), sei (*B. borealis*), sperm (*Physeter macrocephalus*), long-finned pilot (*Globicephala melas*) and northern bottlenose (*Hyperoodon ampullatus*) whales as well as white-beaked (*Lagenorhynchus albirostris*) and white-sided (*L. acutus*) dolphins. We then compare these estimates to those from previous NASS and put them into context with estimates from adjoining areas of the North Atlantic.

Keywords: NASS, North Atlantic, cetaceans, abundance, surveys, Balaenoptera, physalus, musculus, borealis, acutorostrata, Megaptera, Physeter, Globicephala, Hyperoodon, Lagenorhynchus

INTRODUCTION

The North Atlantic Sightings Survey (NASS) was conducted in June/July 2015 and covered a large area of the northern North Atlantic (Figure 1). This was the sixth in a series of major North Atlantic cetacean surveys conducted previously in 1987, 1989, 1995, 2001 and 2007 (Pike, 2009; Pike, Gunnlaugsson, Mikkelsen, & Víkingsson, 2019b; Pike, Gunnlaugsson, Víkingsson & Sigurjónsson, 2019c). The main target species of the surveys have been fin (*Balaenoptera physalus*), common minke (*B. acutorstrata*), long-finned pilot (*Globicephala melas*) (Faroe Islands) and sei (*B. borealis*) (Iceland, 1989) whales. However, all species encountered are registered and abundance estimation is feasible for those that occur in sufficient numbers. These other species include, in most years, humpback (*Megaptera novaeangliae*), blue (*B. musculus*), sperm (*Physeter macrocephalus*) and Northern bottlenose (*Hyperoodon ampullatus*) whales as well as systematic white-beaked (*Lagenorhynchus albirostris)* and white-sided (*L. acutus*) dolphins. Abundance estimates for the above species other than *Lagenorhynchus* spp. dolphins have been published for most surveys prior to 2007 (citations in Discussion).

The NASS have several objectives. The initial surveys provided the first systematic data on distribution and abundance of cetaceans in these waters. In addition to academic interest such data are necessary to manage anthropogenic takes of several species of cetaceans. These include direct takes (whaling) and incidental mortality from bycatch, ship strikes and other human activities.

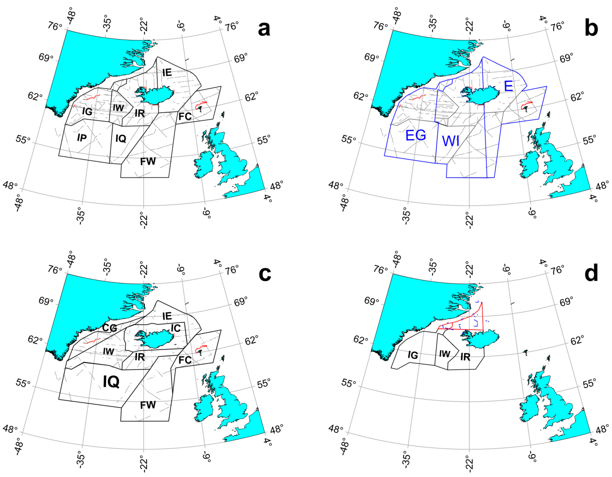

Figure 1. Stratification and realized effort at BSS<6 (a.) and regions used for the fin whale estimate (b.); post-stratification used for minke whales, with realized survey effort at BSS<4 (c.) and realized effort (BSS<6) in the fall capelin survey (d). Compromised transects are red.

The surveys are also necessary for evaluation of the ecological role of cetaceans in the North Atlantic and development

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towards the future goal of ecosystem management of fisheries and other marine resources. As a series now stretching over 3 decades, the NASS data have become invaluable as a tool to monitor changes in distribution and abundance that might be due to environmental changes, such as climate change, or other human activities such as fishing, shipping or whale watching.

Many species of large and medium sized whales in the North Atlantic were sought by whaling operations dating at least as far back as around CE 1000. However, most of the fast swimming rorquals could not be targeted until after 1860 when the development of explosive harpoons and steam driven vessels marked the onset of the so-called modern whaling era. The general pattern of whaling operations has in the past been the initial exploitation of an area with high catches, followed by the rapid depletion of stocks leading to an eventual cessation of commercial operations as they became unprofitable (Ingebrigtsen, 1929). This pattern is well illustrated by the example of the North Atlantic humpback whale. Pelagic and shore-based whaling for humpback whales was conducted in several areas of the North Atlantic, including Iceland, Norway, the Faroe Islands, Eastern North America and Greenland, the Caribbean and Cape Verde Islands, resulting in the catch of approximately 30,000 between 1880 and 1940, by which time the population was severely depleted (Smith & Reeves, 2011). While aboriginal whaling continued off West Greenland (Greenland, 2012) and in the West Indies (Adams, 1971; IWC, 2015), the relatively low levels of catch allowed the stock to recover to levels which may equal or even exceed the estimated pre-whaling numbers (Punt, Friday, & Smith, 2006). A similar trajectory has been documented for fin whales (Pike et al., 2005; Víkingsson et al., 2009, 2015). A similar pattern of decline was likely followed by blue whales; however, their recovery is less well documented and appears to be slower (Sigurjónsson and Gunnlaugsson, 1990). Common minke whales were not as seriously affected by whaling activities in the Central North Atlantic as the larger balaenopterids and are at present close to the estimated pre-exploitation level (NAMMCO, 2017).

While commercial whaling has declined in recent decades, it continues at a relatively small scale in Norway for common minke whales and in Iceland, where no commercial whaling occurred from 1986 to 2005, for common minke and fin whales. Whaling also continues in Greenland for common minke, fin, humpback, bowhead (*Balaena mysticetus*) and long-finned pilot whales, as well as narwhal (*Monodon monoceros*), beluga (*Delphinapterus leucas*), killer whales (*Orcinus orca*), harbour porpoises (*Phocoena phocoena*) and white-beaked dolphins, and in the Caribbean for humpback whales, short-finned pilot whales (*G. macrorhynchus*) and several species of delphinids (Robards & Reeves, 2011). Long-finned pilot whales, Atlantic white-sided dolphins and occasionally bottlenose dolphins (*Tursiops truncatus*) are taken in drive hunts in the Faroe Islands. Therefore, periodic estimates of abundance are required for stock management purposes and to meet the requirements of international management regimes under the International Whaling Commission (IWC) and the North Atlantic Marine Mammal Commission (NAMMCO).

Here we present design-based abundance estimates for fin, common minke, humpback, blue, sei, sperm, long-finned pilot and northern bottlenose whales as well as white-beaked and white-sided dolphins from the Icelandic and Faroese components of the NASS-2015 ship survey. We also present information from a platform-of-opportunity survey conducted later in the same year, in order to assess seasonal changes in distribution and abundance. Where feasible these estimates are corrected for visible whales missed by observers. We also attempt to put these new estimates in the context of those from previous NASS and other surveys in adjoining areas of the North Atlantic.

MATERIALS AND METHODS

Survey design summer 2015

Vessels

Three vessels were used in the survey. Two of these (vessels B and H) were dedicated and sailed a transect design specific to the cetacean survey. One (vessel A) was a fishery research vessel conducting redfish (*Sebastes* spp.), mackerel (*Scomber scombrus*) and oceanographic surveys coincident with the cetacean survey, following a survey and transect design specific to these surveys. The research vessel steamed day and night, largely independent of weather conditions, with cetacean survey being conducted during daylight hours when conditions were acceptable (see below). This vessel covered strata IG and IW (Figure 1) coincident with the redfish survey from 10-29 June, then blocks IR, IE and additional parts of IG and IW from 7 July to 10 August coincident with the mackerel survey. The dedicated vessels surveyed the areas south and north of the fisheries survey area with some overlap during transit, and due to last minute changes when the mackerel survey effort was extended to the South. Vessel B covered mainly strata IP and IQ, with some effort in the western and northern parts of stratum IG and IR. Vessel H covered the Faroese strata FC and FW.

Transect design

Transects for strata FC, FW, IP and the northern part of IR, which were covered by dedicated cetacean survey vessels, were designed using the program DISTANCE 6.2 (Thomas et al., 2010) (Figure 1). In these blocks a double set of equal-spaced zig-zag transects, starting from a random point along the design axis, was applied. In the triangular eastern part of the southern area (IQ), where a zig-zag design would have resulted in uneven coverage, parallel lines (parallel to the eastern boundary) were used. These lines started in the south at the random points where the designed tracks in IP intersected the boundary between these blocks.

The remaining areas were covered by vessel A while also conducting the fish surveys. The redfish survey tracks were designed by the ICES Redfish group and the mackerel survey tracks by the ICES Working Group of International Pelagic Surveys in consulation with the cetacean survey planning group.

Post-stratification

In addition to stratum and total abundance estimates, regional estimates were required for population modelling purposes for fin and minke whales, each of which includes a combination of the original strata (Figure 1). For fin whales, these included combined estimates east and west of 18° W, which required the division of stratum FW into W (FW_W) and E (FW_E) sections (Figure 1). Transects which crossed the dividing line were split and renamed. Separate estimates were performed using the original and post-stratified blocks.

For minke whales the designed strata were post-stratified so that block boundaries aligned with stock divisions recognized by the IWC (Donovan, 1991), and also to correspond with realized effort (Figure 1). This necessitated:

1. Adjustment of the boundaries of IC to correspond to stock area CIC (and also the aerial survey area, see Pike et al. (2019c);
2. Dividing the western parts of blocks IW and IN to make a new stratum corresponding to the CG stock area. The western boundary of this new block CG corresponds roughly to the East Greenland ice edge; and
3. Adjustment of the boundary between FC and FW to correspond with the western boundary of stock areas EW and EN.

For other species, the originally planned strata (Figure 1) were used to estimate abundance.

Field methodology

Independent double platforms were used on all vessels and identical equipment and procedures were used on each platform. On the 2 Icelandic vessels, there were upper and lower platforms with eye height in meters of about 18.6/15.3 on vessel A and about 16.3/10.3 on vessel B. On the Faroese vessel H the 2 platforms were placed side by side with an eye height of about 12.3 m (Figure 2). The platforms did not communicate while on effort and were acoustically and visually isolated. A minimum of 2 observers staffed each platform at all times, and the same observer teams always worked together on shifts. Binoculars were generally in use by at least 1 observer on a platform when conditions were good enough and were used for species identification and to estimate distance using reticle readings when possible. “Distance Sticks” (rulers) were used for distance estimation at closer range, measuring the length between the sighting and the horizon line with the stick held at a set distance from the user’s eyes. Lateral angle from the bow of the vessel to the sighting was estimated using fixed angle boards.

Figure 2. Survey vessel showing side-by side independent observing platforms used during the NASS 2015 Faroese survey. Photo credit: Natural History Museum, Faroe Islands.

Searching was usually abandoned in poor visibility, in Beaufort Sea state (BSS) 6 or more, or when visibility from the vessel was 1 nautical mile (nm) or less. However, due to time constraints, searching was sometimes continued when wind or fog may have influenced the probability of detecting even the large whale species.

If identification and/or group size was uncertain, the platforms on the dedicated vessels could, when abeam, communicate and, at the discretion of the cruise leader, slow, stop or turn to close on a sighting, afterwards returning at 45° into the track while off-effort. Otherwise the survey was done in passing mode. Data were recorded on time stamped digital voice recorders (or paper) and transcribed during rest hours.

Fall 2015 survey

In addition to the summer survey described above, 4 observers were placed on vessel A while conducting a capelin (*Mallotus villosus*) survey to the NW of Iceland from 16 September to 4 October (Figure 3). Field methodology was identical to that described above except that only 1 team of observers was available for each platform and effort hours were limited by this and the shorter day length.

