ANALYSIS OF MINKE WHALE SIGHTING DATA FROM AERIAL SURVEYS OVER PACK ICE IN EAST ANTARCTICA

Kelly, N.[1,2,#], Peel, D.[1,2], Bravington, M.V.[1,2] and Gales, N.[2]
[1] *CSIRO Mathematical and Information Sciences, and Wealth from Oceans National Research Flagship, Castray Esplanade, Hobart, Tasmania, 7000, Australia*
[2] *Australian Marine Mammal Centre, Australian Antarctic Division, Channel Highway, Kingston, Tasmania, 7050, Australia*
[#] *Contact email:* Natalie.Kelly@csiro.au

Abstract
With the aim of studying the abundance and distribution of Antarctic minke whales in pack-ice in east Antarctica, aerial surveys were undertaken in the austral summers of 2008/09 and 2009/10. Our aerial survey programme is the first systematic survey of distribution and abundance of Antarctic minke whales in pack-ice, both within and between summer seasons. During these surveys, around 9 100 km of effort was achieved across 20º of longitude, yielding 76 sightings of minke whales (110 individuals). Model-based estimates of abundances were derived and used to make simple inferences about pack-ice habitat preferences for minke whales. These model-based estimates were also used to test the hypothesis that minke whales have moved into pack ice areas in substantial enough numbers to explain the decreases in abundance reported in the two current circumpolar abundance estimates.

Introduction
Debates concerning conventional line transect estimation methods aside, the Scientific Committee of the IWC has noted an apparent decline in the abundance estimates for Antarctic minke whales (*Balaenoptera bonaerensis*) between the second (CPII: 1985/86-1990/91) and third circumpolar (CPIII: 1991/92-2003/04) IDCR/SOWER ship-based surveys. One theory, reported in Branch (2006; SC/58/IA4), suggests that changes in the ice edge boundary each year, and changes in the number of minke whales present in the pack-ice beyond this boundary, could be responsible for the differences in abundance estimates of whales in open water. In other words, could there have been an increase in the number of minke whales within pack-ice (and open areas within pack-ice), where the research ships can't search? And, if there are substantial numbers of minke whales within pack-ice, are there enough to account for the apparent decrease in abundance?

With the aim of studying abundance and distribution of Antarctic minke whales in pack-ice in east Antarctica, aerial surveys were undertaken in the austral summers of 2008/09 and 2009/10. The survey in the 2008/09 summer was considered a 'pilot' and focussed on the Vincennes Bay polynya in December 2008 (66° 24'S 110° 18'E). Survey effort in the austral summer of 2009/10 started in December 2009 and largely repeated the survey design from the first year, but also targeted areas around the Shackleton Ice Shelf (65° 16.8'S 104° 13.2'E) and the Davis Sea (near 64°S 100°E), and finished with repeated effort over the Vincennes Bay polynya in late January and early February 2010. These areas were not previously considered to harbour significant minke whale numbers, but were targeted to due the presence of nearby airstrips. These aerial surveys are fully described in Kelly *et al.* (2009; SC/61/IA3) and Kelly *et al.* (2010; SC/62/IA8), respectively and a preliminary analysis of these data are presented in Kelly *et al.* (2010; SC/61/IA9).

The first aim of this paper is to present model-based abundance estimates across the aerial survey area and to consider these estimates against the environmental predictors used. The second aim is to estimate the abundance of minke whales in a larger area to that of the survey region; an area comparable to the adjacent IWC-SOWER strata within which Bravington and Hedley (2010) and Okamura and Kitakado (2010) have estimated declines in minke whale abundances between CPII and CPIII.

Methods

Survey area and protocols
As previously mentioned, our aerial survey was constrained to pack-ice areas near to airstrips within the Australian Antarctic Territory. For operational reasons, the survey was based at the Australian Casey station (66° 16.32'S 110° 31.65'E) in both survey years (2008/09 and 2009/10) and at a field camp in the Bunger Hills in the second year (66° 10'S 100° 53'E).

The final survey design represented a trade-off between even spatial coverage throughout pack ice habitats and the targeting of polynyas within the pack ice, as these areas are likely to support higher numbers of minke whales. There was a single stratum for the 2008/09 aerial survey, covering the Vincennes Bay polynya, and the parallel and systematically located transects were orientated north-south and spaced at 10 nm; this stratum is referred to as CA12008. The 2009/10 aerial survey was conducted in three phases, consisting of several strata. The first phase repeated a survey design (but not the exact transects) from the 2008/09 summer period, based in and around Vincennes Bay; there was one stratum in this phase and both the phase and the stratum are referred to as CA1. The second phase, referred to BH1, moved survey effort over to the Shackleton Ice Shelf and the Davis Sea. This second phase contained four strata: Davis Sea South (DSS); Davis Sea North (DSN); Shackleton polynya (SCN); and SOWER-follow stratum (SWF). Equal-spaced zigzag transects were used in the second phase due to low fuel availability. The final phase, referred to as CA2, repeated the CA1 phase (again, transect locations were re-randomised), but also extended transects around 40 nm north of the sea ice boundary. Again, parallel and systematically located transects, which were north-south orientated and spaced at 10 nm, where used. Unfortunately, there was uneven coverage in the final phase, so two new strata were produced after the survey had finished, which split the planned survey area east and west: CA2E (east) and CA2W (east). Details of all strata and the effort achieved are given in Table 1and displayed in Figure 1. A full description of the survey strata are given in Kelly *et al*. (2009; SC/61/IA3) and Kelly *et al*. (2010; SC/62/IA8). A map of all effort, across both survey years, and locations of minke whale sightings is given in Figure 2.

The survey platform was a CASA-212 (400) fixed-wing aircraft. On-effort flying altitude was 228m (750ft) and speed was 204 km hr^{-1} (110 knots). Flights went ahead only if wind speed at the airstrip/station (with some extrapolation to wider survey area given by Bureau of Meteorology forecasters) was less than 22.2 km hr^{-1} (12 knots) and the cloud deck was higher than 244m (800ft).

On board were four observers (two per side of aircraft), a flight leader (seated at the left-rear) and two pilots. The survey was double-platform: the front and back observers were isolated visually with a thick curtain and were not able to hear one another through the intercom system. The observations themselves consisted of cue counting (where possible) and angle of declination when animals were perpendicular, or abeam, to the observer. The flight leader recorded variables that potentially influence the quality of observations, such as Beaufort sea state, glare, cloud cover and type, and an overall sightability score, at the start of each transect and each time these variables changed; and also continuously observed environmental covariates such as concentration of pack-ice.

Table 1 Details of the 2008/09 and 2009/10 aerial survey strata and transects.

Stratum	Stratum area (nm2) - realised	Phase	Start and end date	Total Transect Length (nm) – achieved
Casey 1 2008 (CA12008)	17 668.1	CA12008	11 Dec – 31 Dec 2008	3 397.7
Casey 1 (CA1)	16 238.3	CA1	16 Dec – 27 Dec 2009	1 470.2
Davis Sea South (DSS)	5 181.3	BH01	29 Dec – 30 Dec 2009	552.9
Davis Sea North (DSN)	4 627.4	BH01	30 Dec – 31 Dec 2009	393.6
Shackleton Polynya (SCN)	3 396.7	BH01	31 Dec 2009 – 9 Jan 2010	277.9
SOWER follow (SWF)	1 081.6	BH01	16 Jan – 16 Jan 2010	96.7
Casey 2 (CA2)	24 917.8	CA2	17 Jan – 5 Feb 2010	
CA2-East (CA2E)	5 567.8	CA2	5 Feb – 5 Feb 2010	317.4
CA2-West (CA2W)	19 466.1	CA2	17 Jan – 5 Feb 2010	1 814.9
Totals	55 559.2			4 923.8

* Does not include observer break/rest period

~ Total realised survey area, minus overlapping areas, is 34 159.9 nm^2.

Detection function

Due to the small flat windows in the CASA-212 aircraft, it is very likely that animals were missed on the track-line. Sighting data were corrected for animals missed on the track-line using mark-recapture distance sampling (MRDS) (as per Borchers *et al.* (1998) and Borchers *et al.* (2006)). The detection function analysis, using perpendicular sighting distances, was undertaken in R (R Development Core Team, 2011) using the *mrds* library, which is supplied with the program Distance (Thomas *et al.* 2009).

Across the two survey seasons there were 76 sightings (110 animals in total). Of these, one was made in Beaufort sea state of 5, so this was discarded for fitting a detection function and subsequent spatial density modelling. There were only three sightings made outside of the pack-ice area; these were pooled with the within-ice sightings to fit an overall detection function. It would be preferable to fit detection functions for each year of the survey to avoid confounding any changes in (local) abundance with possible changes in detection probability (Thomas *et al.* 2004). However, as the surveys were conducted over adjacent summer seasons, we feel a combined detection function was a reasonable decision to make in the face of the limited numbers of sightings.

For simplicity, after aircraft side-wise duplicate sightings were assigned, the front observers and back observers were pooled, respectively; so, effectively, there were only two observers in the analysis. A more thorough analysis of observer effects is desirable but simply not possible with so few sightings. The status of duplicate sightings was decided using time abeam and the angle of declination and no error/uncertainty has been considered in this process. Effort was removed from the analysis when Beaufort sea state was greater than 4. A small number of 'like' minke whale sightings were pooled with the minke whale sightings for this analysis. With a combination of aircraft skis and small, flat windows, the maximum declination (from the horizon) that could effectively (and comfortably) be searched was around 62°. At a survey flying height of 228 m, this equates to a distance of 131 m from the track-line that cannot be searched. This distance, therefore, becomes the left truncation distance by default. A right truncation distance was set at 1 085 m. By being isolated both visually and audibly front and back observers are physically independent. And while the aircraft frame starts to taper close to where the front observers sit, we don't believe this provides a substantial increase in available sighting area. We are reasonably confident there was no animal response to the aircraft at the survey height and speed, so point-independence (i.e., observations are only assumed independent at the track-line) is appropriate.

