Distribution and abundance of Antarctic minke whales in sea ice regions of East Antarctica: a summary of results

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Summary
The Australian Government supported aerial surveys over sea ice covered regions of East Antarctica with the aim to begin to estimate the proportion of Antarctic minke whales not accessible to sighting surveys in open water. The 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 sea ice, both within and between summer seasons. During these surveys, around 15 000 km of effort was achieved across 20º of longitude (93-110º E), yielding 65 sightings of minke whales (94 individuals). We produced model-based estimates of uncorrected abundances and densities (uncorrected for availability bias) within sea ice between 93-110ºE, and we present discussion on the range of corrected estimates possible given our current lack of data on availability bias for Antarctic minke whales in sea ice regions. Using 'pro rated' abundances from IDCR/SOWER, leveraged on simple estimates of encounter rate, there is some evidence that between 10 and 50% the minke population may have been within ice over those longitudes 93-113ºE during the 2009/10 summer. So we can conclude that the proportion of minke whales in ice regions is probably considerable, and will be an influence on biases on abundance estimates for open water regions. There is a clear need for more research to estimate availability bias in Antarctic minke whales.

Introduction
One source of bias not explicitly accounted for in the recently revised circumpolar abundance estimates of Antarctic minke whales (IWC 2013) was the proportion of the minke whale population outside the study region during the sighting surveys. During the weeks each summer season that the IDCR/SOWER surveys were conducted, some proportion of the population within the longitudes covered would have been either north of 60°S or inside sea ice regions that circle the Antarctic continent, where the non-ice certified survey vessels were not able to survey. Whilst the proportion of the population north of 60°S is thought to be negligible during the summer months , the proportion within sea ice areas, where minke whales have long been observed to distribute during the summer months (Laws 1977), is potentially much larger.

Some idea of the magnitude of the proportion, and of how much the proportion might vary with sea ice conditions (over a season, many seasons or at decadal scales), would be interesting in its own right, and valuable to the Committee for at least two reasons. First, there was a large drop in the circumpolar abundance estimate between CPII and CPIII, much larger than can be explained by sampling variability alone; although the drop may not be statistically significant after allowing for 'additional variance' (in the proportion of minke whales in survey blocks), that begs the question of why the 'surveyable' proportion of minke whales should vary so much, and differing proportions in the sea ice is one possible explanation (the other being large-scale longitudinal movement). Second, if the proportion of minke whales in areas that cannot be surveyed by ships is high, then there are design implications for any future surveys that aim to estimate absolute abundance, either regional or circumpolar.

With the aim of making a first pass at quantifying the proportion of Antarctic minke whales that may be in summer sea ice regions of East Antarctica, the Australian Government supported aerial surveys during the austral summers of 2008/09 and 2009/10 (following trial flights in 2007/08). Here we present model-based estimates of *uncorrected* densities and abundances (i.e., without accounting for amount of time animals spend away from the surface of water, or availability bias, *sensu* Marsh and Sinclair (1989)) of Antarctic minke whales inside sea ice areas (between 93° and 113°E derived from those aerial surveys). Ideally, aerial survey effort in the open water north of the ice edge would have provided density estimates with which to compare to those estimated inside the ice. Unfortunately, given limited capacity to extend transects north of the ice edge, and relatively poor sighting conditions when such effort was achieved, the resultant low number of sightings meant that such direct comparison was not possible. Therefore, in order to facilitate a comparison, we explored encounter rates in IDCR/SOWER surveys to scale aerial survey results to abundance estimates from adjacent open water.

Methods

The following is a brief description of the aerial surveys. See Kelly et al. (2009) and Kelly et al. (2010) for more details.

Study region and survey design

The aerial surveys were constrained to sea ice covered regions within flight range of airstrips inside the Australian Antarctic Territory in East Antarctica. For operational reasons, the surveys were based at the Casey station (66° 16.32'S 110° 31.65'E) in both seasons (the austral summers of 2008/09 and 2009/10) and some effort was flown from a field camp in the Bunger Hills in the second year (66° 10'S 100° 53'E) (Figure 1).