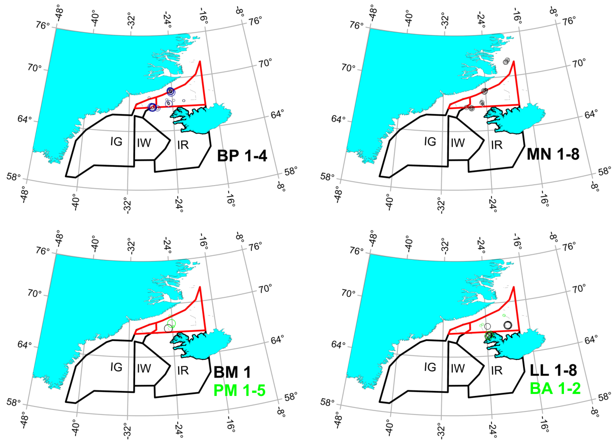

Figure 3. Sightings of cetaceans in the fall capelin survey. Symbol size is proportional to group size range indicated on the panels. Overlap between the summer and fall surveys is outlined in red. BP – fin whale; MN – humpback whale; BM – blue whale; PM – sperm whale; LL – white-beaked dolphin; BA – common minke whale.

Data treatment

Transect revision

In strata covered by the combined cetacean/fisheries research vessel, some cetacean survey effort was maintained while ferrying between transects, resulting in some transects that paralleled the Iceland or Greenland coasts (Figure 1). As these transects are not perpendicular to expected gradients in whale density related to water depth and the shelf break that have been observed in previous surveys, their inclusion could result in positively biased estimates. Sightings from these “compromised” transects were therefore not used to estimate abundance for species other than for *L.* spp. dolphins and common minke whales, for which they were incorporated into the detection function to increase the sample size, but not used to estimate encounter rate or group size.

Species identity

For many sightings there was uncertainty in species identification. Sightings were categorized by the observers according to the degree of confidence in species identification as High, Medium or Low. For those species for which sufficient sightings were available (fin and sperm whales), we assessed the sensitivity of abundance to identification confidence by calculating separate estimates using: 1) sightings for all 3 confidence levels, the “ALL” estimate; and 2) Sightings for the high and medium confidence categories, the “MED” estimate. For other species only the ALL estimate is presented.

Beaufort Sea state

Wind speed meters (m/s) were used on the Icelandic vessels (broken for the first half on vessel B), while BSS was estimated by the shift leader on the Faroese vessel. Wind speed was transformed into BSS for analysis. Only data recorded in BSS≤5 were used in the analyses for large (fin, blue, sei and sperm) whales, resulting in a 5% reduction in effort, while data recorded at BSS≤3were used for common minke whales and dolphins. resulting in a 34% reduction in effort. Data recorded in BSS≤4 was used in analyses for long-finned pilot whales in conformity with previous work on this species (Pike et al, 2019a), resulting in a 24% reduction in realized effort.

Duplicate identification

On the dedicated vessels (B and H) in cases where the vessel closed on sightings after coming abeam, duplicates were determined during the closing. Otherwise duplicates were identified later in the day or post-survey by 1) similarity of sighting location taking into account the time interval between the sightings; and 2) similarity of species identification, group size, cue type and whale heading. Large whale sightings were generally classified as non-duplicates if they differed by 10° or more in angle to track when seen within a short interval by the platforms, or the distance between sighting spots was estimated to be over a mile when different dive cycles were observed over several minutes.

Platform selection

The analytical procedure used required that all information about a sighting seen by both platforms (*i.e.* angle, radial distance, group size, species identification and covariates such as BSS) be the same. In these cases what were considered to be the most reliable measurements were used, such as where one platform had higher confidence in species identification or noted more cues. All else being equal, data from the higher platform were used.

Record selection

Some groups were sighted multiple times by the same platform, and for these several records were available. Only records where the sighting had been identified to species were considered. For duplicate sightings, the record of duplication, or the record closest to that by the other platform was chosen for the estimates of radial distance and angle. For non-duplicates generally the last record before abeam was considered most reliable, as the inclination angle is larger and results not as sensitive to small angles to the track line.

<u>Analysis</u>

Combined platform estimates

Density and abundance were estimated using stratified line transect methods (Buckland et al., 2001) using the DISTANCE 6.2 (Thomas et al., 2010) software package. The perpendicular distance data were truncated such that 10-15% of the greatest distances were discarded.

The Hazard Rate and Half Normal models for the detection function were initially tested, and the final model was chosen by minimization of Akaike's information criterion (AIC) (Buckland et al., 2001). Covariates were considered for inclusion in the model to improve precision and reduce bias. Covariates were assumed to affect the scale rather than the shape of the detection function, and were incorporated into the detection function through the scale parameter in the key function (Thomas et al., 2010). Covariates were retained only if the resultant AIC value was lower than that for the model without the covariate. The following covariates were considered: vessel identity, BSS, cloud cover (scale 1=0%-24%, 2=25%-69%; 3=70%-89%; 4=>90%), visibility (nm), species identification confidence, group size, vessel platform making the sighting (vessel identity combined with: 1=lower on Icelandic vessels, starboard on Faroese vessel, 2=upper or port, 3=both, *i.e.* duplicate sighting), and the observation team on the platforms (1 code for both platforms). In cases where covariates were included, the detection function was estimated at the stratum level and could therefore vary in scale by stratum depending on covariate levels. Stratum and total variance was estimated using the method of Innes et al. (2002).

A high proportion of sightings of dolphins of genus *Lagenorhynchus* were not identified to species, and insufficient numbers of each were identified to species to estimate density separately. A combined detection function including species identity (white-beaked, white-sided, or uncertain) as a covariate in addition to testing those described above was therefore used. The abundance of uncertain dolphins was assigned to species using the proportions of certain identifications of each species by stratum.

Double platform analyses

Only effort that was conducted in full double platform mode was retained for these analyses, which resulted in a small (0.3%) reduction in available survey effort.

Density and abundance were estimated using stratified mark-recapture distance sampling (MRDS) techniques (Laake & Borchers, 2004) using the DISTANCE 6.2 (Thomas et al., 2010) software package. As the platforms were completely independent from one another and did not communicate (except on the dedicated vessels during closings, see above), the “independent observer” (IO) analysis mode was specified. In this mode, the platforms are considered to be equivalent and either platform can “mark” a sighting for the other. We initially attempted 2 types of analyses: using the assumption of “full independence” (FI) wherein sightings from the platforms are considered independent at all perpendicular distances, and under the assumption of “point independence” (PI), wherein sightings from the platforms are considered independent only on the trackline (Laake & Borchers, 2004). The AIC values resulting from both approaches were compared before deciding on a final model. The assumption of point independence requires the estimation of 2 detection functions: one for combined platform (*i.e.* unique) detections, and the other for single platform detections conditional on detection by the other platform (conditional detection function), whereas the assumption of full independence requires only the latter detection function.

The detection function for the combined platforms was modelled as described in the previous section. The conditional detection function was implemented as a logistical model with most of the same covariates (but not the vessel platform making the sighting, as this includes the response variable) available for the combined platform detection function. Again, the final model was chosen by minimization of AIC.

RESULTS

Survey effort

Realized survey effort is summarized in Table 1 and Figure 1. As is usual for this area, weather conditions reduced realized survey effort relative to planned effort considerably. Restriction to effort conducted at BSS≤3, required for estimates for common minke and northern bottlenose whales and dolphins, reduced total available effort by 34%, but this reduction was not evenly spread among strata. The Icelandic survey blocks suffered a reduction of 47% while effort in the Faroese blocks FC and FW was reduced by only 3%. Available effort was particularly sparse in blocks IC, IE and IQ. As expected, the non-dedicated survey vessel, which continued fish survey operations during periods of inclement weather, showed the greatest reduction in realized effort.

Survey effort during the fall survey was severely hampered due to persistent bad weather and short daylight hours (Figure 1).

Table 1. Stratification and survey effort at 2 levels of Beaufort sea state (BSS) for the base stratification (above) and minke whale post-stratification (below). K = number of transects. Block SW is effort outside the survey area, and block X is transit effort within other strata that is not used to estimate encounter rate. Effort is also shown for the fall survey. TOT-F and TOT-I: Tptal effort of the Faroese (H) and Icelandic (A and B) vessels, respectively.

BLOCK	AREA (nm^2)	EFFORT (NM)		K
		BSS<6	BSS<4	
FC	77,857	979	681	5
FW	176,905	1,666	908	9
IE	108,052	922	371	17
IG	93,953	1,710	958	30
IP	139,248	874	390	5
IQ	70,131	372	137	3
IR	108,550	1,323	894	22
IW	37,905	979	675	15
SW	0	118	118	1
X	0	407	303	11
TOT-F	**254,762**	**2,645**	**1,589**	**15**
TOT-I	**557,840**	**6,299**	**3,543**	**103**
TOT	**812,602**	**9,351**	**5,436**	**129**
CG	46,347		756	19
FC	84,816		735	9
FW	170,629		843	9
IC	85,700		410	15
IE	71,325		354	11
IQ	208,126		524	7
IR	52,594		423	6
IW	92,929		949	21
SW	0		118	1
X	0		281	11
TOT-F	**255,445**		**1,578**	**19**
TOT-I	**557,021**		**3,534**	**90**
TOT	**812,466**		**5,393**	**109**
FALL SURVEY	**NA**	**348**	**188**	**NA**

Distribution and abundance

Cetacean sightings are illustrated in Table 2 and Figure 4, and in Figure 3 for the fall survey.

Specifications of the models used in estimating abundance are provided in Table 3 and are described by species below. PI models produced lower values of AIC than FI models for all species, therefore PI models were used in all cases. Stratified abundance estimates for all species are detailed in the Supplementary files.

Fin whale

As in previous surveys, the fin whale was the most commonly sighted species, with over 600 groups sighted. Fin whales were most commonly sighted to the west of Iceland in blocks IW and IG. Unlike in previous surveys, substantial numbers were sighted in the Faroese strata FC and FW. In contrast, very few fin whales were sighted to the east of Iceland in block IE. Sightings of single animals were most common but groups of up to 7 animals were seen. Fin (along with humpback) whales were the most commonly sighted species in the fall survey.

The perpendicular distance distribution was right-truncated at 2,700 m (Figure 5). The half-normal model provided the best fit to the data for both the ALL and MED species certainty classifications. The factor covariate VESSPLATSIGHT, which is the identity of the vessel platform which made the sighting, improved model fit in both cases and was by far the most influential covariate. Vessel A had a wider strip width than the other 2 vessels. For all vessels, duplicate sightings had a narrower strip width than non-duplicates. There was little difference between the strip widths for the upper and lower platforms on vessels A and B, but the port platform made more sightings and had a wider strip width on vessel H. The covariates VISIBILITY, CLOUD and SPECIES_CERTAINTY had less effect but did improve model fit.

Mean school size varied significantly between strata so stratum specific estimates were used. Expected school size (E(*s*)) was higher (not significantly so) in the Faroese strata (FC and FW) and blocks IG and IW than in other areas (Supplementary file 1).

Specifications for the ALL abundance estimate is provided in Supplementary file 1. Restriction to the MED species certainty classification resulted in a loss of 11% of sightings and a reduction in overall abundance of 10%.

The total uncorrected estimate for the survey area using all fin whale sightings (Supplementary file 1) was 31,953 (CV=0.17, 95% CI 22,536 – 45,306). Fin whale density was highest in blocks IG and IW west of Iceland, and lowest in block IE to the east of Iceland.

Table 2. Sightings of cetaceans by stratum. Strata used for minke whales are shaded. BP = fin whale, BA=common minke whale; MN = humpback whale, BM = blue whale, BB=sei whale; PM = sperm whale, GM=long-finned pilot whale; HA=northern bottlenose whale; LL = white-beaked dolphin, LC = white-sided dolphin, L? = unidentified Lagenorhynchus dolphin. Number of ? indicates least level of confidence in species identification included in the sum, i.e ? = high + medium, ?? = high + medium + low.