We fitted models with various permutations of detection function shape (i.e., half-normal versus hazard-rate), and variables plus first order interactions, which may affect scaling of the distance sampling and mark-recapture model components (i.e., distance, Beaufort sea state, group size and sea ice concentration[1]). Model selection was done via minimising the Akaike information criterion (AIC) (Akaike 1974). Once a smaller set of candidate detection functions were found using the AIC, models were checked for realistic and expected parameter estimates and a final 'best' model selected. As pack-ice concentration changed so frequently, transects were split into (approximately) 10 second segments, within which ice concentrations and other environmental covariates are assumed to be homogenous.

Estimating abundance

We used the count method (*sensu* Hedley and Buckland (2004)) to estimate abundance of minke whales in pack ice. The first step of this method involves fitting a detection function to perpendicular sighting distances to estimate effective strip width. Transects were divided into segments with relatively homogenous covariates, such as ice concentrations and general sightability. Ice concentration was the environmental covariate which changed the most rapidly and the resultant segments were around 0.3-0.4 km in length. As described above, the detection function is scaled by a number of covariates that may affect detectability; as these covariates change along a transect, so too will the effective strip width. Each segment then had a number of minke whale sightings (zero for the vast majority of segments) and an estimate of effective strip width. The second step of the count method is then to fit a spatial density model to these segments. The numbers of minke whales sighted in each segment was described by a generalised additive model (GAM; Wood (2006)) with smoothes over spatial and environmental covariates, and an offset value provided by the effective strip area. The effective strip area is the effective strip width multiplied by the segment length; this value is further multiplied by two if the observers on both sides of the aircraft were on effort. The total numbers of whales in each segment, not the numbers of groups, were described by the spatial density models.

Environmental covariates that are selected to describe density of whales must be able to be measured, or inferred, throughout the study area (i.e., not just those measured and recorded along-track). We chose AMSR-E[2] (satellite) sea ice concentration data and a 1 minute gridded bathymetry model to describe and summarise the range of environmental processes which may be influencing minke whale distribution. Bathymetry was selected as a potentially important covariate as it is assumed to influence Antarctic krill distribution in east Antarctica (Nicol *et al*. 2000). Bathymetry information for the region adjacent to our survey area is given in Figure 3. Any residual variance not explained by sea ice concentration or bathymetry may be soaked up by general spatial coordinates, such as longitude and latitude. However, as ice concentration generally scales with latitude in that part of the Antarctic coast line, latitude was not considered further. This spatial density model is referred to as GAM 1.

[1] Sea ice concentration along track was estimated using stills taken with a vertically orientated digital camera (mounted in the based of the fuselage of the aircraft; image footprint approximate 153 m x 102 m (at a flying altitude of 228 m)). An automatic classification algorithm was developed to take still images and estimate the percentage of sea ice coverage in each image, as well as information on ice pan size and numbers. Images were pre-processed to allow for the survey's differing light conditions and then normalised to provide the greatest light contrast. Each pixel of these adjusted images was then classified as either 'ice' or 'water' based on the pixel's intensity in the red spectrum. An analysis of 'clumps' in the images provided a description of ice pan size and number. For MRDS analysis, estimated sea ice concentration was summarised into following bins: 0-5%; 5-30%; 30-60%; 60-90%; and 90-100%.

[2] http://www.iup.uni-bremen.de:8084/amsr/

As one of our aims was to estimate minke whale abundance inside pack ice within Area IVE, we needed to extrapolate from the eastern extent of our survey area across to 130ºE. However, since no sampling occurred east of 113ºE, predictions from the spatial density models for longitudes east of this boundary were not available. Therefore, a second GAM was fitted which used only satellite sea ice concentration and bathymetry information (this model is referred to as GAM 2). Any of these terms could be dropped from the models if they did not offer significant explanatory power.

As there was some evidence of overdispersion when a Poisson distribution was assumed within the GAMs (data not shown), a Tweedie distribution (Jørgensen 1987) was used. The parameter to apply with the Tweedie distribution was estimated by examining randomised quantile residuals (Dunn and Smyth 1996) from the GAMs.

By applying a log link function, the resultant spatial density model (GAM 1) can be summarised as

$$E(n_i) = \exp[\log(2l_i w\hat{p}_i) + s(\text{lon}_i) + s(\text{ice}_i) + s(\text{bathy}_i)]$$

where $E(n_i)$ is the expected number of minke whales in the *i*th segment; l_i is the length of that segment; w is the right truncation distance (1 085 m); $\hat{p}_i$ is the estimated probability of detection of a group of minke whales in the *i*th segment; lon_i is the midpoint of the *i*th segment; ice_i and bathy_i denote the sea ice concentration and bathymetry value taken from the nearest ice concentration or bathymetry grid point; *s* is a smooth function. Tensor product smoothes were also explored as a way to account for interactions between the covariates. GAM 2 is identical, except that longitude has been removed. It should be noted that GAM 1 and GAM 2 are fitted using exactly the same data, just that GAM 2 does not involve longitude.

To estimate abundances across the various survey strata, and to extrapolate out to 130ºE, a number of prediction grids were produced. The grid points that come with the satellite sea ice data were selected as a convenient grid as this avoided the need to reprocess the ice data into another grid scale. AMSR-E satellite data comes at a grid spaced at 6.25 km. For each survey strata, sea ice data from the mid-date was used to produce the relevant prediction grid.

In order to produce prediction grids for areas inside pack-ice, regions between the Antarctic coast line and a more northern ice edge boundary (approximately 3% ice concentration) were delineated. These regions also included all 'open water' within pack ice areas. To avoid extrapolating over years, sea ice data for prediction was selected from 2009 and 2010 (i.e., seasons in which the aerial survey ran); to make these comparable to IWC-SOWER estimates from CPII and CPIII, approximate dates that IWC-SOWER voyages visited the areas previously were selected, being the third week in January. So, the resultant prediction grids were based on ice data from 20 January 2009 and 22 January 2010.

Estimating variance of an abundance estimate

It is common practice to use a moving block boot strap approach to estimate the variance of an abundance estimate derived from density surface modelling (Thomas *et al.* 2010). However, as the bootstrap approach can be problematic, Bravington and Hedley have developed a method that propagates uncertainty in the detection function through the spatial density modelling step. This method of estimate variance in abundance estimates using spatial density model was used here and is fully described in Williams *et al.* (2011).

Results and Discussion

Comparing the AIC from all permutations of the detection functions and potential scaling variables, and their first order interactions, the most promising combination was a hazard-rate detection function with a distance sample model scaled by group-size, binned sea ice concentration and Beaufort sea state; and a mark-recapture model specified by distance, Beaufort sea state and group-size; the pooled detection function is given in Figure 4. The estimated mean detection probability at the track-line for the primary observer was 0.76 (CV = 0.05) and pooled probability of detection was 0.94 (CV = 0.03).

A spatial density surface comprised of a tensor product smooth between longitude and sea ice concentration, see Figure 5; the other component of that GAM, a smooth across bathymetric data, is given in Figure 6. Points were added to Figure 5 to demonstrate the range of segment data the spatial density model is based on; the range of bathymetry data is given in the rug plot at the bottom of Figure 6. The covariate space has been reasonably evenly sampled. The resultant abundance estimates and CVs are given in Table 2. These abundance estimates have not been corrected for availability bias. Discussion on this final step is offered further below.

Before we discuss the abundance estimates, we can explore some of the features of the GAMs to infer some habitat preferences. The tensor product smooth between sea ice concentration and longitude (see Figure 5) shows both a region of open water within pack ice with high predicted density (a point estimate of around 0.011 minke whales per 1 km^2) in Vincennes Bay (around 110ºE) and such a region with relatively low predicted density (a point estimate of around 0.005 animals per 1 km^2) in the Davis Sea (95ºE). The slight increase in the predicted densities in near 100% sea ice concentrations around 100ºE arose due to number of sightings in and around the Shackleton polynya. Despite the northern tip of the Shackleton polynya having a high concentration of ice in January 2010, these areas were also directly over the shelf-break (around 1 000m bathymetric contour); even though the ice edge had not receded over the shelf-break, this region may still have harboured attractive levels of Antarctic krill. This is further born out by a peak in the predicted density over a seafloor depth of around 1 500m (see Figure 6). In taking longitude out of the spatial density model (i.e., GAM 2), similar patterns continue to be observed (see Figure 7).

A striking result is the difference in abundance estimates (using GAM 1) between December 2008 and 2009 in Vincennes Bay (CA12008 versus CA1, see Table 2 for abundance estimates and Figures 11 and 12 for geographical distribution of predictions), with almost 3.5 times more whales predicted in the 2008 stratum than in 2009. There were far more minke whale sightings made during December 2008 as compared to December 2009 effort (Kelly *et al.* 2010; SC/62/IA8). Sea ice conditions were substantially different between the two seasons, with Vincennes Bay being clearer of ice in December 2008 as compared to December 2009. We can also compare abundance estimates within a single season, although, due to the differences in strata areas, we need to use densities instead of abundance estimates. The mean predicted density of minke whales in Vincennes Bay during December 2009 was around 0.007 animals per km^2, and then in February 2010 was 0.011 animals per km^2 (i.e., almost doubled). During the month in between surveying these two strata, ice had cleared somewhat from Vincennes Bay and a thick band of pack ice that had been blocking the entry to Vincennes Bay had weakened (see Kelly *et al.* (2010; SC/62/IA9) for further details). However, given the CVs of these abundance estimates/densities are high, it is unlikely they are significantly different (not tested here). Kelly *et al.* (2010; SC/62/IA8) offers more discussion on the potential environmental drivers for these observed differences in minke whale densities across the survey area.

The CVs for the western-most strata (i.e., DSS, etc) are high due to the relatively few transects flown as compared to the Vincennes Bay area (i.e., the confidence intervals around the GAM in the western area are much wider). It was expected that the CVs for GAM 2 for survey strata would be smaller as compared to GAM 1 as the covariate space of bathymetry and sea ice concentration were both covered reasonably evenly and thoroughly (see Figure 7). This is despite the fact that GAM 1 described more of the variation in the distribution of minke whale sightings (data not shown).

Table 2 Prediction grid areas and abundance estimates for each survey strata and within-pack ice regions between 100º and 130ºE; date of sea ice variable used for both GAMs is also given. Abundance estimates for survey strata using GAM 2 are also provided for comparison (italics).