Final survey designs represented a trade-off between even spatial coverage over various sea ice habitats, and the targeting of polynyas within sea ice, as these areas of open water were thought more likely to support higher numbers of minke whales. Within flying distance of both Casey station and the Bunger Hills field camp there are four annually recurring polynyas, known as Vincennes Bay (65.97°S 108.30°E), Cape Poinsett (65.57°S 113.63°E), Shackleton Ice Shelf (65.28°S 104.22°E) and the Davis Sea (65.73°S 93.06°E), see Arrigo and van Dijken (2003) for further details. These four polynyas are located within a 20° band of longitude, and represent the broad range of sea ice habitats present in East Antarctica. The location and extent of these target polynyas were delineated prior to the start of each survey using satellite derived sea ice concentration data. Daily sea ice concentrations, gridded to a resolution of 6.25 km, were obtained from the Institute of Environmental Physics at the University of Bremen, Germany (http://www.iup.uni-bremen.de/seaice/amsr/). The sea ice concentrations were calculated with the ARTIST Sea Ice (ASI) algorithm using AMSR-E (Advanced Microwave Scanning Radiometer) data (Spreen et al. 2008).

Over the two seasons the aerial surveys were flown, the polynyas were surveyed in such a way to allow inter and intra-season, and longitudinal comparisons of densities of Antarctic minke whales. Vincennes Bay and Cape Poinsett polynyas were surveyed in December 2008, and again in both December 2009 and January-February 2010. The Shackleton Ice Shelf and the Davis Sea polynyas were surveyed December 2009-January 2010. There was also a small area surveyed in an attempt to target waters that had, a couple of days earlier, been surveyed by the SOWER vessel. In both survey seasons, transects over Vincennes Bay and Cape Poinsett polynyas (henceforth, referred to as Vincennes Bay) were parallel and systematically placed, and spaced at 10 nm; these were oriented north-south to be roughly perpendicular to both the shelf-break (depth of 1000 m) and average summer sea ice edge (Figure 1, upper and middle panel), both features considered to be important Antarctic krill habitat (Nicol 2006). For the Davis Sea and Shackleton polynyas, transects were equal-spaced and zigzag due to low fuel availability at the Bunger Hills field camp (Figure 1; lower panel). During the third coverage of Vincennes Bay, transects were extended further north in order to survey in open water beyond the sea ice edge.

Survey platform

The survey platform was a high-winged CASA-212 (400) aircraft. The target on-effort flying altitude was 213 m (700 ft), and speed was 204 km hr^{-1} (110 knots).The surveys were undertaken in a double-platform (double-observer) configuration, with two independent observing positions along each side of the aircraft. On board were four observers (two per side of aircraft), a flight leader (seated at the left-rear) and two pilots. The front and back observers were isolated visually with a curtain and not able to hear one another through the intercom system. Observers were encouraged to search ahead and as close to the trackline as possible. This was, however, quite difficult as the CASA-212 windows were flat and quite small (width: 280 mm; height: 270 mm).

The observations recorded for sightings consisted of species, group size and other group characteristics, and an indication of certainty for these. A Suunto inclinometer was used to measure the angle of declination (from the horizon) to the centre of a group when the sighting was abeam. Angles were measured to the closest 1°. The perpendicular distance from the trackline to the sighting was calculated using the declination angle and altitude of the aircraft.

There was also a video/digital stills camera system located in the aircraft. These cameras recorded the presence of whales in the area under the aircraft inaccessible to the observers and were also a permanent record of local sea ice characteristics. The digital-still camera system consists of three Nikon D-200 cameras, with 35mm lenses; one in the bottom of the fuselage behind a Perspex window, and two mounted obliquely at windows on either side of the aircraft. The system was designed to provide wide coverage, including under the aircraft and covering part of the observers' field-of-view (approximately 30º to 60º from the horizon). The cameras took images approximately every second which, at survey speed and altitude, gave complete coverage along track. Aerial photographs were used to estimate sea ice concentration directly beneath the aircraft using a cluster analysis (based on a mixture model) over a large set of images, to classify pixels as 'ice' or 'not ice' based on their RGB values. Hence we could calculate percentage ice cover in each image.

Detection function

Distance sampling (DS) methods were used to estimate the probability of detection as a function of distance from the trackline (Buckland et al. 2001). The double-platform configuration was used to estimate detection probability at the trackline via a mark-recapture (MR) approach (Laake and Borchers 2004, Borchers et al. 2006). The product of DS and MR results (MRDS) allows estimation of abundance without the assumption that $g(0)=1$ (Laake and Borchers 2004). Point independence between the independently operating observers was assumed for the purposes of estimating detection probability as a function of distance from the trackline. The MR component of the MRDS was estimated using a logistic model; the intercept of which was used to estimate detection probability at the trackline. Finally, a multiple covariate distance sampling (MCDS) model framework was used to estimate the detection function across both observers (Marques and Buckland 2004), with the assumption that detection at the trackline is certain (i.e. $g(0)=1$). The MCDS model gave the shape of the detection function.