BLOCK		BP		BA	MN	BM	BB		PM		GM	HA	LL	LC	L
		BP?	BP??	BA??	MN??	BM??	BB?	BB??	PM?	PM??	GM??	HA??	LL??	LC?	L?
FC	CG	24	36	18	5		0	0	9	9	37	33	0	4	0
FW	FC	58	69	32	9	3	2	3	44	45	25	6	0	9	0
IE	FW	8	8	10	7	1	0	0	0	5	20	0	1	0	0
IG	IC	237	250	20	21	17	12	12	23	23	16	2	4	2	5
IP	IE	23	27	7	0	2	16	19	9	10	8	0	3	1	1
IQ	IQ	4	6	0	0		0	0	0	0	0	0	1	0	0
IR	IR	44	47	2	59	16	0	0	8	10	25	3	13	0	13
IW	IW	128	150	8	4	6	3	3	16	18	30	4	5	0	0
SW	SW	4	4	0	0	1	0	0	9	10	5	0		0	0
X	X	33	36	37	1	1	2	2	4	5	28	5	2	4	3
TOT-F	**TOT-F**	**82**	**105**	**42**	**14**	**3**	**2**	**3**	**53**	**54**	**62**	**39**	**0**	**13**	**0**
TOT-I	**TOT-I**	**445**	**489**	**55**	**91**	**43**	**31**	**34**	**65**	**76**	**104**	**9**	**27**	**3**	**19**
TOT	**TOT**	**560**	**630**	**134**	**106**	**47**	**35**	**39**	**122**	**135**	**194**	**53**	**29**	**20**	**22**

Table 3. Model specifications for abundance estimates. Species definitions are given in Table 2. DS Model – Distance model; MR Model – Mark recapture model. PI – point independence; HN – half-normal; HZ – hazard rate; Covariate definitions: DIST – perpendicular distance; VESSPLATSIGHT – vessel platform which made the sighting; VISIBILITY – approximate visibility in km; CLOUD – proportional cloud cover; VESSOBS – vessel observing team making the sighting; SPECIES CERT – species identification certainty, 3 levels; BSS – Beaufort sea state; VESS2 – vessel identity, vessels A and B combined; VESS3 – vessel identity, vessels A and H combined; Adj. – adjunct; Cos - cosine adjunct.

SPECIES	TRUNCATION (m)	DS MODEL		MR MODEL	
		KEY	Covariates/Adj	TYPE	Covariates
BP ?	2,700	HN	*VESSPLATSIGHT* *VISIBILITY*	PI	*DISTxVESSOBS*
BP ??	2,700	HN	*VESSPLATSIGHT* *VISIBILITY* *CLOUD* *SPECIES CERT*	PI	*DISTxVESSOBS*
BP?? Fall	3,000	HN			
BA??	800	HN	*SIZE*	PI	*BSSxVISIBILITY*
MN??	2,500	HN		PI	*DIST+BSS*
MN?? Fall	1,800	HN			
BM?	3,000	HN	Cos	PI	*DIST*
BM??	3,000	HN	Cos	PI	*DIST*
BB??	3,000	HN	*VESS3*	PI	*DIST*
BB?	3,000	HN	*VESS3*	PI	*DIST*
PM??	2,700	HZ	*VESS2*	PI	*DIST+VESS*
PM?	2,700	HZ	*VESS2*	PI	*DIST+VESS*
GM??	2,000	HZ	*BSS*	PI	*DIST+SIZE*
HA??	1,200	HN	*SPECIES CERT*	PI	*DIST*
L?	1,200	HN	*SPECIES*	PI	*DIST*

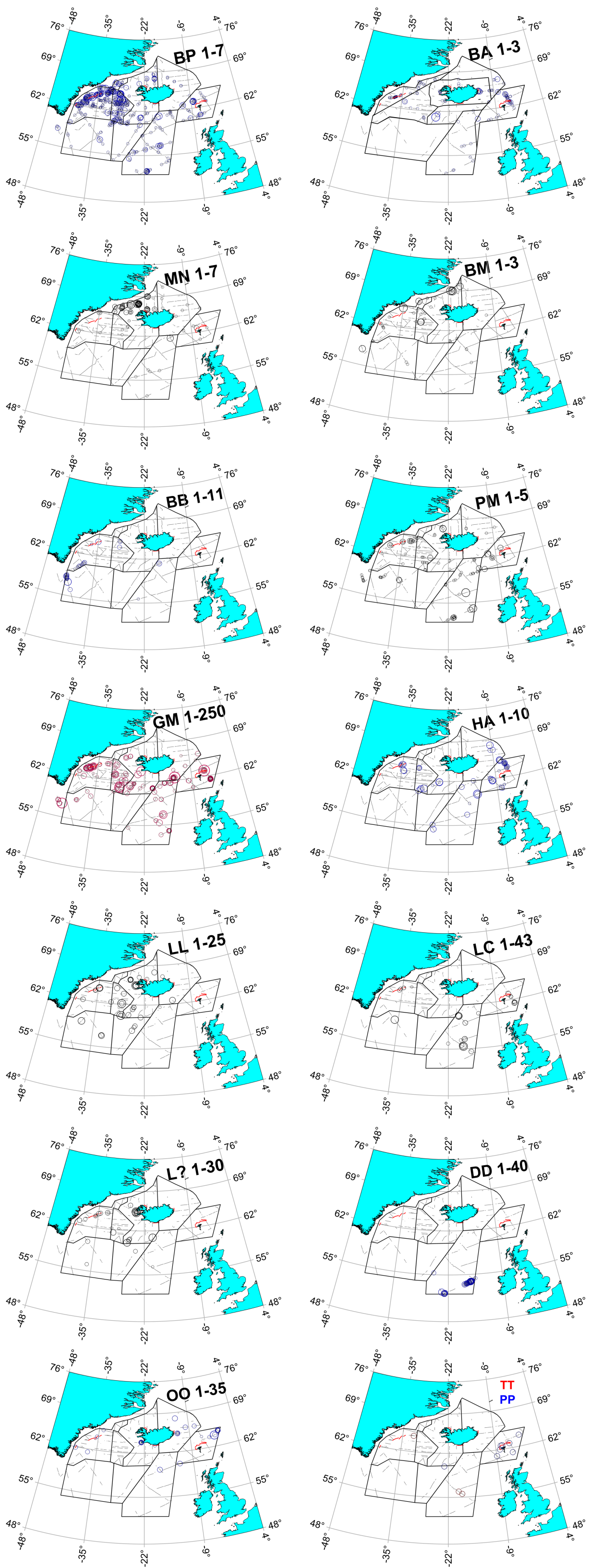

Figure 4. Sightings of cetaceans. Symbol size is proportional to group size indicated on the panels. BP – fin whale;, BA – common minke whale; MN – humpback whale; BM – blue whale; BB – sei whale; PM – sperm whale; GM – long-finned pilot whale; HA – northern bottlenose whale; LL – white-beaked dolphin; LC – white-sided dolphin; L? – unidentified *Lagenorhynchus* spp. dolphin; DD – short-beaked common dolphin; OO – killer whale; TT – common bottlenose dolphin; PP – harbour porpoise.

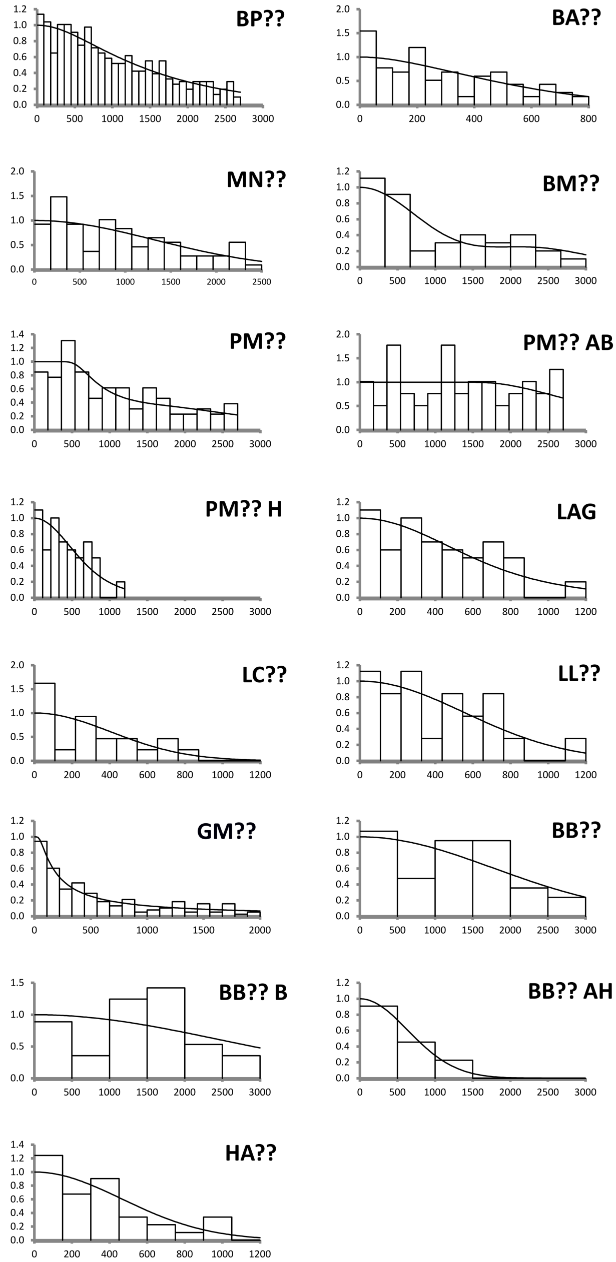

Figure 5. Detection functions. See Table 2 and Figure 2 for species definitions. Vessel codes follow species ID in some cases. LAG – all dolphins of genus *Lagenorhynchus*. Number of ? indicates least level of confidence in species identification included in the detection function, *i.e.* no ? = high, ? = medium, ?? = low.

Corrected estimate

Sightings are specified by vessel and platform in Table 4. On vessel A, the platforms had approximately equal numbers of sightings, and about one third of all sightings were duplicates. On vessel B, platform 1 made 47% more sightings than platform 2, and the proportion of duplicates was slightly lower than that on vessel A. Platform 2 made over twice as many sightings as platform 1 on vessel H, and the proportion of duplicates was lower than on the other 2 vessels. The proportion of duplicates was higher for the higher certainty fin whale identifications on all 3 vessels. Overall the proportion of duplicate sightings was 28% for the ALL species certainty classification.

Table 4. Sightings of cetaceans by vessel and platform at the truncation distance indicated besides the species identification. See Table 2 for species definitions. Platform 1: top on vessels A and B, port on vessel H. Platform 2: lower on vessels A and B and starboard on vessel H. Platform 3: duplicate sightings.

VESSEL	PLATFORM	BP?? 2,700		BA?? 800		MN?? 2,500		BM?? 3,000		PM?? 2,700		BB?? 3,000		GM? 2,000		HA?? 1,200		L 1,200		LL?? 1,200		LC? 1,200	
		NO.	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**	**NO.**	**%**
A	1	75	30	17	41	23	48	9	47	19	39	1	25	34	44	2	40	8	31	2	15	3	60
	2	85	34	18	44	15	31	9	47	15	31	1	25	22	28	3	60	16	62	9	69	2	40
	3	88	35	6	15	10	21	1	5	15	31	2	50	22	28	0	0	2	8	2	15	0	0
	Total	**248**	**100**	**41**	**100**	**48**	**100**	**19**	**100**	**49**	**100**	**4**	**100**	**78**	**100**	**5**	**100**	**26**	**100**	**13**	**100**	**5**	**100**
B	1	63	42	9	50	14	40	7	41	3	43	11	41	10	43	1	14	10	53	4	44	1	100
	2	45	30	5	28	8	23	3	18	0	0	8	30	7	30	2	29	5	26	3	33	0	0
	3	43	28	4	22	13	37	7	41	4	57	8	30	6	26	4	57	4	21	2	22	0	0
	Total	**151**	**100**	**18**	**100**	**35**	**100**	**17**	**100**	**7**	**100**	**27**	**100**	**23**	**100**	**7**	**100**	**19**	**100**	**9**	**100**	**1**	**100**
H	1	25	26	9	38	2	13	0	0	13	25	3	100	25	47	12	50	9	64	0	0	9	64
	2	50	52	14	58	13	87	1	33	35	67	0	0	19	36	10	42	4	29	0	0	4	29
	3	21	22	1	4	0	0	2	67	4	8	0	0	9	17	2	8	1	7	0	0	1	7
	Total	**96**	**100**	**24**	**100**	**15**	**100**	**3**	**100**	**52**	**100**	**3**	**100**	**53**	**100**	**24**	**100**	**14**	**100**	**0**	**0**	**14**	**100**
ALL	1	163	33	35	42	39	40	16	41	35	32	15	44	69	45	15	42	27	46	6	27	13	65
	2	180	36	37	45	36	37	13	33	50	46	9	26	48	31	15	42	25	42	12	55	6	30
	3	152	31	11	13	23	23	10	26	23	21	10	29	37	24	6	17	7	12	4	18	1	5
	Total	**495**	**100**	**83**	**100**	**98**	**100**	**39**	**100**	**108**	**100**	**34**	**100**	**154**	**100**	**36**	**100**	**59**	**100**	**22**	**100**	**20**	**100**

Since nearly all effort was conducted in full double platform mode, the best detection function models from the combined platform analyses were retained in the PI models (Table 3). In all cases, the best conditional model (as indicated by minimum AIC) included the interaction term between perpendicular distance (DIST) and VESSOBS, the identity of the vessel combined with the particular team occupying the platforms. The average combined platform probability of sighting a whale at perpendicular distance 0 ($p(0)$) was 0.87 (CV=0.03) for all fin whale sightings and 0.90 (CV=0.03) for fin whales identified with high and medium confidence. The total corrected estimate for the survey area using all fin whale sightings (Supplementary file 1) was 36,773 (CV=0.17, 95% CI 25,811 – 52,392)

Fall survey

A sufficient number of sightings (45) were made to support density estimation for fin whales. A half-normal model using a truncation distance of 3,000 m was used. Density of fin whales in the area was 0.058 whales nm^{-2}, over 3 times higher than the density in the same area realized in the summer survey (Supplementary file 1).