Stratum and date	Mid-date surveyed	Area of prediction grid (km^2)	GAM 1 (N~te(lon,ice)+s(bathy))		GAM 2 (N~te(bathy,ice))	
			Abundance est.	CV	Abundance est.	CV
Casey 1 2008 (CA12008)	28 Dec. 2008	55 937.5	1322.35	0.17	*1266.38*	*0.17*
Casey 1 2009 (CA1)	22 Dec. 2009	55 898.4	373.06	0.19	*440.08*	*0.18*
Davis Sea South (DSS)	30 Dec. 2009	17 851.56	268.91	0.41	*352.57*	*0.18*
Davis Sea North (DSN)	31 Dec. 2009	16 757.8	173.25	0.38	*216.78*	*0.17*
Shackleton Polynya (SCN)	7 Jan. 2010	11 757.8	169.59	0.43	*81.49*	*0.25*
SOWER follow (SWF)	16 Jan. 2010	3 867.2	102.94	0.42	*58.21*	*0.22*
CA2-East (CA2E)	5 Feb. 2010	19 648.4	232.37	0.43	*384.00*	*0.24*
CA2-West (CA2W)	25 Jan. 2010	68 046.9	705.00	0.21	*722.22*	*0.20*
Inside ice 100-130E: 20 Jan 2009		198 671.9			2309.31	0.16
Inside ice 100-130E: 22 Jan 2010		233 476.6			1394.78	0.21

Using GAM 2 (i.e., spatial density model without longitude), we estimated the number of minke whales within the pack ice zone (i.e., in ice concentrations >3%, where IWC-SOWER research vessels would not usually travel) between 100 and 130ºE (IWC Management Area IVE) for 20 January 2009 and 22 January 2010 to be around 2310 and 1395, respectively (see Table 2). The differences in the abundance estimates between the two years is largely driven my differences in sea ice concentrations. This is demonstrated in Figure 10 (upper panel), where the relative frequency of grid cells with open water was much higher for 20 January 2009 than for 22 January 2010.

In order to compare the numbers of minke whales predicted within the pack ice zone between 100 and 130ºE (Area IVE), we first need to correct these estimates for availability bias. Any attempt to estimate the absolute abundance of a marine mammal must include an estimate of the amount of time these animals are 'available' or 'visible' to be seen and counted (Marsh and Sinclair 1989). By ignoring the fact that marine mammals are only at the surface for a fraction of the time, the subsequent abundance estimate will be negatively biased. Unfortunately, we have no way to directly estimate this availability bias in Antarctic minke whales at this time[3]. One possibility is to use data for other similar species. Heide-Jørgensen *et al.* (2009) used radio-tagging to get an availability bias estimate of 0.12 (i.e., these animals are only available to be observed a proportion of 0.12 of the time) for North Atlantic minke whales, but water clarity, atmospheric conditions, whale size, and possibly whale behaviour are very different in the Antarctic (D. Pike *pers. comm.*). Inside the Antarctic pack ice zone, for example, minke whales are often clearly identifiable underwater, so availability is not necessarily limited by surfacing. The availability of North Atlantic minke whales is probably lower than the availability of Antarctic minke whale, and so provides one lower bound for availability (and thus an upper bound for abundance). Using this lower-bound assumption, and with using this availability bias estimate as a straight multiplier, the corrected abundance (i.e., maximum point estimate) of Antarctic minke whales in pack ice between 100 and 130ºE is around 19 244 for 20 January 2009 and 11 620 for 22 January 2010.

According to Bravington and Hedley (2010; SC/62/IA12), the number of minke whales to be found in the region bounded by 100 and 130ºE, and between the ice edge and 60ºS, dropped by 13 000 between CPII and CPIII (both north and south strata); Okumura and Kitakado (2010; SC/62/IA3) estimated a decrease of 24 000 animals across the same strata. The numbers of minke whales we predict to be in the pack ice zone in Area IVE, after applying an availability bias of 0.12, are indeed comparable to these abundance decreases, for the 20 January 2009 abundance estimate at least. However, for the theory of minke whales moving further in the pack ice zone to fully account for the estimated decrease in minke whale numbers in Area IVE one would have to assume that there were absolutely no minke whales in the ice during the CPII period. Furthermore, we are assuming that the availability bias of 0.12 is appropriate for Antarctic minke whales, which, as we have discussed is most likely not the case. Finally, without further aerial survey effort, across more years and sea ice conditions, there is simply no way of knowing how representative the abundance estimate in January 2009 is for Area IVE in the current period, let alone whether it is directly comparable to what was occurring a decade ago.

Our aerial survey programme is first systematic survey of the distribution and abundance of Antarctic minke whales in pack-ice, both within and between summer seasons. The results of these surveys provide a glimpse of the inter- and intra-annual variations in minke whale abundance and distributions within pack ice. These results also highlight the potential for fluctuations in abundance estimates of minke whales in pack ice due to the year the survey happens to run (those familiar with IWC-SOWER data would not be surprised to hear that process error or additional variance is also likely to be operating within the pack ice zone). While the results of our aerial survey programme in east Antarctica cannot fully resolve the problem of where the missing minke whales have gone, they do start to provide general estimates of the numbers of animals in the pack ice zone and a potential upper bound on those estimates. Furthermore, these data will help test long held assumptions about minke whale distribution within pack ice zones, in particular with the observation that not all polynyas contain substantial numbers of minke whales (compare the Davis Sea and Vincennes Bay).

Acknowledgements

We wish to warmly thank the remaining members of observing team, Josh Smith and Shannon McKay and, in particular, our flight leader, Amanda Hodgson. We are also indebted to Skytraders pilots and engineers for their professionalism and enthusiasm and to the air-ground support staff. We also want to thank Rob Brittle and Jenn McGhee for running a fantastic field camp at Bunger Hills, and to Martin Boyle and Andy Cianchi for operational support at Casey. The survey programme was supported by Robb Clifton, Anthony Hull and Adrian Pate from Tasmania, with the help of many other people at the Australian Antarctic Division. Thank-you, too, to Graham Cook and Narelle Campbell (station leaders) and everyone else at Casey station for their support. Furthermore, we thank the Bureau of Meteorology, particularly Manfred Greitschus, Amy Bulters and Briony Macpherson, for weather forecasting during our aerial survey. We also acknowledge the support given to the aerial survey programme by the Scientific Committee of the IWC. We are appreciative for the patience and guidance of Sharon Hedley. And we are especially grateful for the local weather information and track locations supplied by the IWC-SOWER voyage (in particular, Keiko Sekiguichi and Laura Morse) in addition to their invaluable moral support over the summer season. This research was funded by the Government of Australia.

[3] There is a project under the Southern Ocean Research Partnership (SORP) which plans to tag Antarctic minke whales along the Antarctic Peninsula {Childerhouse, 2011 #3235}; data from this project should start to give us an indication as to availability bias for this species.

References

Akaike, H. (1974). New look at statistical-model identification. IEEE Transactions on Automatic Control AC19: 716-723.

Borchers, D. L., Buckland, S. T., Goedhart, P. W., Clarke, E. D. and Hedley, S. L. (1998). Horvitz-Thompson estimators for double-platform line transect surveys. Biometrics 54(4): 1221-1237.

Borchers, D. L., Laake, J. L., Southwell, C. and Paxton, C. G. M. (2006). Accommodating unmodeled heterogeneity in double-observer distance sampling surveys. Biometrics 62(2): 372-378.

Bravington, M. V. and Hedley, S. L. (2010). Antarctic minke whale abundance from the SPLINTR model: some 'reference' dataset results and 'preferred' estimates from the second and third circumpolar IDCR/SOWER surveys, Paper SC/62/IA12, presented to the IWC Scientific Committee, June 2010, 15 pp (unpublished).

Childerhouse, S. (2011). Revised project outlines for the Southern Ocean Research Partnership, Paper SC/63/O13, presented to the IWC Scientific Committee, 32 pp. (unpublished).

Dunn, P. K. and Smyth, G. K. (1996). Randomized quantile residuals. Journal of Computational and Graphical Statistics **5**: 236-244.

Hedley, S. L. and Buckland, S. T. (2004). Spatial models for line transect sampling. Journal of Agricultural Biological and Environmental Statistics **9**(2): 181-199.

Heide-Jørgensen, M. P., Witting, K. L., Laidre, K. L. and Hansen, R. G. (2009). Revised estimates of minke whale abundance in West Greenland in 2007, Paper SC/61/AWMP4, presented to the IWC Scientific Committee, 19 pp (unpublished).

Jørgensen, B. (1987). Exponential dispersion models. Journal of the Royal Statistical Society Series B **49**: 127-162.

Kelly, N., Peel, D., Bravington, M. V. and Gales, N. (2010). Aerial survey of minke whales off East Antarctica: Report on 2009/10 Survey, Paper SC/62/IA8, presented to the IWC Scientific Committee, 24 pp (unpublished).

Kelly, N., Peel, D., Bravington, M. V. and Gales, N. (2010). Preliminary analysis of minke whale sighting data from 2009/10 aerial survey off East Antarctica, Paper SC/62/IA9, presented to the IWC Scientific Committee, June 2010, 6 pp (unpublished).

Kelly, N., Peel, D., Pike, D., Bravington, M. V. and Gales, N. (2009). An aerial survey for Antarctic minke whales in sea ice off east Antarctica: a pilot study, Paper SC/61/IA3, presented to the IWC Scientific Committee, June, 2009, (unpublished).

Marsh, H. and Sinclair, D. F. (1989). Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. Journal of Wildlife Management **53**: 1017-1024.

Nicol, S., Pauly, T., Bindoff, N. L., Wright, S., Thiele, D., Hosie, G. W., Strutton, P. G. and Woehler, E. (2000). Ocean circulation off east Antarctica affects ecosystem structure and sea-ice extent. Nature 406, 504-507.

Okamura, H. and Kitakado, T. (2010). Abundance estimates of Antarctic minke whales from the historical IDCR/SOWER survey data using the OK method, Paper SC/62/IA3, presented to the IWC Scientific Committee, (unpublished).

Thomas, L., Laake, J. L., Rexstad, E., Strindberg, S., Marques, F. F. C., Buckland, S. T., Borchers, D. L., Anderson, D. R., Burnham, K. P., Burt, M. L., Hedley, S. L., Pollard, J. H., Bishop, J. R. B. and Marques, T. A. (2009). Distance 6.0. Release 2, Research Unit for Wildlife Population Assessment, University of St. Andrews, UK. http://www.ruwpa.st-and.ac.uk/distance/

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A. and Burnham, K. P. (2010). Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology **47**(1): 5-14.