Detection function (DS) and probability of detection on the trackline (MR) were estimated using the *mrds* package (Laake et al. 2013) in R (R Core Development Team 2013). Only sightings made during double-platform effort were included in detection function analyses. Covariates tested in the MDCS component, in addition to perpendicular distance, included sightability (a compound variable which describes the overall ease to observe whales dependent on weather conditions and ambient light levels), sea state, group size and mean local sea ice concentration. Half-normal and hazard-rate forms of the DS model were tested. For the MR component, covariates tested included perpendicular distance, group size, sightability, sea state and mean local sea ice concentration. Ice concentration was tested in both components to test for evidence that increasing complexity in the visual field may decrease the probability that a sighting is made. Akaike's information criterion (AIC) was consulted in selecting a best set of models. Perpendicular distances were truncated to exclude the furthest 5% of detections (Buckland et al. 2001). A left-truncation distance of 113 m was applied because the small windows and the presence of landing skis obscured the view directly beneath the aircraft to an angle of declination of around 62° from the horizon (unpublished field data). Sightings, and associated covariates, from both survey years were pooled to estimate a single detection function.

Estimating abundance and density

A density surface modelling approach was used to produce predictions on how the density of minke whales varied over space, and with some environmental covariates. It should be noted that until densities, or subsequent abundance estimates, can be corrected to account for the amount of time minke whales are diving at depth, or unavailable to be seen by observers (availability bias, see below), these results are 'relative' or 'uncorrected'.

The count method, as described by (Hedley and Buckland 2004), in combination with spatial generalised additive models (GAMs), was used to estimate trend in densities of minke whales across the study area. The response variable was the number of animals per 'segment' of transect, where the segment length was selected to ensure relative homogeneity in sighting conditions within a single segment. An offset variable was incorporated in the model to account for changes in estimated probabilities of detection within each segment, which ultimately manifest in differences in effective search areas of the segments. The offset, or the logarithm of the effective search area, was estimated using the MRDS model described above.

The modelling for the density surfaces was undertaken in R (R Development Core Team, 2013) using the *mgcv* package (v1.7-28) when fitting GAMs (Wood 2006). A Tweedie distribution (Jørgensen 1987) was used to model the count data. Variance from the detection function fitting was propagated through the GAMs to the ultimate abundance estimates using a method described in Williams et al. (2011) and Miller et al.(2013). Variables included in the spatial model included longitude and sea ice concentration (AMSR-E) across the survey area. A linear year term was also included in the spatial models. Abundances and densities were estimated within sea ice areas where aerial survey effort was undertaken. In order to produce a prediction grid for an area inside sea ice—for the longitudinal extent covered by the aerial surveys—a region between the ice edge (approximate 3% ice concentration) and the Antarctic coast line was selected. This area also included all ‘open water’ within the sea ice zone. Predictions associated with daily satellite sea ice data are relevant to the particular day sea ice data was derived for. The coordinates of the prediction grid correspond to the grids points of the AMSR-E sea ice data, which are spaced at 6.25 km intervals.

IDCR/SOWER voyages

The main goal of our aerial surveys was to see whether the abundance of minke whales in the sea ice is likely to be ’large enough to matter’, compared to the abundance in the open water areas that vessels, like those used during IDCR/SOWER surveys, could safely operate in. As mentioned above, we could not collect enough sighting data to allow direct comparisons of ‘inside ice’ and ‘outside ice’ densities of minke whales from the aerial surveys, so we have tried instead to work towards an upper bound on an absolute abundance within sea ice covered areas, which can then be compared with absolute abundances in open water from IDCR/SOWER’s CPII and CPIII, throughout similar longitudes. An obvious possible confounding issue, is that the longitudinal distribution of minke whales (in open water and in the adjacent sea ice) might have been quite different between the CPII/III survey years and our survey years. (Exploration of intra- and inter-season variation in sea ice conditions (e.g., Massom et al. (2013)) is one example of how this might come about.) We can, to some extent, check this because there were additional post-CPIII SOWER survey seasons in this region in our survey years. Although the coverage of those post-CPIII surveys is insufficient absolute abundance estimate for the open water areas, there was substantial effort fairly close to the ice edge using similar protocols to CPII/III. Hence, we can compare weather-adjusted encounter rates—for primary IO (independent observer) mode—from the post-CPIII to the CPII/III IDRC/SOWER cruises, to get some idea of whether our aerial surveys were undertaken in years which were reasonably typical in terms of minke whale longitudinal distribution.