Common minke whale

Highest numbers of common minke whales were sighted in 2 areas: to the east of Iceland in blocks FC, FW and the eastern part of IC, and off the East Greenland coast in block CG (Table 2, Figure 4). In the latter area, 39% of these sightings were seen on "compromised" transects parallel to the East Greenland coast. No minke whales were seen to the north of Iceland in blocks IC and IE, but effort was very sparse in these areas. No minke whales were sighted SW of Iceland in block IQ. Almost all sightings were of single animals. Nine minke whale sightings were made in the fall survey, and 6 of these were made just off the coast of NW Iceland.

Sightings from compromised transects were included in the detection function, but not to estimate encounter rate or expected cluster size. The distribution of perpendicular distances was peaked within 200 m of the transect (Figure 5), followed by a steep decline to about 1,000 m, followed by a long, low-frequency tail. Fitting this distribution required adjuncts (*i.e.* shape parameters) to the key function which are not recommended in MRDS analyses (Thomas et al., 2010). We therefore chose a more severe truncation than the normally recommended 10-15%, to obviate the need for additional shape parameters. Truncation to 800 m reduced the number of available observations by 28%. The half-normal model with the scale covariate group size provided the best fit to the data.

Abundance estimates by stratum for the combined platforms are shown in Supplementary file 2. Density was highest in blocks FC and IC, and these 2 strata contributed over 60% of the total abundance estimate of 23,407 (CV=0.28, 95% CI 13,035 – 42,032).

Corrected estimate

On vessel A, the platforms had approximately equal numbers of sightings, with 15% of sightings as duplicates (Table 4). On vessels B and H, platform 1 made about twice as many sightings as platform 2, and the proportion of duplicates was 22% on vessel B and 26% on vessel H. Overall the proportion of duplicates on all 3 vessels was 21%.

The best conditional model (as indicated by minimum AIC) included the interaction term between BSS and Visibility in addition to perpendicular distance. The average combined platform probability of sighting a whale at perpendicular distance 0 ($p(0)$) was 0.51 (CV=0.18). The total corrected estimate for the survey area was 42,515 (CV=0.31, 95% CI 22,896 – 78,942).

Fall survey

Only 1 minke whale sighting was made in the overlap area between the summer and fall surveys, as opposed to 8 in the summer survey. Mean encounter rate was 66% higher in the summer than in the fall in the same area.

Humpback whale

As in most previous surveys, humpback whales were most commonly sighted to the north and northwest of Iceland in blocks IW and IG (Table 2, Figure 4). Unlike in previous surveys, substantial numbers were sighted in the Faroese strata FC and FW. In contrast no humpback whales were sighted to the south of Iceland in blocks IR, IQ and IP. Humpback whales occurred most commonly as single animals but rarely larger groups of up to 7 were sighted, particularly in the eastern part of the survey area.

A truncation distance of 2,500 m was found to be suitable (Figure 5), however other truncation distances were tried and results were not sensitive to truncation.

School size ranged from 1 to 7 and varied between strata so stratum-level estimates were used. Expected school size was significantly higher ($P<0.05$) in the Faroese strata (FC and FW) than in the Icelandic blocks which had sightings (Supplementary file 3).

The half-normal model provided the best fit to the data in all cases (Figure 5). No covariates improved the fit of the model and no adjustment terms were required. Total abundance, including all species certainty categories and excluding compromised transects, was 6,643 (95% CI 3,543 – 12,456) (Supplementary file 3). Exclusion of the lowest confidence species identifications resulted in a 4% decrease of this estimate.

Corrected estimate

On both Icelandic vessels (A and B), the lower platform (1) sighted more humpback whales than the upper one (Table 4). The proportion of duplicate sightings was 22% on vessel A and 38% on vessel B. On the Faroese vessel (H), the port platform (2) sighted over 6 times the number of sightings made by platform 1, and no duplicate sightings were identified. Overall 24% of sightings were identified as duplicates

The same distance detection model from the combined platform analysis (see above) was retained in the PI model. The best conditional detection function, as indicated by minimal AIC, included the covariates distance and BSS. Models including vessel identity in the conditional detection function were tested but these had higher AIC and produced implausibly low values for $p(0)$ for the Faroese vessel, and thus extremely high estimates of abundance for the strata it covered. Both distance and BSS were negatively correlated with the probability of sightings being duplicates. The average combined platform probability of sighting a whale at perpendicular distance 0 ($p(0)$) was 0.69 (CV=0.21). The total corrected estimate, using all categories of species certainty and excluding compromised effort, was 9,867 (95% CI 4,854 – 20,058) (Supplementary file 3).

Fall survey

A total of 45 humpback whale sightings were realized, sufficient to support density estimation using a truncation distance of 2,500 m and a half-normal model with no adjuncts or covariates. Mean density for the survey effort was 0.109 whales nm^{-2} with no valid variance, 25% higher than density in the same area realized in the summer survey.

Blue whale

Sightings of blue whales were concentrated to the north and west of the survey area, particularly off the E coast of Greenland (Table 2, Figure 4). Blue whales were uncommonly sighted in the eastern half of the area. Only 1 blue whale was sighted in the fall survey.

The frequency of perpendicular distances showed an initial steep decline then stabilized between 1,000 to 2,500 m (Figure 5). Best fit was achieved with a half-normal function with 1 cosine adjunct, resulting in an effective strip half-width of 1,319 m. A truncation distance of 3,000 m was found to be suitable (Figure 5).

Most sightings (81%) were of single blue whales, and the maximum group size observed was 3. Density and abundance was greatest in block IR which alone accounted for about half of the total estimate of 2,490 (CV=0.36, 95% CI 1,234 – 5,022) (Supplementary file 4). Exclusion of the most uncertain species identifications reduced abundance by 6%.

Corrected estimate

Icelandic vessels A and B made similar numbers of blue whale sightings, but 39% of sightings on vessel B were duplicates while only 4% were duplicates on vessel A. Vessel H accounted for only 3 sightings, 2 of which were duplicates (Table 4).

Best fit was for the conditional detection function was achieved using distance only as a covariate. This resulted in an estimated *p*(0) of 0.83 (CV=0.11). Corrected abundance in the survey area totalled 3,000 (CV=0.40, 95% CI 1,377 – 6,534) (Supplementary file 4).

Fall survey

Only 1 blue whale was observed on the fall capelin survey. Encounter rate was over 6 times greater in the corresponding area in the summer survey.

Sei whale

Sei whales were most commonly sighted to the west of Iceland, especially in blocks IG and IP off southeast Greenland (Table 2, Figure 4). Sightings were concentrated on 2 transects at the western edge of these blocks. None were sighted to the north of Iceland or in the fall survey. Sei whales were usually sighted as solitary animals or pairs, and rarely in groups as large as 8 animals.

Detections of sei whales declined steeply with distance on vessels A and H, but the distribution was relatively flat on vessel B (Figure 5). Best fit was achieved with a half-normal function with a 2-level covariate for vessel identity (A+H and B). Effective strip width was applied at the stratum level and ranged from 795 m to 2,400 m, depending on the vessel that covered the stratum. Density was highest in stratum IP, which accounted for 69% of the total estimated abundance of 3,127 (CV=0.51, 95% CI 964 – 10,142) (Supplementary file 5). Omission of the least certain class of species identification resulted in a loss of 10% of sightings and a reduction in overall abundance of 4%.

Corrected estimate

Of the 34 sei whales sighted within the truncation distance of 3,000 m, 30% were seen by both platforms. However, this varied from 0% on vessel H to 50% on vessel A (Table 4). Best fit of the conditional detection function was realized with a covariate for perpendicular distance, resulting in an estimated average *p*(0) of 0.83 (CV=0.17) and a total estimated abundance of 3,767 (CV=0.54, 95% CI 1,156 – 12,270) (Supplementary file 5). Omission of the least certain class of species identification resulted in a reduction in overall corrected abundance of 6%.

Sperm whale

Sperm whales were found throughout the survey area but were seen in greatest numbers in the Faroese blocks FC and FW (Table 2, Figure 4). They occurred most commonly as single animals but were rarely found in groups of up to 5 in number. Four sightings were made in the fall survey.

The frequency distribution of perpendicular distances to sperm whale sightings was flat out to about 500 m from the trackline and was best modelled using a hazard rate function with the scale covariate for vessel identity adjusted to combine the 2 Icelandic vessels A and B (Figure 5). The detection function for the Icelandic vessels was flat out to 2,000 m from the trackline, while that for vessel H declined steeply from 0 to 1,000 m from the trackline.

Density and abundance were highest in the Faroese blocks FC and FW which together accounted for 79% of the total estimate of 7,257 (CV=0.35, 95% CI 3,461 – 15,215) (Supplementary file 6). Density was also relatively high on transects south of Greenland outside of the survey area (SW in Supplementary file 6), however these sightings did not contribute to the total estimate. Exclusion of the least certain species identifications reduced total abundance by 3%.

Corrected estimate

Of the 76 sightings made by the Icelandic vessels A and B, 29% were duplicates. In contrast, only 6% of the sightings made on vessel H were duplicates (Table 4). Best fit for the conditional detection function was achieved using the covariates distance and vessel identity adjusted to combine vessels A and B. The proportion of sperm whales detected on the trackline (*p*(0)) was estimated to be 0.34 (CV=0.42) for the combined vessels. Corrected abundance for the survey areas was estimated to be 23,166 (CV 0.59, 95% CI 7,699 – 69,709), with 91% of this total accounted for by the Faroese blocks FC and FW (Supplementary file 6).

Fall survey

Only 1 sperm whale was detected in the overlap area between the fall capelin survey and the summer survey. However, encounter rate was nearly the same in the area in the summer and the fall.

Long-finned pilot whale

Long-finned pilot whales were sighted throughout the central and southern parts of the survey area, and were most common in the Faroese blocks FC and FW, and blocks IR and IW southwest of Iceland (Table 2, Figure 4). None were sighted to the north of Iceland. Long-finned pilot whale group sizes ranged most commonly from 1 to 60 but there were a few sightings of large groups of up to 200 animals. All but 1 of these large groups were sighted at a distance greater than 1,000 m from the transect line. No long-finned pilot whale groups were sighted in the fall survey.

The frequency of long-finned pilot whale sightings declined steeply with distance from the transect line, with a long low-frequency tail out to the truncation distance of 2,000 m. Best fit was achieved using a Hazard Rate model with the covariate *BSS* (Figure 5), resulting in effective strip widths of 496 m. Density and abundance were highest in blocks IR and IW to the west of Iceland, and total abundance was 278,153 (CV=0.35, 95% CI 128,948 – 600,002) (Supplementary file 7).