Thomas, L., Burnham, K. P. and Buckland, S. T. (2004). Temporal inferences from distance sampling surveys. Advanced Distance Sampling. S. T. Buckland*et al.* Great Britain, Oxford University Press**:** pp. 71-107.

Williams, R., Hedley, S. L., Branch, T. A., Bravington, M. V., Zerbini, A. N. and Findlay, K. P. (2011). Chilean Blue Whales as a Case Study to Illustrate Methods to Estimate Abundance and Evaluate Conservation Status of Rare Species. Conservation Biology **25**(3): 526-535.

Wood, S. N. (2006). Generalized Additive Models: An Introduction with R. USA, Chapman and Hall.

Figures

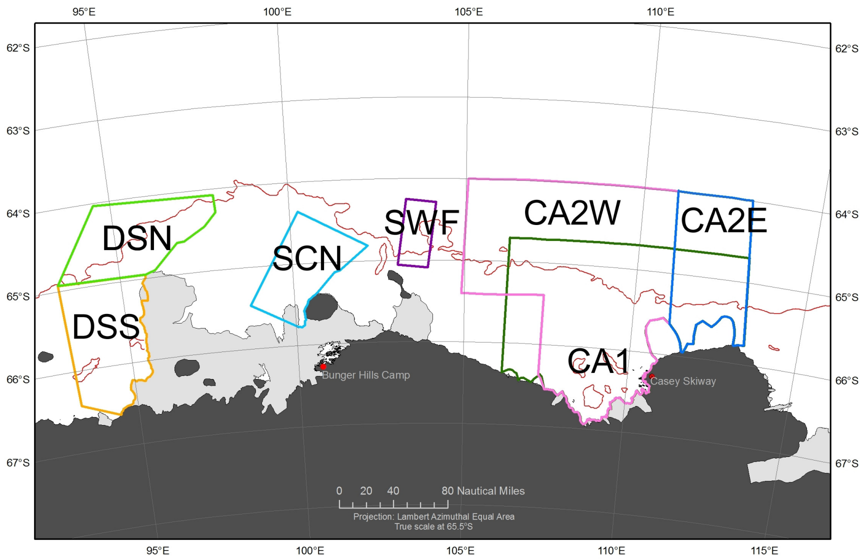


Figure 1 The single stratum of the CA1 phase (Vincennes Bay) is in dark green; strata within the BH1 phase (Shackleton Ice Shelf and Davis Sea): Davis Sea South (DSS) given in yellow, Davis Sea North (DSN) in bright green, Shackleton polynya (SCN) in aqua, and SOWER-follow stratum (SWF) in purple; strata within the CA2 phase (Vincennes Bay): western stratum (CA2W) given in pink and the eastern stratum (CA2E) in blue. Continuous red line is the 1000m bathymetric contour. See Kelly *et al.* (2009; SC/61/IA3) for map of CA12008 stratum.

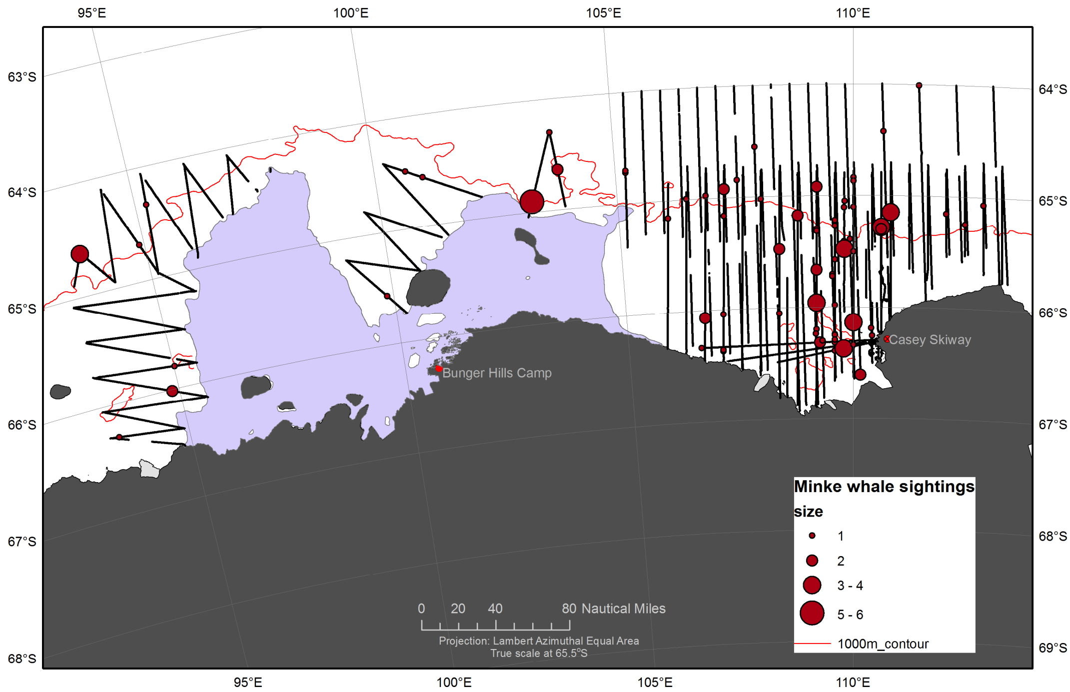


Figure 2 Survey effort combined across 2008/09 and 2009/10 seasons. Red circles indicated positions of Antarctic minke whale sightings; group size indicated by size of red circle.

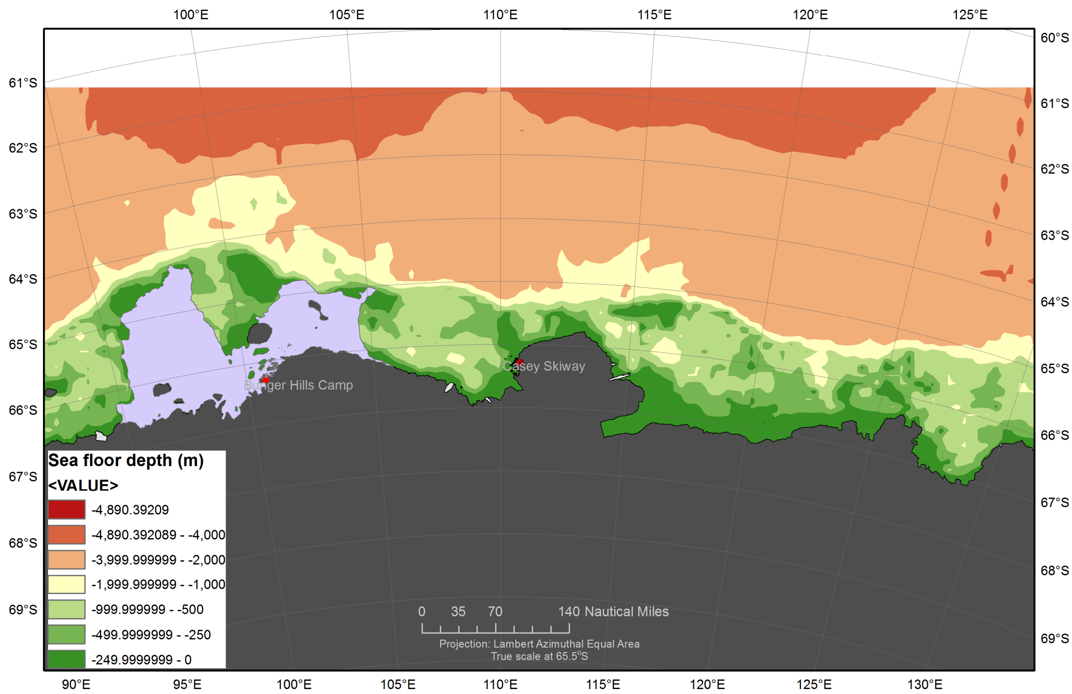


Figure 3 Bathymetry in the area 100-130ºE.

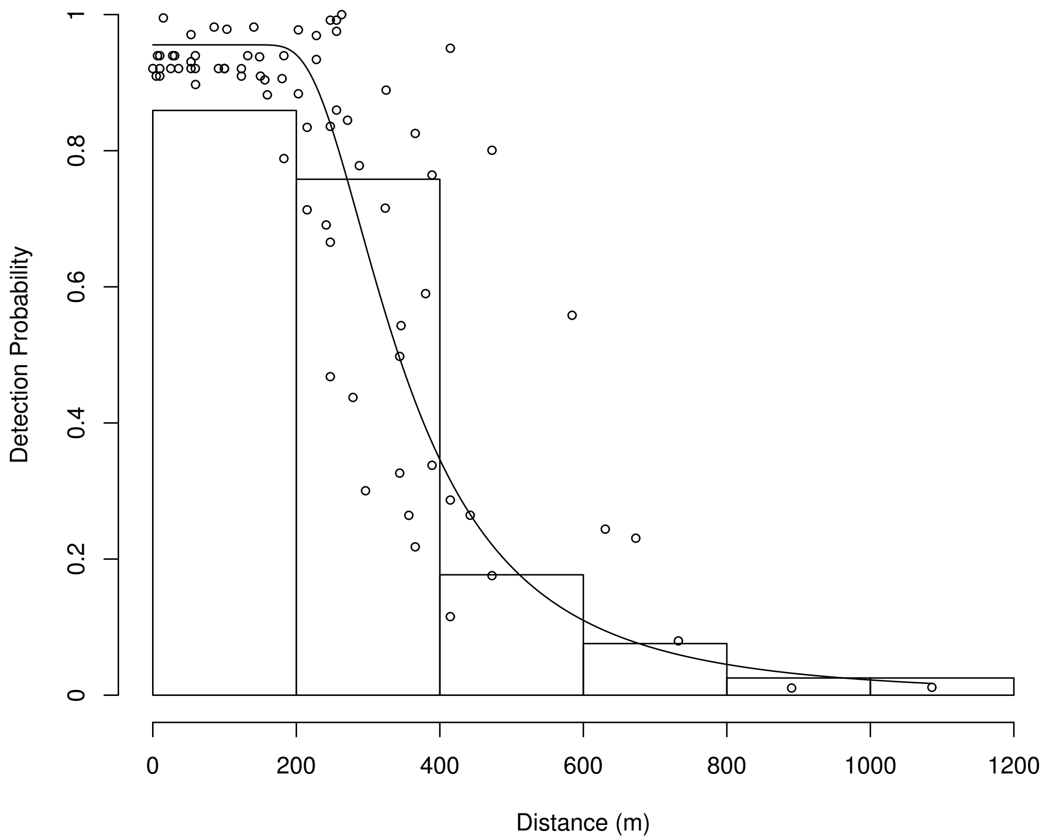


Figure 4 Detection probability of the pooled detections from both rear and front observers. The distances of sightings were right truncated at 1 085 m; a left truncation of 131 m was also applied. Detection function modelled as a hazard-rate function.