Throughout CPII and CPIII of IDCR/SOWER, survey vessels operated in the vicinity of the aerial survey study area in the summers of 1988/89 and 1998/99, respectively—broadly corresponding to IWC Management Area IV (70-130°E). Details of the surveys undertaken in these two summers can be found in Branch and Butterworth (2001) and Branch (2006). During the ‘experimental years’ after the finish of CPIII in 2003/04, SOWER vessels surveyed open-water regions adjacent to the sea ice edge in Management Area IV in the summers of 2007/08 (Ensor et al. 2008), 2008/09 (Ensor et al. 2009) and 2009/10 (Sekiguchi et al. 2010), with a primary aim of collaborating with the Australian aerial surveys, which were running inside the sea ice over those seasons.

With the exception of the 2009/10 season, logistical constraints prevented SOWER vessels from operating across similar longitudinal extents whilst the aerial surveys were operating. For example, whilst SOWER effort undertaken in 2007/08 corresponds in longitudinal extent to effort achieved with the aerial surveys in subsequent seasons, no aerial survey effort was achieved in that summer (it was, instead, considered a flight trial). Because of the longitudinal coverage, 2007/08 SOWER effort is, however, included in this comparison. SOWER effort in the summer of 2008/09 was not considered in this study as it targeted open-water further to the west (i.e., 82-95°E) than any longitudinal coverage achieved under the aerial surveys, in addition to the fact that somewhat different survey design principles (for example, more tracking along the sea ice edge (Ensor et al. 2009)) where adopted in that year to those adhered to throughout CPII and CPIII.

Results and Discussion

Achieved effort and sightings

Achieved effort (in each survey area) is shown in Figure 1 and summarised in Table 1. More details about coverage of each survey, in particular the corresponding sea ice conditions, are given in Kelly *et al*. (2009) and Kelly *et al*. (2010). In total, there were 65 sightings of Antarctic minke whales, eight of these were 'like' minke sightings.

Detection function

Detection distances were right-truncated at 590 m for fitting the detection function. 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 half-normal detection function with a distance sample model scaled by group size (binned as: group size of 1; group size of 2; and a group size of 3-6), and a mark-recapture component specified by the binned group size variable and local sea ice concentration (binned as: 0-10%; 10-100%). The pooled detection function is given in Figure 3; see the Appendix for more details on this MRDS model fit. The estimated mean detection probability at the track-line (i.e., $g(0)$) for a single observer was 0.60 (CV = 0.12) and pooled probability of detection (i.e., that at least one observer in the double-platform configuration would see a sighting if it was on the track line) was 0.82 (CV = 0.08). Group size was the dominant covariate influencing the probability of detection. The effective strip width (one-side of aircraft) of the DS component was 0.22 km for group size 1, 0.45 km for group size 2, and 0.47 km for group size of 3+. Furthermore, an increase in group size from either 1 to 2, or 2 to 3+ increased the probability of that at least one observer would see the sighting by 2.5 times; moving from areas with greater than 10% sea ice concentration to open water areas increased the decreased the probability that at least one observer would see a sighting by 2.6. Permutations of including/excluding other covariates did not change, to any great degree, estimates of single- or double-platform effective strip widths.

Density surface models and abundance estimates

A segment length of 30 km was selected in order to balance between overdispersion in the number of animals sighted and having too much heterogeneity in density within a single segment. A spatial density surface, comprising a combination of smooths of longitude and sea ice concentration, and survey year as parametric factor, assuming a Tweedie distribution with a power variance value of 1.4, was judged to be the best GAM to describe the distribution of densities in the survey region, see Figure 4, and Appendix for more details on this MRDS model fit. The resultant uncorrected abundance estimates and CVs are given in Table 2. Again, please note these abundance estimates have NOT been corrected for availability bias. Discussion on this final step is offered further below. The selected detection function contained group size as a variable, and variance from estimating the frequency distribution of group size was propagated through to the ultimate abundance estimates using the delta method. The distribution of predicted uncorrected densities across various surveyed regions is given in Figure 6.

We were initially concerned about the modelled peak in uncorrected minke whale density between 100 and 105°E (see Figure 4, upper left panel), especially given a relatively low amount of effort contributed to this model feature (the 'SOWER follow' block, see Figure 2). However, effort and sighting data from the 2009/10 SOWER survey—which was surveying near the ice edge in this longitudinal band in the weeks on either side of the date that aerial survey effort that detected this feature was achieved—provided independent evidence that minke whales were in higher densities, as compared to areas further to the east (with the assumption that the higher density region extended on either side of the sea ice edge). Therefore, we decided to include this high density feature in estimating minke whale abundance and density across the aerial survey region.