Corrected estimate

Of the 154 sightings made within the truncation distance of 2,000 m, 37 (24%) were seen by both platforms (Table 4). This varied between vessels, with 17% of sightings duplicated on the Faroese vessel H, and 28% on the Icelandic vessels A and B combined. Best fit for the conditional detection function was achieved with covariates for perpendicular distance and group size, the latter of which increased the probability of detection. The proportion of sightings detected on the transect line was estimated as 0.74 (CV=0.09) (Supplementary file 7), and corrected abundance was 344,148 (CV=0.35, 95% CI 162,795 – 727,527) (Supplementary file 7).

Northern bottlenose whale

Northern bottlenose whales were sighted across the survey area mainly between latitudes 60° and 65° N. They were especially common in the Faroese block FC. None were sighted close to Iceland and few were seen in the northern part of the survey area. No northern bottlenose whales were seen in the fall survey. Groups of 1 to 5 animals were most commonly sighted.

Best fit of the detection function was achieved using a half-normal function with no adjuncts and including a scale covariate for species identification certainty, with decreasing certainty widening the *esw* (Figure 5). Effective strip half-width ranged from 500 m to 616 m depending on the proportion of less certainly identified sightings in the stratum (Supplementary file 8). Density in the Faroese stratum FC was much higher than in any other block, and this stratum alone accounted for 57% of the total uncorrected estimate of 18,375 (CV=0.59, 95% CI 5,128 – 65,834)

Corrected estimate

Of the 36 sightings made within the truncation distance of 1,200 m, 17% were sighted by both platforms (Table 4). This varied between vessels, with no duplicate sightings on vessel A, and vessel H, which accounted for 67% of total sightings, having a duplication rate of 8%. The conditional detection function included perpendicular distance only, resulting in an estimated *p*(0) of 0.92 (CV=0.09) and a total corrected estimated abundance of 19,975 (CV=0.06, 95% CI 5,562 – 71,737).

White-beaked and white-sided dolphins

White-beaked and white-sided dolphins are not easily discriminated at sea and a relatively high proportion (31%) of sightings were classified as *Lagenorhynchus* spp. dolphins. White-beaked dolphins were found almost exclusively in the western half of the survey area, most frequently off western Iceland and close to East Greenland. White-sided dolphins were found in the Faroese blocks FC and FW, and less frequently near East Greenland (Table 2, Figure 4). *Lagenorhynchus* spp. dolphins were rarely sighted as single animals, and were more commonly in groups ranging in size from 2 to 43 animals. Eleven groups of white-beaked dolphins in groups ranging in size from 1 to 8 were sighted in the fall survey. Most of these were seen close to the coast of NW Iceland.

The combined detection function for all sightings of *Lagenorhynchus* spp. dolphins used a half-normal key with no adjuncts and a covariate for species identity (Figure 5). Individual detection functions for white-beaked and white-sided dolphins were similar in shape but white-beaked dolphins were detected slightly farther from the trackline than white-sided dolphins.

Sightings of all 3 categories of dolphins (white-beaked, white-sided and *L*. spp.) were recorded in blocks IG and IP, and the proportions of white-sided and white-beaked were used to allocate the abundance of *L*. spp. dolphins to each species (Table 2). In block IR all dolphins which were positively identified were white-beaked, so all *L*. spp. sightings in this block were assigned to this species.

Abundance estimates for each species using the proportional allocation of *L*. spp. are shown in Supplementary files 9 and 10. White-beaked dolphins occurred in all the Icelandic strata but were most abundant in block IR, which accounted for nearly half the total uncorrected estimate of 48,752 (CV=0.31, 95% CI 26,562 – 89,478). This is 27% higher than the estimate using only positive identifications of white-beaked dolphins.

White-sided dolphins occurred in greatest density and abundance in block FW, which accounted for 66% of the total estimate of 40,173 (CV=0.48, 95% CI 15,334 – 105,248). This is 29% higher than the estimate using only positive identifications of white-sided dolphins.

Corrected estimate

The Faroese vessel H had the lowest rate for duplication of *Lagenorhynchus* spp. dolphins, in this case all of white-sided dolphins, of 7%, compared to 14%, mostly for white-beaked dolphins, realized on the combined Icelandic vessels. Best fit for the conditional detection function was achieved using only the covariate perpendicular distance. The proportion of dolphins detected on the trackline (*p*(0)) was estimated as 0.31 (CV=0.55). Total abundance corrected for perception bias was 159,000 (CV=0.63, 95% CI 49,957 – 506,054) for white-beaked dolphins and 131,022 (CV=0.73, 95% CI 35,251 – 486,981) for white-sided dolphins.

Fall survey

Twelve groups of white-beaked dolphins were seen on the fall survey, while no sightings were made in the same area during the summer survey.

Other species

Other species sighted in the survey for which abundance has not been estimated included short-beaked common dolphins (*Delphinus delphis*) (69 sightings), killer whales (37 sightings), harbour porpoises (9 sightings) and common bottlenose dolphins (3 sightings) (Figure 4).

DISCUSSION AND CONCLUSIONS

Potential biases

Coverage

Ice coverage and fog hampered effort in the western and northwestern areas near the East Greenland coast, an area where densities of fin (Víkingsson et al., 2015), minke (Pike et al., 2009a) and humpback (Paxton et al., 2009) whales have been high in some previous surveys. The area closer to the East Greenland coast was covered by a concurrent aerial survey (Hansen et al., 2019). Coverage was also poor, particularly at low Beaufort sea states, around coastal Iceland (Figure 1). This area was to be covered by a concurrent aerial survey (Pike, Gunnlaugsson, & Víkingsson, 2019c), however that survey was unsuccessful due to adverse weather conditions. While poor coverage will not necessarily cause bias, it will make the estimates less precise.

A contiguous area NE of Iceland around Jan Mayen Island was covered simultaneously by a Norwegian vessel (Leonard & Øien 2019a).

Including compromised effort that was aligned with expected density gradients would have increased estimates for some species. We consider this a bias and therefore chose not to include this effort in the final abundance estimates. Sightings on these transects were included in the detection functions for common minke whales and dolphins, however this should not cause a bias as the same observers and field techniques were used as in other areas.

Species identification

In this survey observers recorded 3 levels of confidence in species identification. The proportion of low confidence sightings ranged from 13% for blue whales to 3% for minke whales. While about 4% of sightings of white-beaked dolphins were classified as low confidence, 31% of sightings of dolphins of genus *Lagenorhynchus* (white-beaked or white-sided) were not identified to species.

We chose to include all identification confidence classes in our final abundance estimates, while assessing the sensitivity of the estimates to the exclusion of low confidence identifications in cases where these sightings exceeded 5% of the total (*i.e.* for fin, sei and sperm whales). While it is likely that some of the low confidence sightings were mis-identified and their inclusion could therefore lead to positive bias, it is also likely that some low confidence sightings of similar species were mis-identified, potentially leading to the opposite bias. For example, fin, blue and sei whales occur in the survey area and are easy to confuse at sea. The problem is likely most severe for blue whales, which are outnumbered by more than an order of magnitude by fin whales. It is highly likely that some proportion of low confidence fin whale sightings were actually blue whales, which could lead to a negative bias in the blue whale estimate. While the converse is also true, the potential bias for the fin whale estimate is proportionally less severe.

Bias in distance estimation

Bias in distance measurement can be a serious problem in distance sampling surveys as it leads directly to bias in abundance estimation (Buckland et al., 2001). Pike et al. (2019b) noted that the primary platforms in the 2007 survey underestimated distances by eye to targets by about 10% in trials. Comparison of distances to duplicate sightings by the primary and tracker platforms also suggested a negative bias by the primary platform. In 2007 binoculars were not in regular use for distance estimation on the primary platform. Distance measurement experiments were not conducted during the 2015 survey as the main emphasis was on using binocular reticles for distance estimation and distance estimation was constantly scrutinized by observers comparing their readings and by comparison to re-sightings and distances measured when closing on sightings. Also, distance estimations from the upper platform were prioritized over the lower platforms, other things being equal as mentioned above. Future surveys should incorporate a method of validating a proportion of distance estimations, for example by using an Unmanned Aerial Vehicle to measure some distances.

Earlier NASS which used closing mode frequently used the closing position to estimate radial distance and angle to the track line. The 2015 survey did not use direct closing so this option was not available. Passing mode surveys frequently use the first estimated radial distance and angle, even if the group is seen again later, primarily to eliminate potential bias due to responsive movement (Buckland et al., 2001). The first detected distance is greater and therefore at a smaller declination angle and frequently at a small angle to the track line and so is less precise. If responsive movement is not expected, using later detections closer to the vessel should improve the accuracy of distance measurements. We examined these potential biases in distance estimation for humpback and fin whales and found that the choice of first or later sightings had no detectable effect on the distance distributions.

Perception bias correction

This is the first NASS in which full Independent Observer (IO) mode, with each vessel incorporating 2 independent, isolated platforms using identical methods, has been used. Previous surveys which have used double platforms (2001, 2007) have used Buckland-Turnock (BT) (Buckland & Turnock, 1992) mode, with a tracker platform scanning ahead of the field of view of the primary platform using binoculars and tracking sightings until they were sighted by the primary or passed abeam (Pike et al., 2019b; Víkingsson, et al. 2015; Víkingsson et al., 2009). As the tracker platform is not independent (*i.e.* it monitors the primary platform), tracker platform sightings are considered “trials” for the primary platform and the perception bias correction is applied to the primary platform only, unlike IO mode in which bias is estimated for the combined sightings by both platforms.

Estimates of $p(0)$ for fin (0.87) and humpback (0.69) whales were quantitatively similar to those observed in previous surveys (Pike et al., 2006, 2019b), and were of similar magnitude to that estimated for blue whales (0.83). However, the Faroese vessel had no duplicate sightings of humpback whales so there are no data to estimate $p(0)$ for that vessel. Perception bias for the Faroese blocks is therefore a function of the combined data from all vessels. Estimation excluding data from the Faroese vessel resulted in a corrected abundance estimate of similar magnitude for the Icelandic strata.

Perception bias for minke whales (0.51) has not been previously estimated for the Icelandic and Faroese components of NASS, but was similar in magnitude to that observed in Norwegian ship surveys (Schweder, 1999; Schweder, Skaug, Dimakos, Langaas, & Øien, 1997; Skaug, Øien, Schweder, & Bothun, 2004).

In contrast our estimates of *p*(0) were anomalously low for dolphins and sperm whales at 0.31 (CV=0.55) and 0.34 (CV=0.42) respectively. Precision is also low for both estimates. The magnitude of the estimates reflects the low rate of between-platform duplication for sightings of these species. Furthermore the available covariates did not constrain the estimates of *p*(0) well. The proportion of sightings that were duplicated was particularly low on the Faroese vessel H at 6% for sperm whales, compared to 29% for the combined Icelandic vessels, and 7% for dolphins, compared to 14% for the Icelandic vessels. It is unlikely that the number of duplicate sightings was underestimated for these species, as we were conservative in duplicate identification in the sense that the criteria we used are more likely to overestimate the number of duplicate sightings (*i.e.* by identifying pairs as duplicates when they are not). Also, if there was a systematic failure to identify duplicates, we would expect to see this for other species as well, but the duplicate proportions for fin, blue, common minke and humpback (except on the Faroese vessel) whales were not unduly low. This may to some extent reflect the fact that the main target species of the survey were fin and common minke whales, which may have reduced the importance of sightings of non-target species to observers.

Responsive movement

A key assumption of distance sampling is that animals do not move in response to the vessel prior to being detected by the observer (Buckland et al., 2001; Buckland & Turnock, 1992; Burt et al., 2014). Some cetaceans, particularly some species of dolphins and possibly northern bottlenose whales, move towards vessels (attractive movement), while others, such as common minke whales, may move away (aversive movement). Attractive movement will result in a larger than expected number of sightings near the trackline and therefore a positively biased abundance estimate, while aversive movement will have the opposite effect. While methods are available to detect responsive movement, such as using asymmetrical platforms (B-T mode) (Buckland & Turnock, 1992), these were not implemented in this survey.