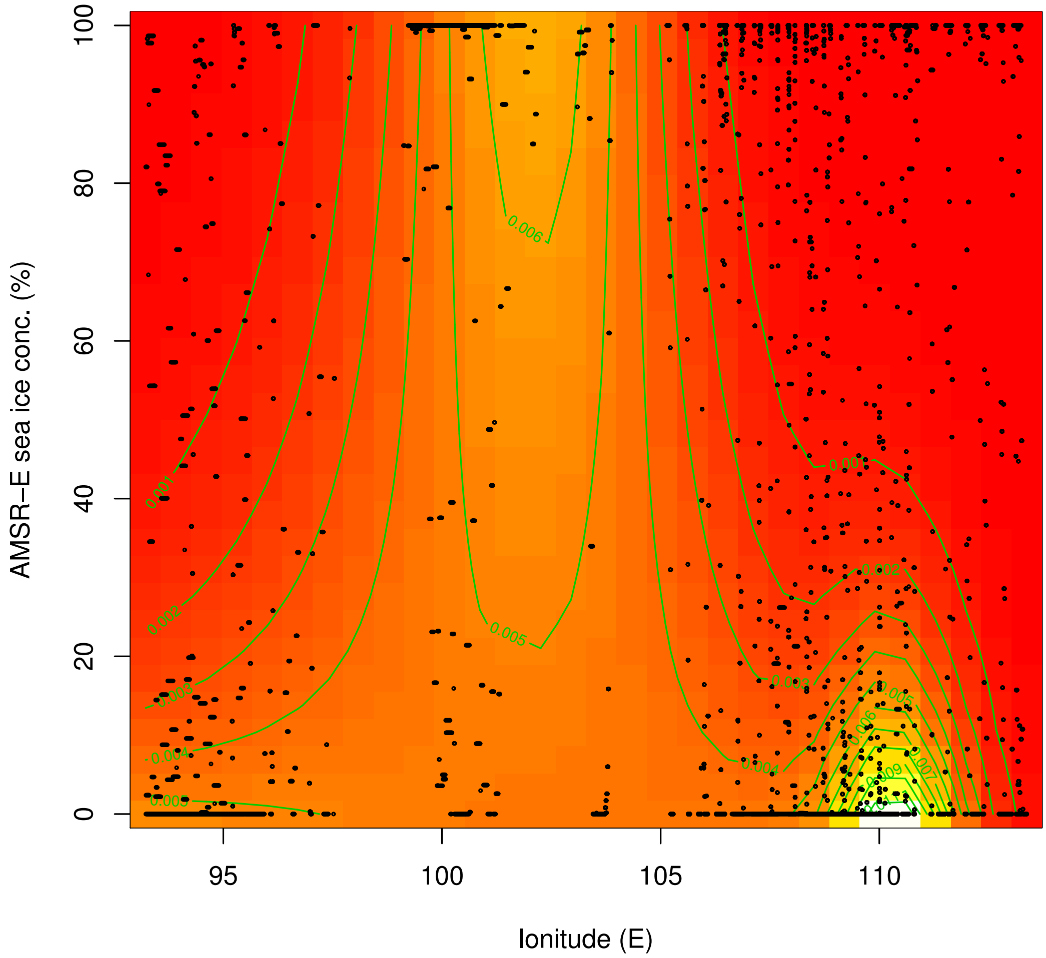


Figure 5 Predictions resulting from tensor smooth of longitude and ice concentration for spatial density GAM 1; contours represent estimated densities of minke whales for a 1 km^2 region; black dots represent spread of sample points in covariate space.

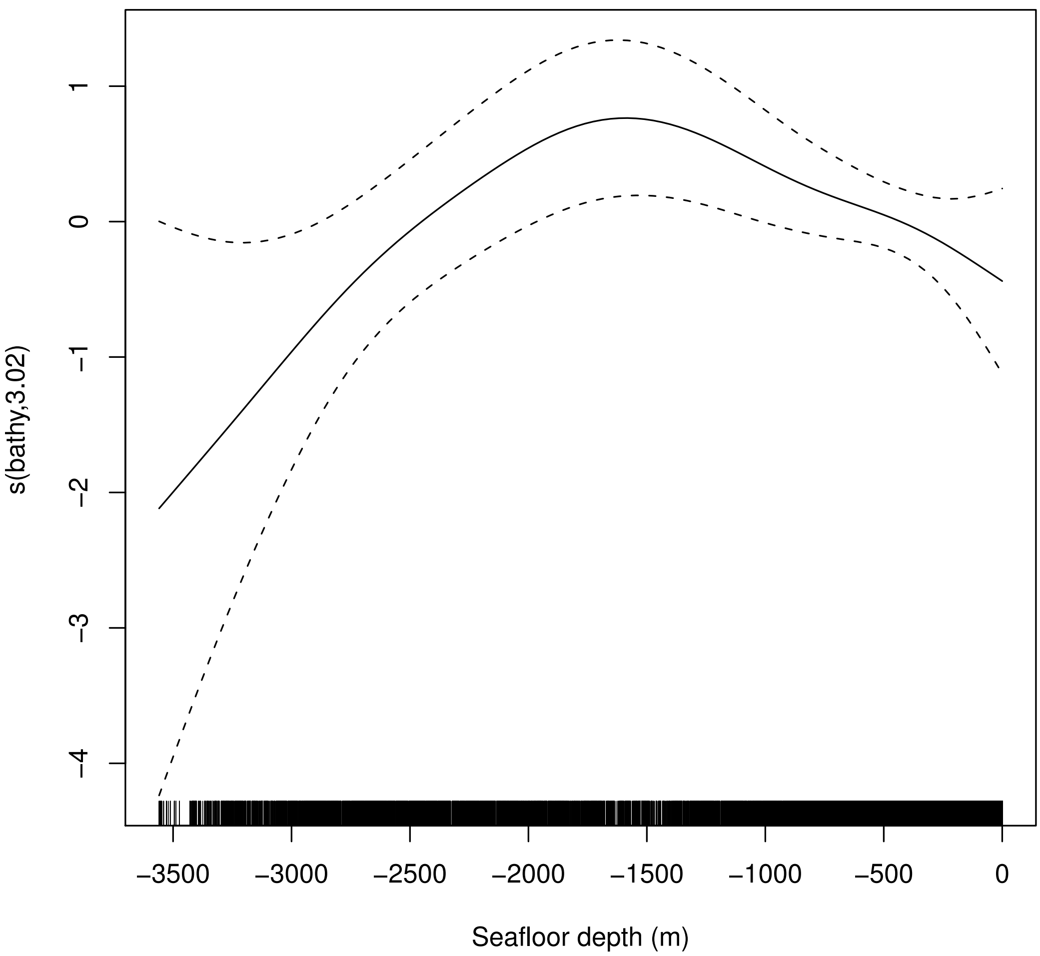


Figure 6 Contribution of bathymetry covariate to the spatial density model GAM 1. Y-axis in log-space.

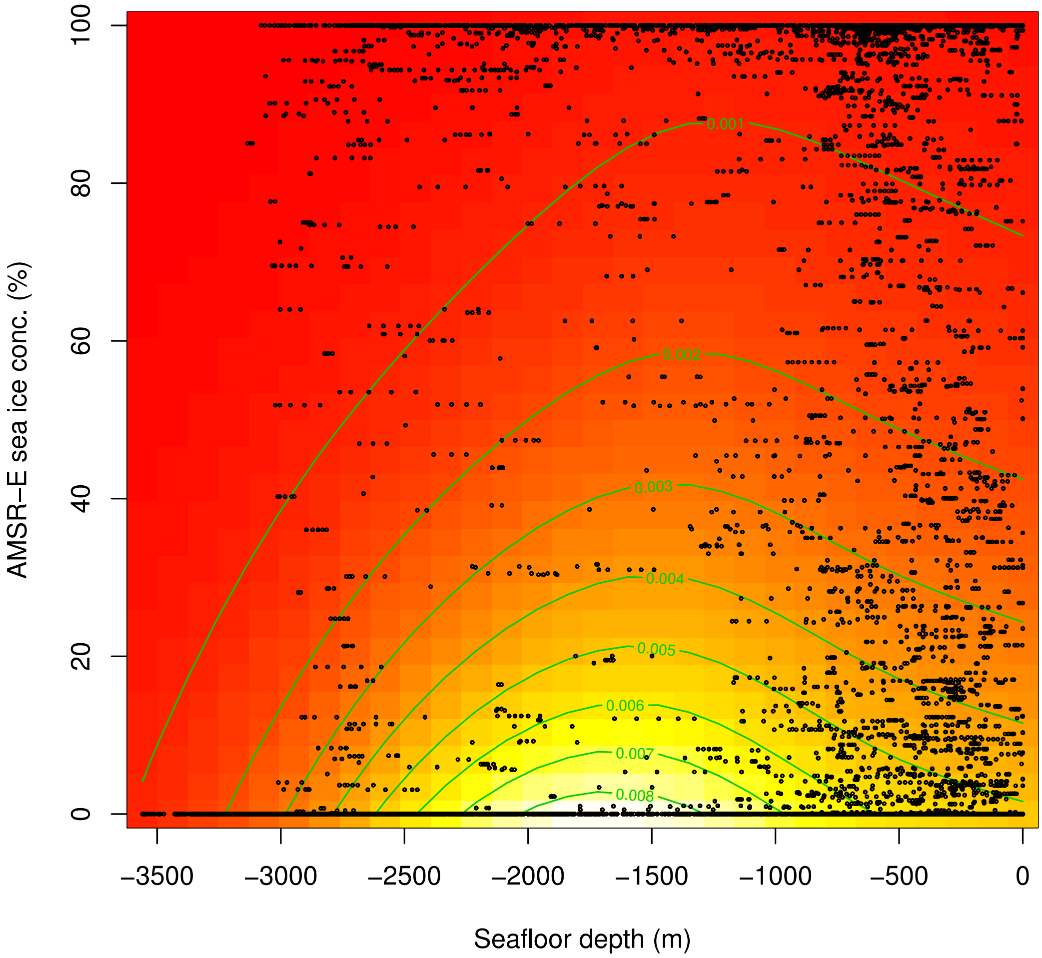


Figure 7 Predictions resulting from tensor smooth of bathymetry and ice concentration for spatial density GAM 2; contours represent estimated densities for a 1 km² region; black dots represent spread of sample points in covariate space.

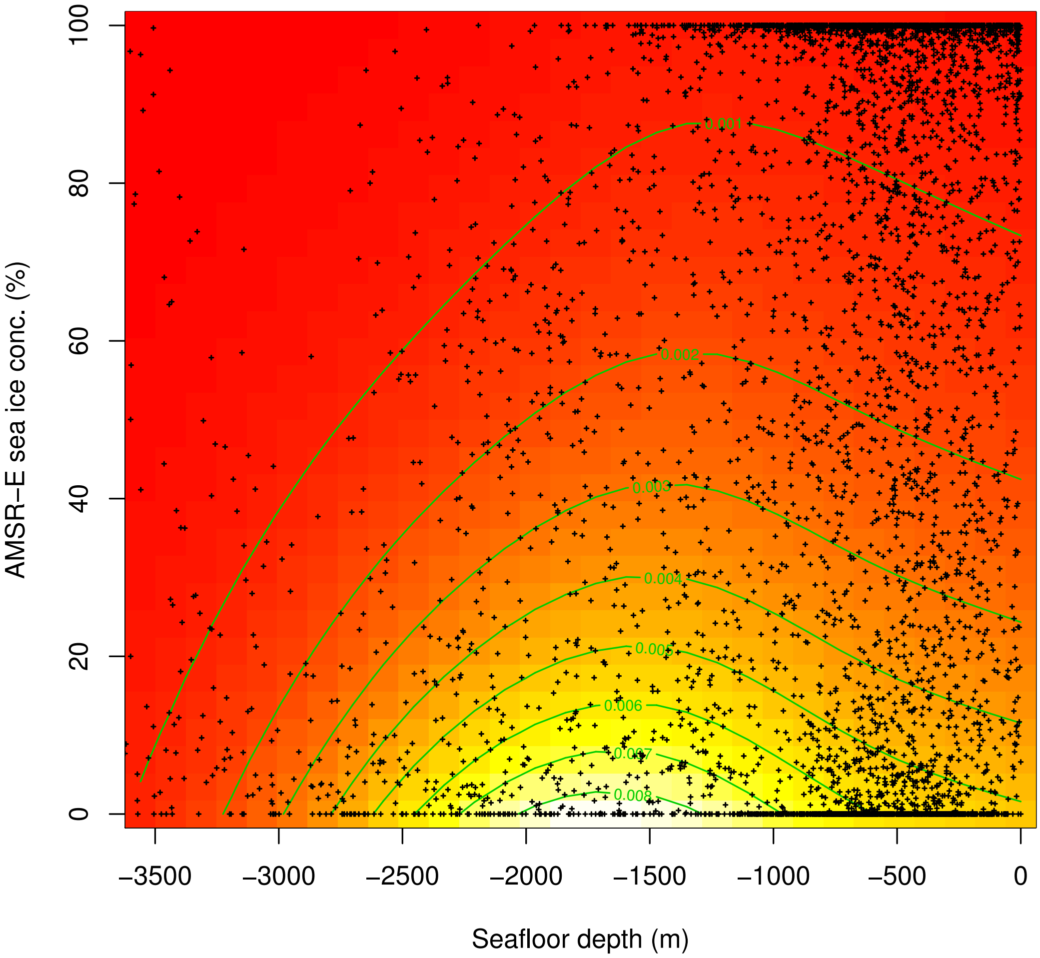


Figure 8 Locations of prediction points in covariate space for prediction grid spanning 100-130ºE on 20 January 2009.

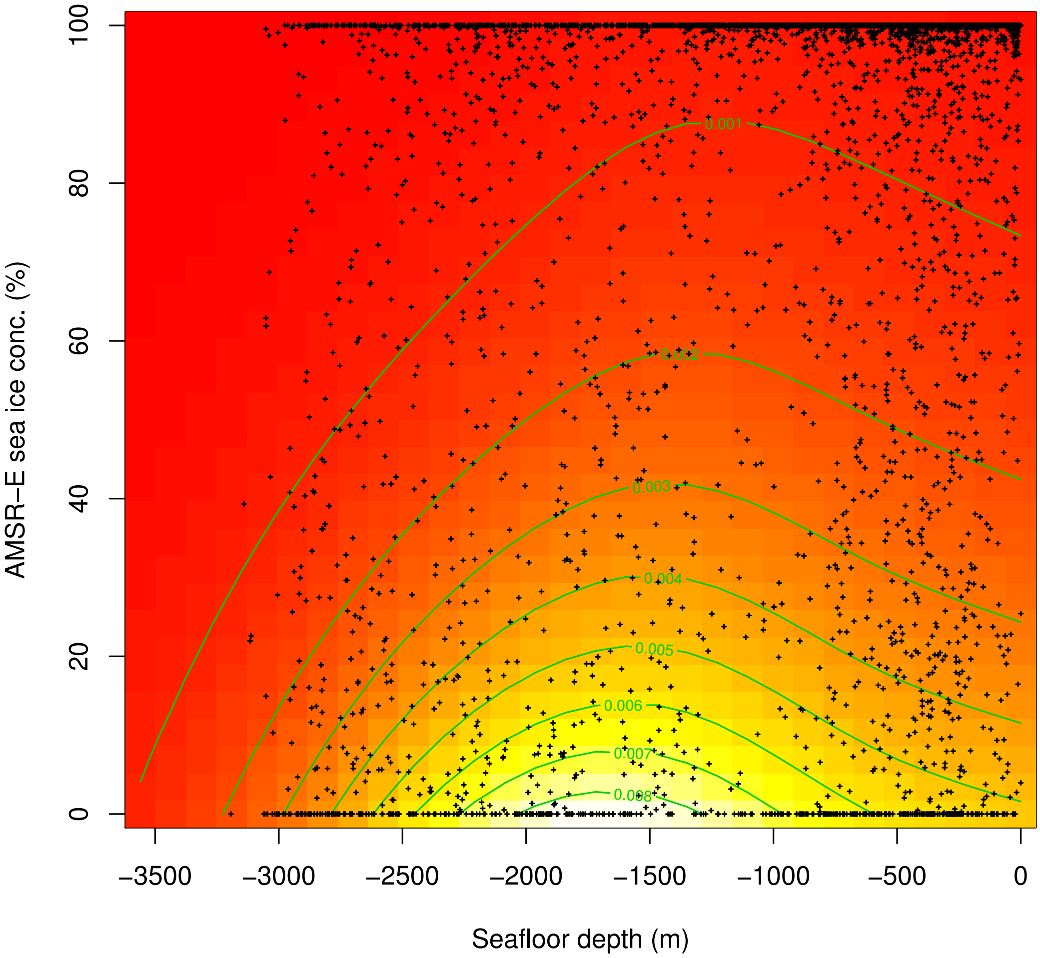


Figure 9 Locations of prediction points in covariate space for prediction grid spanning 100-130ºE on 22 January 2010.

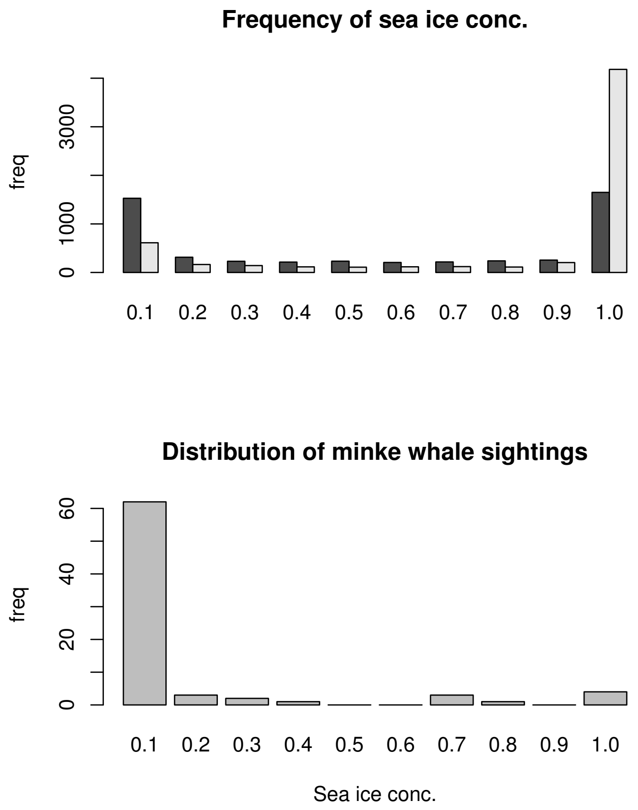


Figure 10 Upper plot: frequency of sea ice concentrations (binned at 10% intervals) for prediction grids for 20 January 2009 (darker grey) and 22 January 2010 (lighter grey). Lower plot: the frequency of minke whale sightings in each sea ice concentration (also binned at 10% intervals).