Previous NASS which used B-T mode have not shown unequivocal evidence for responsive movement for any species, however detection was confounded to some extent by a suspected negative bias in primary platform distance estimates in 2007 (Pike et al., 2019b). Palka and Hammond (2001) used changes in swimming direction to show some aversive movement among minke whales and white-sided dolphins, and possible attractive movement by white-beaked dolphins. However, the specifics of these behaviours varied between areas of the North Atlantic, and possibly between survey ships. The recent SCANS-III survey found no evidence of responsive movement for any species (including all species dealt with in this paper) in the Northeast Atlantic just to the east of our survey area (Hammond et al., 2017).

Modelling the sight-resight data under the assumption of full independence (FI) can, in theory, provide unbiased estimates of abundance when responsive movement is suspected (Burt et al., 2014). However, such estimates are almost invariably negatively biased because of unmodelled heterogeneity in detection probability. In most cases, all the factors that affect detection are not recorded by the observers, which results in their detections not being independent from one another. We compared FI models to PI models for all estimates, and in every case PI models had lower values of AIC.

Responsive movement is likely of greatest concern for our estimates for white-beaked and white-sided dolphins, and for northern bottlenose whales. Dolphins have been shown to respond to survey ships with aversion (white-sided) or attraction (white-beaked) in some areas (Palka & Hammond, 2001). Some other dolphin species, such as short-beaked common dolphins react strongly to vessels and can show a strong attraction (Canadas, Desportes, & Borchers, 2004). Northern bottlenose whales approach vessels in some areas (Benjaminsen & Christensen, 1979; Reeves, Mitchell, & Whitehead, 1993). If future NASS target species that are likely to react to vessels, alternative field methods that provide the data needed to correct for this should be employed.

Allocation of unidentified *Lagenorhynchus* dolphins to species

White-beaked and white-sided dolphins are of similar size and colouration. Both species form tightly packed groups that range widely in size and exhibit very active surface behaviours. As their ranges overlap in the NASS survey area, these common characteristics make them difficult to discriminate at sea, and additionally makes it difficult to obtain accurate group size estimates.

Given the relatively low number of detections, we were not able to develop individual detection functions for each species. However, the inclusion of a species identity covariate in the detection function should have largely alleviated this issue, so long as the detection functions for each species were similar in form.

As 31% of sightings of dolphins of genus *Lagenorhynchus* were not identified to species, we chose to allocate the abundance of unidentified dolphins to species by the proportion of sightings identified to species in each stratum. Of course, we have no means to determine if these allocations are correct. This potential bias affects mainly our estimate for white-beaked dolphins, for which the estimate including the allocated unidentified sightings is 48% higher than that which does not. This is mainly due to the inclusion of unidentified sightings in block IR, in which 100% of the identified sightings were of white-beaked dolphins. It therefore seems likely that the species allocation in this block is reasonably secure.

Dolphins were not target species of this survey, and the relatively high number of unidentified sightings, as well as the low rate of between-platform duplication of sightings, may partially result from this. If estimates for dolphins become a priority, observers should receive additional training in dolphin identification, possibly by including dolphin experts as observers. Further effort may also have to be allocated towards closing on some dolphin groups to obtain accurate species identifications and group sizes.

Comparison to previous estimates

Fin whales

Víkingsson et al. (2009) provide regional abundance estimates for fin whales for all NASS up to 2001, and Víkingsson et al. (2015) extend this series to 2007. In the area between Iceland and East Greenland, roughly equivalent to our West region (EG + WI in Figure 1b), fin whale numbers, uncorrected for perception and availability biases, increased from 3,600 (CV=0.18) in 1987 to 14,000 (CV=0.18) in 2001, a rate of increase of 10% p.a. (95% CI 6% – 14%) (Víkingsson et al., 2009). There was no detectable change in abundance in other areas. Abundance in this area in 2007 was similar to that seen in 2001, suggesting that the increase in numbers in this area had ceased (Pike et al., 2019b; Víkingsson et al., 2015). The W region had an uncorrected abundance of 27,843 (95% CI 19,693 – 39,366) in 2015 (Supplementary file 1), suggesting a substantial albeit non-significant (*P*>0.05) increase since 2007 in this area.

The abundance of fin whales around the Faroe Islands and to the south of Iceland (blocks FC + FS) was also strikingly high compared to earlier surveys. Density surface analyses by Víkingsson et al. (2015) identify this as a very low density area in all NASS prior to 2015. Pike et al. (2019b) estimated 417 fin whales in this area (their blocks FS + FE) in 2007, compared to over 11,000 in 2015 (Supplementary file 1). It is interesting to speculate that this might have been due to a northern incursion of fin whales into the area from the Spanish stock area, where earlier and recent surveys found fin whales to be abundant (Buckland et al., 1992; Hammond et al., 2013, 2017; Sanpera & Jover, 1989).

Density of fin whales in the fall survey NW of Iceland was about 3 times that estimated in the summer survey in the same area (Supplementary file 1). While fin whales have been previously observed in this area, apparently associated with aggregations of capelin (Víkingsson, 2004), this is the first estimation of density from so late in the year. The apparent increase in density in the northern part of the survey area suggests that fin whales may remain in northern waters longer than previously assumed, and that they may actually move farther north late in the season. However, it should be kept in mind that the fall survey was designed for estimating the biomass of capelin that aggregates in this particular area during autumn.

While overall abundance over the entire survey area is not directly comparable between NASS as coverage has varied between surveys, the numbers seen here are the highest of any NASS in the Central North Atlantic. This suggests either an increase in abundance in northern areas or a distributional shift, or a combination of both of these. A distributional shift is not unlikely as Víkingsson et al. (2015) have demonstrated that fin whales have both increased in abundance and changed their distribution patterns within the NASS survey area between 1987 and 2007. This was associated with an increase in sea surface temperature and height, and probably prey availability, particularly in the western part of the area. It appears that this pattern may be continuing, allowing this species to expand its range and numbers in the Central North Atlantic. Surveys in the southeastern part of the North Atlantic (SCANS and CODA), including the last one conducted in 2016, have not shown any corresponding decrease in fin whale numbers further south (Buckland et al., 1992; Hammond et al., 2009, 2013, 2017; Sanpera and Jover, 1989). This suggests an overall increase in fin whale abundance in the wider North Atlantic area.

Hansen et al. (2018) provided a fully-corrected estimate of 6,440 (CV=0.26, 95% CI 3,901 – 10,632) for the coastal area off East Greenland in August 2015. Correcting for the minor overlap between the 2 areas and summing the estimates gives a total of 42,976 (CV=0.15, 95% CI 35,200 – 52,496) for the combined survey areas.

Recent estimates of fin whale abundance in the Norwegian survey area to the east and north of Iceland and the Faroes suggest numbers in the low thousands (Øien, 2009; Leonard & Øien 2019a,b,c,d)

Common minke whales

The distribution of common minke whales was similar to that seen in previous surveys. Highest densities were observed in Icelandic coastal waters, close to the east coast of Greenland, and around the Faroes. Common minke whale density in the area around the Faroes seems to vary considerably between surveys, with relatively high numbers seen in 1987 and 2001. Notably in 2015 no minke whales were seen to the north of Iceland, an area of high density in other years. However, realized effort in this area was very low in 2015, and a concurrent aerial survey that was supposed to cover the area was unsuccessful (Pike et al., 2019c).

Pike et al. (2009a, 2019b) provide regional abundance estimates for minke whales from surveys conducted in roughly the same area as this in 1987, 1989, 1995, 2001 and 2007 while Pike et al. (2019c) provide estimates for recent aerial surveys around Iceland. As not all surveys covered Icelandic coastal waters (block IC in this survey), we compared estimates excluding this area. Uncorrected abundance outside coastal waters was between 12,000 and 14,000 from 1987 to 1995 in all years except 2001, when it was substantially higher at 26,000. In most years the estimated abundance is therefore comparable to our estimate of about 13,000 minke whales outside of IC. The 2001 survey extended NE of Iceland into the area around Jan Mayen Island, and a substantial proportion of the abundance estimate was realized in that area. The Jan Mayen area was covered in 2015 by a Norwegian vessel, but the results of that survey are not yet available.

Ship survey estimates from Icelandic coastal waters have varied between 6,000 (1995) and 13,500 (1989), comparable to our uncorrected estimate of 6,470 (CV=0.46). This area corresponds to the aerial survey area that has been flown using cue-counting methods starting in 1987 (Borchers et al., 2009; Pike et al., 2019c). These surveys, which should provide largely unbiased estimates, have shown a marked decline in minke whale abundance in the area since 2001, when total abundance was 43,633 (95% CI 30,148 – 63,149) to 2016, when abundance was estimated as 13,497 (95% CI 5,347 – 34,067).

Hansen et al. (2018) provided a fully-corrected estimate of 2,614 (CV=0.39, 95% CI 1,256 – 5,440) for the coastal area off East Greenland in August 2015. Correcting for the minor overlap between the 2 areas and summing the estimates gives a total of 45,008 (CV=0.29, 95% CI 30,592 – 66,217) for the combined survey areas.

Only 1 sighting of a common minke whale was made on the fall survey NW of Iceland, while the encounter rate in the same area during the summer was about 3 times as high. Common minke whales were not observed associated with capelin schools in the fall. While this might suggest that they leave the area earlier than some other species, satellite tagging conducted between 2001 and 2011 suggests initiation of autumn migration after mid-October (Víkingsson and Heide-Jørgensen, 2015).

Humpback whales

Pike et al. (2005) provide regional abundance estimates for humpback whales from surveys conducted in roughly the same area as this in 1987, 1989, 1995 and 2001, and Víkingsson et al. (2015) extend this series to 2007. Abundance increased dramatically from 1987 to 2001, with most of this increase attributable to growth in the population summering around Iceland. Abundance in a roughly equivalent area was 11,060 (CV=0.33) in 1995 and 13,965 (CV=0.27) in 2001. The 2007 uncorrected estimate equivalent to that presented here was 14,553 (95% CI 5,819 – 27,906), and correction for perception bias increased this to 18,722 (95% CI 7,114 – 49,266). Our uncorrected point estimate (6,643, 95% CI 3,543 – 12,456) is more than 50% lower than that estimated in 2007, however the difference is not statistically significant (*P*>0.05).

A contiguous area northeast of Iceland around Jan Mayen Island and east to the coast of Norway was covered simultaneously by Norwegian vessels (Solvang & Øien, 2017). While these data have not yet been analyzed, few sightings of humpback whales were made, suggesting that the Icelandic and Faroese surveys captured the main concentrations of humpback whales in the area during the summer.

An aerial survey conducted off East Greenland in August 2015 (Hansen et al., 2018) provided a fully corrected estimate of 4,012 (95% CI 2,044 – 7,873) humpback whales. Correcting for the small overlap between our survey area and this one, the 2 estimates combined total 13,916 (95% CI 9,590 – 20,193). While this is quite similar to NASS estimates from 1995, 2001 and 2007, it should be noted that those surveys did not cover the area close to East Greenland surveyed by Hansen et al. (2018) because of pack ice cover. We therefore cannot determine if the distribution of humpback whales close to the East Greenland coast is a new phenomenon, perhaps accounting for the apparent decrease in the Icelandic strata. In any event it appears that the rapid increase in humpback whale abundance observed around Iceland from 1987 to 2007 has ceased and that the abundance in the area has probably stabilized or may be decreasing.

Humpback whales have long been known to occur on the capelin fishing grounds in Icelandic waters throughout the winter (Magnusdottir, Rasmussen, Lammers, & Svavarsson, 2014; Víkingsson, 2004). Density of humpback whales was quite similar in this area in the summer and the fall (Supplementary file 3), suggesting that humpback whales remain in the area N and NW of Iceland in the fall. Whale observers indicated that humpback whales were consistently associated with areas of high capelin density, although this has not been formally analysed.