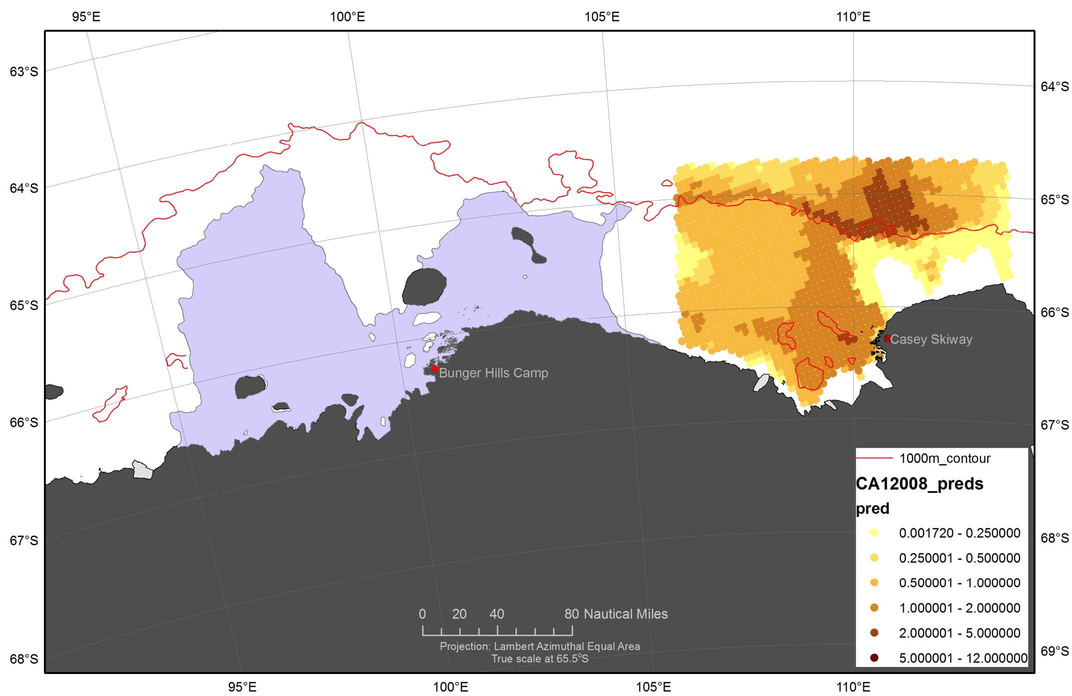


Figure 11 Spatial density model predictions of minke whale densities (per 39.1 km^2 grid cell) for CA12008 stratum. Minke whale density predictions based partially on AMSR-E sea ice data from 28 December 2008.

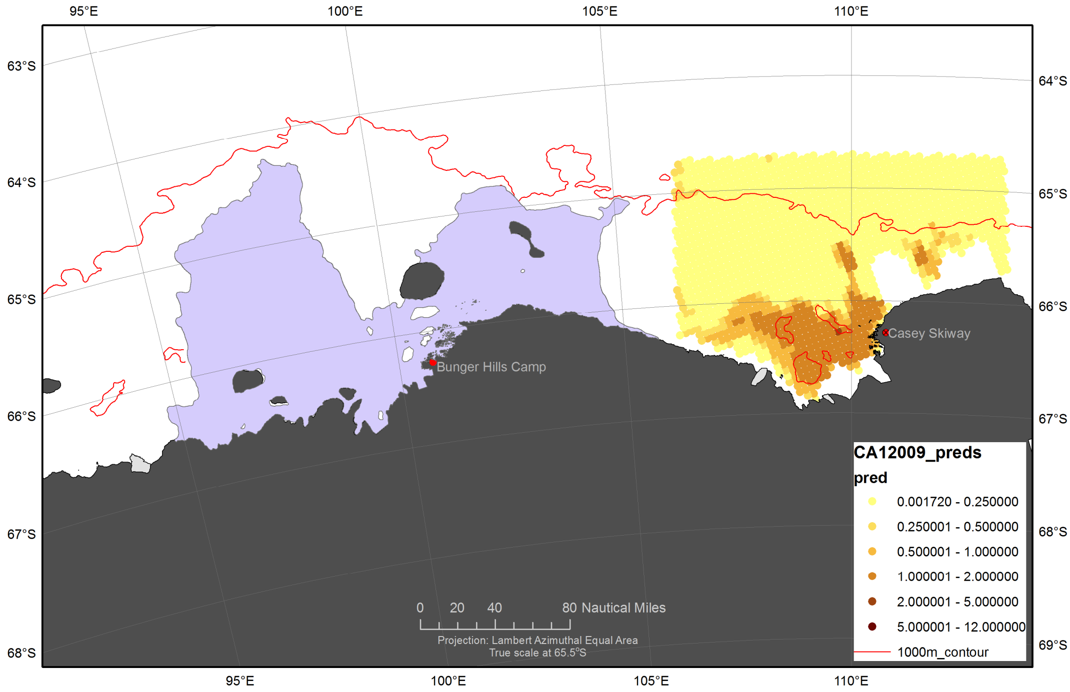


Figure 12 Spatial density model predictions of minke whale densities (per 39.1 km^2 grid cell) for CA1 (2009) stratum. Minke whale density predictions based partially on AMSR-E sea ice data from 22 December 2009.

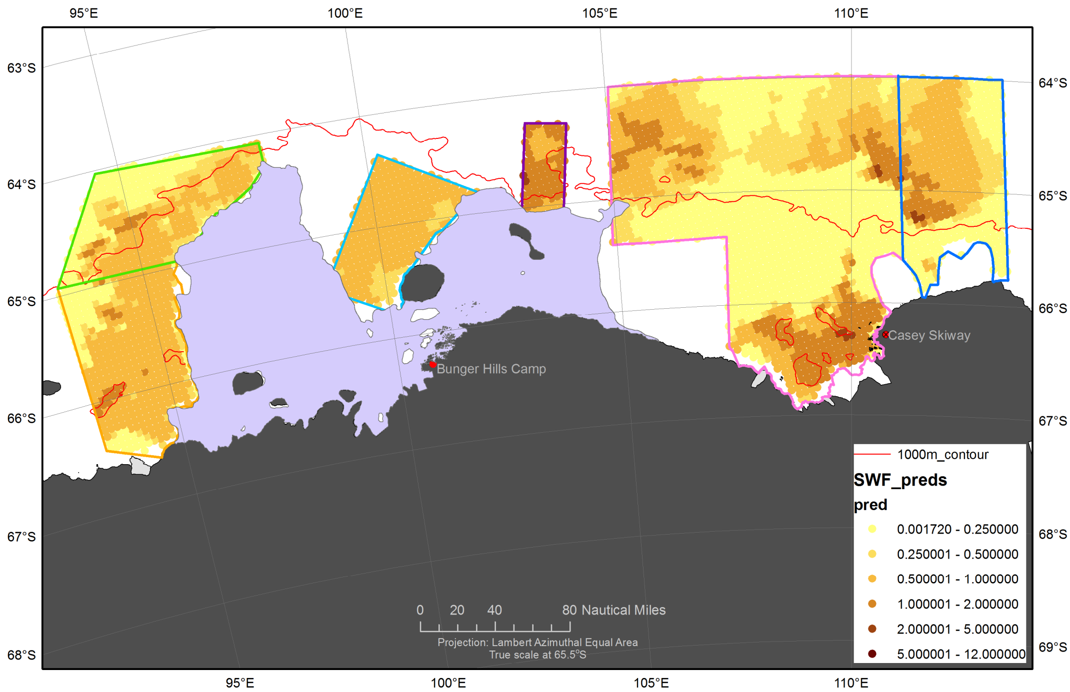
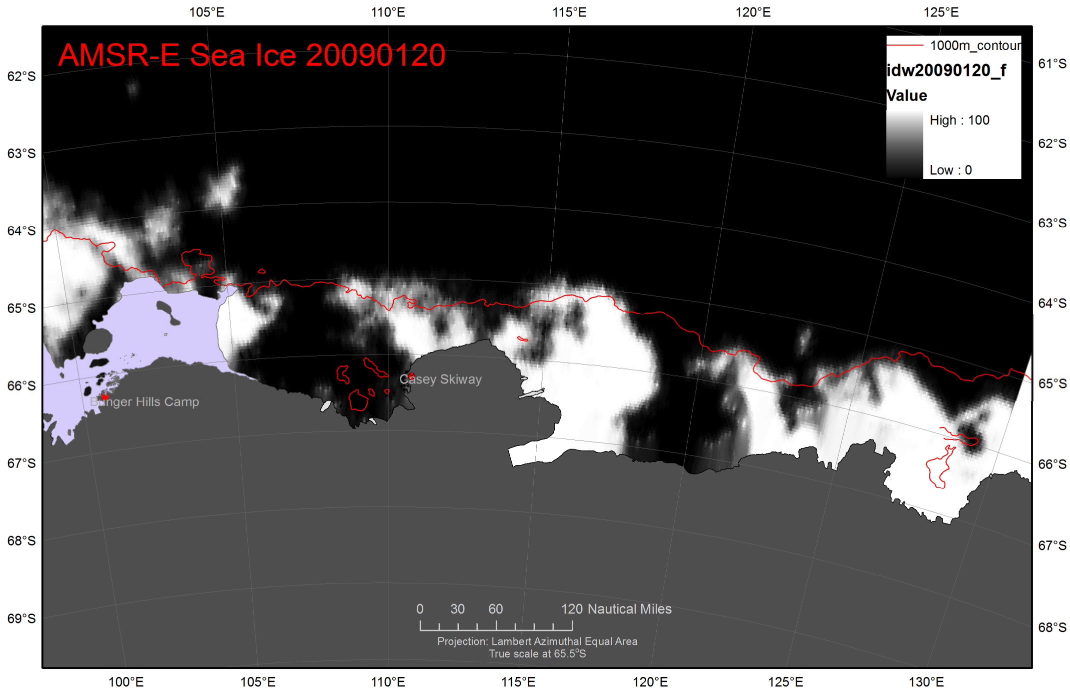


Figure 13 Spatial density model predictions of minke whale densities (per 39.1 km^2 grid cell) for DSS, DSN, SCN, SWF, CA2W and CA2E strata. Strata boundaries included for clarity. Minke whale density predictions based partially on AMSR-E sea ice data from mid-date that each stratum was surveyed (see Table 2 for details).