Blue whales

As in all previous NASS, blue whales (Figure 6) were most commonly sighted to the west and north of Iceland. No blue whales were sighted close to the coast of Iceland, which is unsurprising as coastal aerial surveys conducted after 2001 have also sighted few (Pike et al., 2019c). Blue whales also appear to be quite rare to the east of Iceland. Víkingsson et al. (2015) noted an apparent northward shift in distribution of blue whales in coastal Icelandic waters during 1987-2004.

A challenge particular to estimating blue whale numbers is the difficulty of discriminating them at sea from fin whales, which outnumber blue whales in the area by more than an order of magnitude. However, exclusion of the most uncertain blue whale sightings decreased abundance by only 6%, despite there being 13% fewer sightings. Most of the very uncertain sightings were far away, reducing their influence on the estimated abundance. It is likely that some proportion of uncertain fin whale sightings were in fact blue whales, which could bias our estimate negatively.

Figure 6. Blue whale. Photo credit: Natural History Museum, Faroe Islands.

Pike, Gunnlaugsson, Víkingsson & Øien (2009c) provide uncorrected abundance estimates for all surveys up to 2001. No estimate is available for 2007 as there were only 14 sightings in that survey (Pike et al., 2019b). Abundance was highest in 1995 and 2001 at just over 1,000 animals and increased significantly over the period at a rate of 9% (95% CI 3% – 14%). Our uncorrected estimate (Supplementary file 4) is more than double those from 1995 and 2001, although not significantly different from either (*P*>0.05). This suggests that blue whale numbers have increased in the area, particularly to the west of Iceland.

Only one blue whale was spotted off East Greenland in a concurrent aerial survey, suggesting that blue whales are not common there (Hansen et al., 2019). Blue whales were also not commonly seen in Norwegian surveys to the north and east of our survey up to 2001 (Øien, 2009), and sightings from recent surveys are too few to develop abundance estimates (Leonard & Øien, 2019abcd). It appears therefore that this survey may capture the major concentration of blue whales in the central North Atlantic. Our corrected estimate of 3,000 (95% CI 1,377 – 6,534) is therefore the best available estimate of blue whale numbers in this area.

Only one blue whale was sighted in the capelin survey in October in an area where 13 sightings were made in the summer (Supplementary file 4), making the encounter rate in the summer about 6 times higher in this area. Blue whales may depart from northern areas earlier in the fall than fin or humpback whales.

Sei whales

While the sei whale (Figure 7) has been a target species of the NASS, most of the surveys have not been optimized for the known spatial and temporal distribution of this species. Catches of sei whales to the west of Iceland in the 20th century showed a seasonal peak in late August and September, which perhaps continued later as whaling operations generally ceased in September (Sigurjónsson & Víkingsson, 1997). The spring migrations of sei whales have been further clarified by recent satellite tag applications conducted near the Azores in May and June (Olsen et al., 2009; Prieto et al., 2014; Víkingsson & Gunnlaugsson, 2010). Most of these animals migrated northwards through the Labrador Sea and had reached southwest Greenland by July. Unfortunately, the tags did not transmit long enough to determine if these same animals moved into Denmark Strait in August. However this pattern is apparently quite variable and the whalers knew of "sei whale years" when sei whales moved into northern areas earlier in the season and in greater numbers than in most years (Ingebrigtsen, 1929; Prieto, Janiger, Silva, Waring, & Gonçalves, 2012). All NASS except NASS-89 have been conducted in late June and July, when sei whales are generally in low abundance in northern areas. NASS-89 was conducted later in the season (July-August) and covered areas farther to the south of the other surveys, for the express purpose of obtaining a better estimate for sei whales (Sigurjónsson et al., 1991).

Figure 7. Sei whale. Photo credit: Gísli Víkingsson, Marine and Freshwater Research Institute, Iceland.

Estimates of the abundance of sei whales have been produced for all previous NASS and reflect the variability in distribution and migration timing for this species. The 1987 survey did not extend far to the south and probably as a result the estimate for that year was quite low: 1,293 (95% CI 434 – 3,853) (Cattanach, Sigurjónsson, Buckland, & Gunnlaugsson, 1993). Abundance was estimated as 10,300 (95% CI 6,150 – 17,260) in 1989 (Cattanach et al., 1993) and most of the animals were concentrated near the southern limit of the survey area, at about 50° N. This suggests that even that survey did not capture the entirety of the stock as it migrated north. The estimates for the common area surveyed in 1987 and 1989 were nearly the same. Seen in this context the estimate from the 1995 survey of 9,249 (95% CI 3,700 – 23,116) (Borchers & Burt, 1997) is surprisingly high. Most of the sei whales seen in 1995 were well to the north of those encountered in 1989, and the 1995 survey did not cover the high-density southern areas of the 1989 survey. It appears that 1995 might have been a "sei whale year", when sei whales migrated earlier and farther north than in most years. Estimates for 2001 (Pike, Gunnlaugsson, Víkingsson & Mikkelsen, 2011) and 2007 (Pike et al., 2019b) were roughly comparable to those from earlier surveys (other than 1995) and with our 2015 estimate when coverage issues are considered. The "extension survey" conducted in 2007 outside the T-NASS core area revealed a concentration of sei whales to the south of Greenland, and the total estimate for 2007 including extension vessel sightings was 9,737 (95% CI 4,189 – 19,665) (Pike et al., 2019b).

Such variation in migratory timing and route may be related to the feeding pattern of the species. Sei whales feed nearly exclusively on euphausids and copepods (Sigurjónsson, 1995), and tend to congregate at oceanic fronts where their prey is concentrated (Skov et al., 2008). As the location of these fronts is itself somewhat variable, this may partially explain the inter-annual variability in sei whale distribution.

Sei whales are rarely seen in the northern parts of the survey area and are rarely sighted in Norwegian surveys in the Northeast Atlantic (Christensen, Haug & Øien, 1992; Leonard & Øien 2019abcd; Øien, 2009). Sei whales were commonly taken in coastal whaling operations off western and northern Norway in the late 19th and early 20th centuries (Prieto et al., 2012), so it is possible that distribution in this area has changed or that a local stock was extirpated by whaling. Similarly, occurrence seems to be low off Spain and the European coast. Recent European surveys have sighted few sei whales (Hammond et al., 2013; Hammond et al., 2017), as did Spanish components of the NASS conducted in 1987 and 1989 (Cattanach et al., 1993). Similarly, recent surveys off east and west Greenland (Hansen et al., 2018) and eastern Canada (Lawson & Gosselin, 2018) have sighted few sei whales. Sei whales are present off the eastern seaboard of the USA during the summer in relatively small numbers, with a recent modelled summer abundance of 1,519 (CV=0.30) (Roberts et al., 2016). Taken together, these surveys suggest a population in excess of 10,000 sei whales in the North Atlantic. This should be considered a minimum as no surveys have likely captured the entire North Atlantic population. For example, substantial numbers of sei whales have been sighted to the southwest of the NASS area along the mid-Atlantic ridge in a survey conducted in June and July 2004 (Waring, Nøttestad, Olsen, Skov, & Víkingsson, 2009).

Sperm whales

The distribution of sperm whales was similar to that seen in previous surveys, with the largest numbers of sightings around the Faroes and to the southwest of Iceland (Gunnlaugsson et al., 2009; Pike et al., 2019b; Sigurjónsson et al., 1991, 1989; Sigurjónsson, Víkingsson, et al., 1996). Large numbers have also been sighted to the northeast of the survey area off the coast of Norway in some previous (Øien, 2009) and recent (Leonard & Øien 2019a,b,c,d) surveys and to the southeast off the coasts of France and Spain (Hammond et al., 2009, 2017). Three sightings of sperm whales were made in a concurrent aerial survey off East Greenland (Hansen et al., 2019) but no estimate was developed for that area.

Only male sperm whales have been captured or stranded in Icelandic and adjacent waters, consistent with extreme sexual segregation in northern waters with females and young being restricted to waters further south (Whitehead, 2003). They are usually observed as solitary animals, and occasionally as pairs in the surveys, although mass standings of larger groups have been observed in recent decades (Gísli Víkingsson, unpublished data). Females and family groups were observed only on the NASS 1989 survey, which extended south of 55° N (Sigurjónsson et al., 1991).

Sperm whales are extreme deep divers, often remaining underwater for periods of an hour or more (Jaquet et al., 2000; Papastavrou et al., 1989; Whitehead et al., 1992). They also exhibit strong sexual dimorphism with males being much larger than females, and able to make longer dives (Jaquet et al., 2000; Whitehead et al., 1992). This has implications for abundance surveys as sperm whales may be underwater during the passage of the vessel and thus not detectable by observers, termed availability bias. Gunnlaugsson et al. (2009) used a combination of cue-counting and line transect sampling to estimate availability bias as 0.71 for the 2001 NASS. However, this estimate is survey-specific as it depends on platform height, the use of binoculars and other field procedures. Our estimate is corrected for perception bias but not for availability and is likely negatively biased by an unknown magnitude.

Sperm whales vocalize frequently and are readily detected using acoustic arrays. Barlow and Taylor (2005) used both visual and acoustic detection in a survey of the Northeast Pacific and found that visually detected groups were always detected acoustically, but the converse was not true. Hammond et al. (2009) found that estimates of sperm whale abundance in European waters based on acoustic detections exceeded those based on visual detections in the same strata. If estimates of sperm whale abundance are required from future surveys, the feasibility of using acoustic survey methodologies should be explored, although such attempts were unsuccessful in NASS-2007 due to equipment issues.

Sperm whales have not been a target species of the NASS but some previous estimates are available. Gunnlaugsson and Sigurjónsson (1990) derived an estimate, uncorrected for perception or availability biases, of 1,256 (CV=0.17) for the 1987 survey. Gunnlaugsson et al. (2009) provide an uncorrected estimate of 6,726 (CV=0.39) for a roughly comparable area from the 2001 survey, which is similar to our uncorrected estimate of 7,368 (CV=0.35, 95% CI 3,548 – 15,300). The uncorrected estimate from 2007 of 6,429 (CV=0.28, 95% CI 3,412 – 10,007) is also similar in magnitude to our uncorrected estimate, however the corrected estimate from 2007 is about half of our corrected estimate, primarily because *p*(0) was higher for the 2007 survey (Pike et al., 2019b).

To the east of our survey area, Øien (2009) provided estimates, uncorrected for perception or availability, of 4,319 (CV=0.20) and 6,207 (CV=0.22) for the 1995 and 1996-2001 Norwegian surveys respectively, and more recent surveys will allow these estimates to be updated (Leonard and Øien, 2019a,b,c,d) Further to the south, Rogan et al. (2017) provide an estimate uncorrected for perception or availability of 7,035 (CV=0.28) sperm whales from the CODA survey carried out in 2007, and Hammond et al, (2017) provide an uncorrected estimate of 13,518 (95% CI 6,181 – 29,563) for a similar area in 2016. As these survey areas do not overlap with ours, and all estimates are certainly negatively biased, it is likely that more than 30,000 sperm whales occupy the northern parts of the Central and Eastern North Atlantic during the summer.

Long-finned pilot whales

Long-finned pilot whales (Figure 8) are primarily an offshore, oceanic species although they can also be found in coastal areas. In the Northeast Atlantic during the summer months they are most abundant in water depths exceeding 1,000 m over areas of moderate bottom slope (Rogan et al., 2017). They appear to have a more coastal distribution off Canada (Lawson & Gosselin, 2018) and the Northeastern USA (Roberts et al., 2016).

The distribution of long-finned pilot whales observed in 2015 was similar to that seen in previous NASS, with largest numbers sighted around and to the south of the Faroe Islands, and to the south and west of Iceland (Borchers et al., 1996; Buckland et al., 1993; Pike et al., 2019b; Pike et al., 2003a). The 1989 survey, which extended farther south and was conducted about 2-3 weeks later in the year than other NASS, produced the largest uncorrected estimate of 660,387 (CV=0.33, 95% CI 351,099 – 1,242,131) (not including strata covered by Spanish vessels). Our uncorrected estimate (Supplementary file 7) is the second-largest of the series. However, all the surveys used different stratifications and covered somewhat different areas, so their estimates are not directly comparable. Pike et al. (2019a) provides a trend analysis of long-finned pilot whale abundance using only the common areas covered by all NASS. No significant trends in abundance were detected over the period 1987-2015, however power analysis suggested that the rate of decrease would have to exceed 2% - 4% (depending on assumptions) to be detectable.

Figure 8. Long-finned pilot whales. Photo credit: Natural History Museum, Faroe Islands.

None of the NASS have covered the total summer range of long-finned pilot whales in the Northeast and Central Atlantic. Long-finned pilot whales occur to the east and southeast of the survey area off Britain, Ireland in the Bay of Biscay (Buckland et al., 1993; Hammond et al., 2017; Rogan et al., 2017). Recent estimates from this general area, corrected for whales missed by observers but not for submerged whales, range from 172,195 (CV=0.35, 95% CI 88,194 – 336,206) in 2005-7 (Rogan et al., 2017) to 25,577 (CV=0.35, 95% CI 13,350 – 49,772) in 2016 (Hammond et al., 2017). The former estimate included a larger area and is likely more complete.

Long-finned pilot whales are rarely sighted to the northeast of the NASS area in the Norwegian and Barents Seas, and no abundance estimates have been derived for this area (Nils Øien, *pers comm.*).

Long-finned pilot whales are rarely sighted off East Greenland, but are frequently sighted and hunted off southwest Greenland (Hansen et al., 2019; Hansen & Heide-Jørgensen, 2013). The most recent estimate from 2015, corrected for whales missed by observers and submerged whales, was 9,190 (CV=0.50, 95%

CI 3,625 – 23,234) (Hansen et al., 2019). Further west, a fully corrected estimate for long-finned pilot whales off Eastern Canada from 2016 totalled 28,218 (CV=0.36) (Lawson & Gosselin, 2018). Long-finned pilot whales also occur off the Northeastern USA, but there they co-occur with short-finned pilot whales (*Globicephala macrorhynchus),* and the 2 species are difficult to discriminate at sea. A recent estimate of 18,977 (CV=0.11) (Roberts et al., 2016) includes both species.

Taken together, recent estimates suggest a population of well over 500,000 long-finned pilot whales in the North Atlantic. This must be considered a minimum estimate because some areas where long-finned pilot whales are known to occur, such as Davis Strait and the Labrador Sea, and the offshore waters of the Northeastern USA, remain poorly or un-surveyed. Furthermore, most estimates come from ship surveys that are not corrected for whales that are submerged during the passage of the ship, although this may not be a large bias as long-finned pilot whales rarely dive for more than 18 minutes and dives are usually much shorter than this (Heide-Jørgensen et al., 2002).

Northern bottlenose whales

Northern bottlenose whales (Figure 9) are primarily an offshore, deepwater species, although they do occur in nearshore areas where deep water is found (Reeves et al., 1993; Whitehead & Hooker, 2012). They prefer cool, subarctic waters, and are usually found north of 40° N in the North Atlantic (Committee on the Status of Endangered Wildlife in Canada, 2011). Although northern bottlenose whales have not been a primary target species of the NASS, the surveys have been conducted primarily in offshore, deepwater areas known to be prime habitat for this species.

Figure 9. Northern bottlenose whales. Photo credit: Natural History Museum, Faroe Islands.

Northern bottlenose whales are extreme deep divers, reaching depths approaching 1,500 m and with dive durations of 70 minutes or more (Hooker & Baird, 1999). They also undertake shorter, shallower dives in addition to deep feeding dives. In all, they may spend 60% to 70% of their time beneath the surface. Therefore, as with sperm whales, estimates for this species are likely subject to negative bias by availability, or whales that are submerged and therefore invisible to observers. Correction for availability bias would require data on diving from the survey area, which is not yet available for the NASS area. Any correction would also be survey-specific as it would depend on the survey mode employed, use of visual aids, etc. The NAMMCO Scientific Committee suggested that, based on available dive data and the characteristics of the sighting data, only about 1/5 of northern bottlenose whales would have been available for sighting in the 1987 and 1989 NASS (NAMMCO, 1995). However, later surveys used higher platforms with longer sighting distances, and the resultant bias would likely have been less. Nevertheless, we must regard our estimate for this species as being negatively biased by availability, probably by a substantial amount.

A countervailing positive bias may result from vessel attraction by this species (see above), however the methodology used in this survey does not produce data to detect or correct for this bias. Responsive movement was not detected in ship surveys conducted in European waters (Hammond, et al., 2009; 2017).

The distribution of northern bottlenose whales seen in 2015 was similar to that from most previous surveys, with greatest numbers sighted in deep waters around the Faroe Islands and to the west of Iceland (Pike et al., 2019b; Pike, Gunnlaugsson, Víkingsson, Desportes, & Mikkelsen, 2003b; Sigurjónsson et al., 1991, 1989; Sigurjónsson, Gunnlaugsson, Víkingsson, & Gudmundsson, 1996). In 1987 and 2001, many sightings were made to the northeast of Iceland around Jan Mayen Island, however the 1995 and 2007 surveys sighted few northern bottlenose whales in this area, despite considerable effort. While our 2015 survey did not cover the area around Jan Mayen, it was covered by a concurrent Norwegian survey, resulting in only 3 sightings (Nils Øien, *pers. comm*.). However, the following year, 22 were sighted in the same area with a similar amount of survey effort (Nils Øien, *pers. comm*.). It appears that the distribution of northern bottlenose whales can be quite variable, particularly at the northern edge of their distribution. This may be a result of changes in the distribution of their predominantly squid prey (Bloch et al., 2009; Hooker et al., 2001; Santos et al., 2001), or variations in the timing of seasonal migrations (Benjaminsen & Christensen, 1979; Bloch et al., 2009).

Previous estimates of abundance are available for all NASS except that from 1989 and 2007, when sightings were too few. Abundance was estimated as 5,827 (CV=0.15) from the 1987 ship survey (Gunnlaugsson & Sigurjónsson, 1990), however this estimate was derived using what would now be considered non-standard methods and is uncorrected for any biases. Pike et al. (2003) used conventional distance sampling to estimate uncorrected abundance from the 1995 and 2001 ship surveys as 27,879 (CV=0.67, 95% CI 12,396 – 62,700) and 24,561 (CV=0.23, 95% CI 15,261 – 39,528) respectively. The latter 2 estimates do not differ significantly from our estimate for 2015.

Northern bottlenose whales are rarely sighted in Norwegian surveys covering the Norwegian and Barents Seas, despite intense survey coverage over the past 30 years (Øien & Hartvedt, 2011). Most sightings have been in the vicinity of Svalbard and Jan Mayen. This was an area of intensive whaling for this species in the past (Reeves et al., 1993) and it seems possible that the population using this area may have been severely reduced.

To the east of the NASS area, abundance of all beaked whales combined, corrected for perception but not availability, was estimated as 11,394 (CV=0.50, 95% CI 4,494 – 28,888) in the 2016 SCANS survey (Hammond et al., 2017). However, the majority of these animals were sighted in the Bay of Biscay and were more likely of other species, primarily Cuvier's beaked whale (*Ziphius cavirostris*). An estimate of northern bottlenose whales only from the CODA survey conducted in 2007 and including the Faroese NASS survey block, corrected for perception but not availability biases, totalled 19,539 (CV=0.36, 95% CI 9,921 – 38,482) (Rogan et al., 2017). Sightings were concentrated around the Faroe Islands and therefore the estimate is not additive to ours. Distribution was strongly associated with the 2,000 m depth contour.

Northern bottlenose whales are rarely sighted in aerial surveys carried out in coastal Icelandic waters (Pike, Paxton, Gunnlaugsson, & Víkingsson, 2009b; Pike et al. 2019c) and off West and East Greenland (Hansen et al., 2018). Similarly, few were sighted off Newfoundland and Labrador in aerial surveys carried out in 2007 and 2016 (Lawson & Gosselin, 2018). A small resident population of a few hundreds of animals resides over a deep-water canyon known as The Gully on the Scotian Shelf off Nova Scotia (Committee on the Status of Endangered Wildlife in Canada, 2011). Farther to the south, sightings of northern bottlenose whales are rare off the US eastern seaboard (Roberts et al., 2016).

The above suggests that the NASS survey area indexes a large proportion of the total population in the North Atlantic. One area that has not been well covered by any recent surveys is Davis Strait and southern Baffin Bay, an area where northern bottlenose whales have been caught in past whaling (Reeves et al., 1993). Taken together, information from recent surveys suggests a minimum size for the North Atlantic population of at least 20,000 animals. However, the population is likely much larger than this because of uncorrected biases and areas of known habitat that have not been well covered by surveys.

White-beaked and white-sided dolphins

Numbers of dolphins have not been properly estimated for NASS ship surveys prior to 2007, although uncorrected estimates of around 90,000 for both species combined have been published using approximations for strip width (Sigurjónsson and Víkingsson, 1997). The uncorrected estimate for white-beaked dolphins from 2007 of 86,255 (95% CI 30,512 – 243,835) is not significantly different than ours, nor is that for white-sided dolphins of 32,396 (95% CI 14,609 – 71,838) (Pike et al., 2019b). Corrected estimates from 2007 are lower in magnitude than ours (but not significantly so) mainly because $p(0)$ was higher for these species in that survey.

Estimates for white-beaked dolphins have been provided from NASS aerial surveys on the Icelandic continental shelf. White-sided dolphins were rarely spotted in these surveys. Uncorrected estimates ranged from 11,000 in 1995 to 43,000 in 2016 (Pike et al., 2009b; Pike et al., 2019c). Estimates corrected for perception bias were provided for 2001, 2007, 2009 and 2016, and ranged from 31,663 (95% CI 17,679 – 56,672) in 2001 to 59,966 (95% CI 24,907 – 144,377) in 2016. These estimates are not corrected for availability bias which is likely substantial for this species from an aerial platform (Pike et al., 2019c). Even so they are comparable to the sum of our estimates from blocks IE and IR from the ship survey, which fully encompass the aerial survey area, of 85,000.

To the north and east of our survey area, a survey conducted in 1995 produced an uncorrected estimate of 91,000 (CV=0.59) *Lagenorhynchus* dolphins, the great majority of which were likely white-beaked dolphins (Øien, 1996). Abundance estimates for the period 2002-2018 are presented by Leonard & Øien, (2019b,c,d). To the south and east the most recent SCANS survey estimated 36,287 (CV=0.29, 95% CI 18,694 – 61,869) white beaked and 15,510 (CV=0.72, 95% CI 4,389 – 54,807) white-sided dolphins (Hammond et al., 2017). From an aerial survey concurrent with ours, Hansen et al. (2019) provide a fully-corrected estimate of 11,889 (CV=0.50) white-beaked dolphins in Greenlandic waters. Taken together, these estimates of largely non-overlapping areas indicate abundances exceeding 300,000 white-beaked and 200,000 white-sided dolphins in the central and eastern portions of the North Atlantic.

ADHERENCE TO ANIMAL WELFARE PROTOCOLS

The research presented in this article has been done in accordance with the institutional and national laws and protocols for animal welfare that are applicable in the jurisdictions where the work was conducted.

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Corrigendum

Due to an error by the authors in interpreting an external reference, a correction has been applied to p.14, section Fin whales, the fully corrected estimates.

Original pdf (early online version published 2019)

Hansen et al. (2018) provided a fully-corrected estimate of 1,932 (CV=0.24, 95% CI 1,204 – 3,100) for the coastal area off East Greenland in August 2015. Correcting for the minor overlap between the 2 areas and summing the estimates gives a total of 38,468 (CV=0.16, 95% CI 28,065 – 52,727) for the combined survey areas.

Corrected pdf (this version, published January 6 2020)

Hansen et al. (2018) provided a fully-corrected estimate of 6,440 (CV=0.26, 95% CI 3,901 – 10,632) for the coastal area off East Greenland in August 2015. Correcting for the minor overlap between the 2 areas and summing the estimates gives a total of 42,976 (CV=0.15, 95% CI 35,200 – 52,496) for the combined survey areas.

The original pdf can be obtained by contacting the NAMMCO Secretariat at nammco-sec@nammco.org