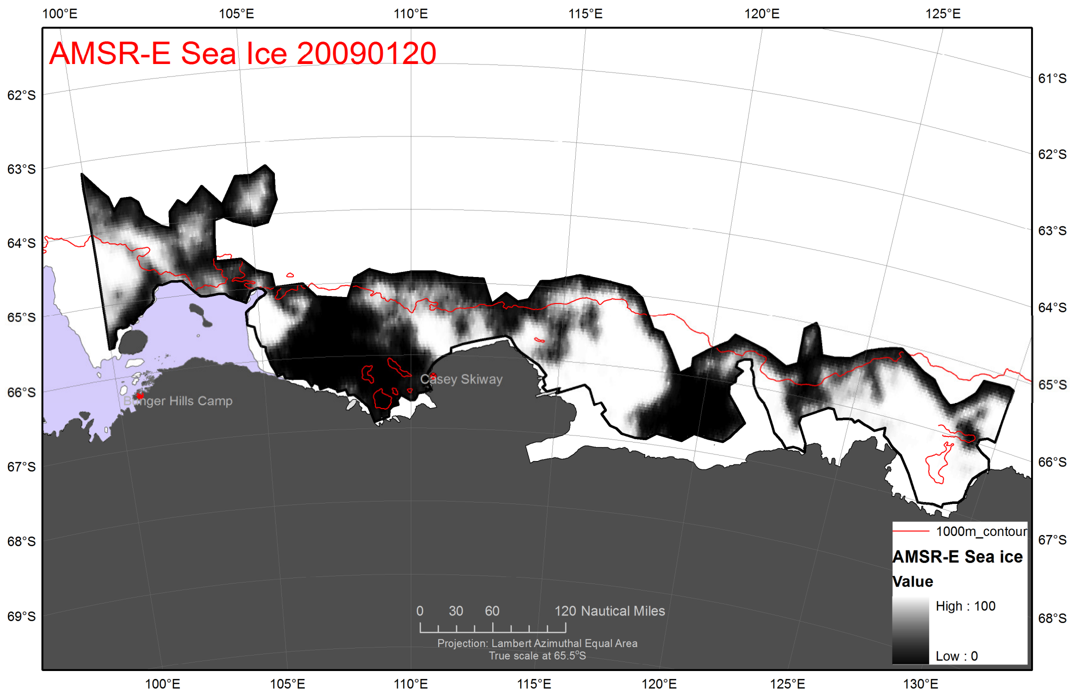


Figure 14 Upper: Sea ice concentrations (AMSR-E satellite) from 20 January 2009.
Lower: corresponding sea ice concentrations masked by polygon defining inside of pack ice (ice edge defined as 3% ice concentration) on 20 January 2009 between 100 and 130ºE. The slivers between the sea ice and the putative coast line represents areas that sea ice data is not available (probably due to outdated GIS masks used in generating the ice data).

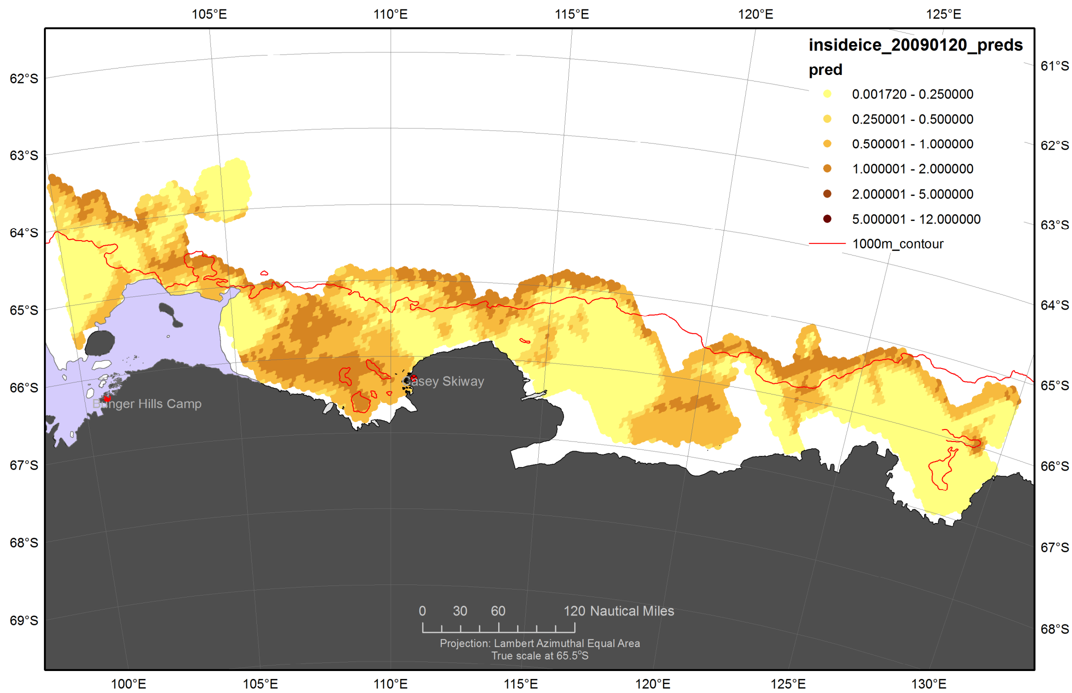


Figure 15 Spatial density model predictions of minke whale densities (per 39.1 km^2 grid cell) inside pack-ice (ice edge defined by 3% concentration) between 100 and 130ºE. Minke whale density predictions based partially on AMSR-E sea ice data from 20 January 2009.

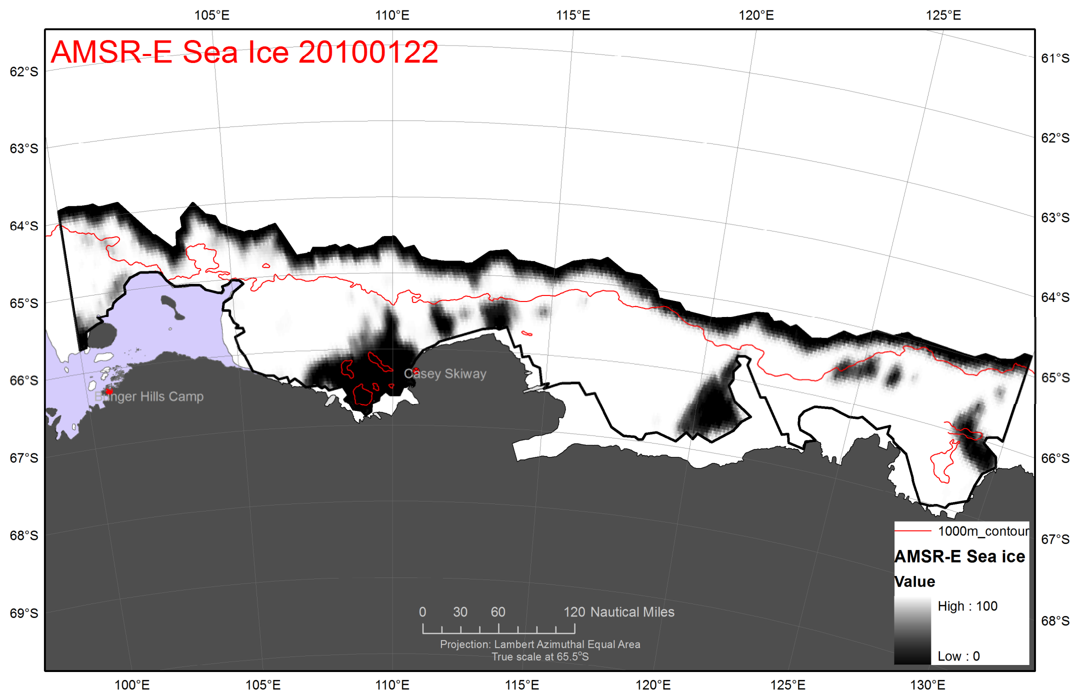


Figure 16 Sea ice concentrations masked by polygon defining inside of pack ice (ice edge defined as 3% ice concentration) on 22 January 2010 between 100 and 130ºE.

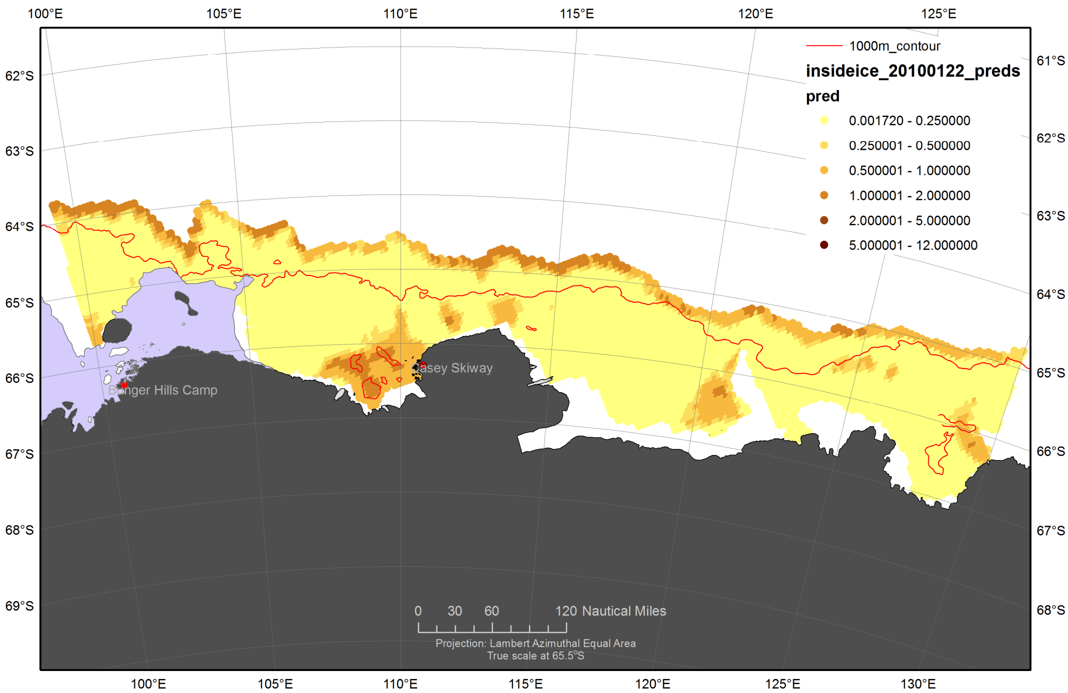


Figure 17 Spatial density model predictions of minke whale densities (per 39.1 km^2 grid cell) inside pack-ice (ice edge defined by 3% concentration) between 100 and 130ºE. Minke whale density predictions based partially on AMSR-E sea ice data from 22 January 2010.