A striking result is the difference in uncorrected density estimates between December 2008 and 2009 in Vincennes Bay, with almost 10 times the density of whales predicted in the 2008 season than in 2009. There were far more minke whale sightings made during December 2008 as compared to December 2009. 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. However, as survey year (a statistically significant variable) was accounted for in the GAM-based density estimates, it may be that there is more longitudinal movement between seasons than driven purely by seasonal sea ice conditions.

We can also compare uncorrected density estimates within a single season. The mean predicted uncorrected density of minke whales in Vincennes Bay during December 2009 was around 0.002 animals per km^2, and then in February 2010 was 0.003 animals per km^2, suggesting a very slight increase in density. During the month in between the repeat surveying of Vincennes Bay (i.e., December 2009 versus late January/February 2010), ice had cleared somewhat and a thick band of pack ice that had been blocking the entry to Vincennes Bay had weakened (see Kelly et al. (2010) for further details). However, given the CVs of these estimates of uncorrected abundance/densities are high, especially relative to the increase in estimated density over a year, it is unlikely they are significantly different (not specifically tested here). As an empirical check, three animals in two groups were observed in 3355 km of effort during the survey of Vincennes Bay in December 2009; eight animals in eight groups was observed in 4116 km of effort in the same area in January/February 2010 (see Table 1). This corresponds to a doubling of the raw encounter rate. Therefore, it may be valid to conclude that the slight increase in estimated uncorrected densities of minke whales in Vincennes Bay between December 2009 and late January/February may be more than just an artefact of thinning ice conditions over that time. It is, however, difficult to judge whether this is truly due to changes in sea ice conditions, or if more animals moved into the area.
The longitudinal gradient across the areas of the Davis Sea, the Shackleton Ice Shelf polynyas (including the SOWER follow effort), and further east to Vincennes Bay, are associated with considerable variations in predicted uncorrected densities minke whale, see Table 2. (Comparison of these densities with the assumption they are synoptic is reasonable given these areas were surveyed over a five week period.) Moving east between the Davis Sea and the Shackleton Ice Shelf polynya, there is a three-fold increase in uncorrected densities; moving further east again, there is a nine-fold decrease. (Note, the CVs on the estimated uncorrected densities for the western-most areas (Davis Sea, Shackleton Iceshelf polynya, etc) are high due to the relatively few transects flown (i.e., low total effort) as compared to the Vincennes Bay area (as demonstrated with the increasing confidence intervals around the longitude GAM in the western area)).

Finally, the ratios of differences in uncorrected density between areas, and within and between years, remained fairly constant over different configurations of predictor variables with candidate GAMs (e.g., we tested various combinations of variables, including within tensor product smooths of predictors). Furthermore, as explored above in more detail, uncorrected densities in different survey areas, and within and between survey seasons, scaled roughly with encounter rates (Table 2) and are, therefore, are unlikely to be the product of a spurious model.

We may conclude that uncorrected densities of minke whales within sea ice regions of East Antarctica are far from being homogenous in time, or over space (this study was able to explore, in particular a longitudinal gradient). There was a linear relationship between satellite-derived sea ice concentration and uncorrected minke whale density, where—inside sea ice regions—density decreased by about 19% for each 10% increase in ice concentration (see Figure 4). However, as these models were fitted with prediction in mind, and not inference of habitat preferences (e.g., multicollinearities in predictor variables were not explored to any great degree), it probably is not advisable to extend these results to predict for minke whale habitats beyond the longitudinal extents, and seasons, that the aerial surveys operated within. (That does not, of course, preclude the possibility that these data may be used for that purpose in the future.)

Availability bias

For an area of sea ice (i.e., out to an edge defined by 3% satellite ice concentration), between 93 and 113°E, on 22 Jan 2010 (the date selected to correspond to the approximate mid-point of the 2009/10 SOWER survey, the uncorrected abundance estimate of minke whales was 1635 animals (CV=0.41)). To reiterate, this value remains uncorrected for availability bias. In simplest terms, availability bias is the proportion of time animals remain at depths beyond which observers of an aerial survey cannot detect them.

We currently have no way to directly estimate availability for Antarctic minke whales. One possibility is to use data from other similar species. Heide-Jorgensen et al. (2010) used radio-tagging to get an availability bias estimate of 0.11 (CV=0.36) (i.e., these animals are only available to be observed a proportion of 0.11 for an observing period of just over two seconds) 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.*) Some empirical evidence for mean differences in behaviour between Antarctic and North Atlantic minke whales can be found in dive data. For example, Hedley (2012) reported a mean diving time of around 140 seconds for single Antarctic minke whales, whilst Christiansen et al. (2011) suggested that the mean dive time for North Atlantic minke whales might be around 86 seconds (averaged over regular and deep diving behaviours).
However, we have no way of knowing at this time how that might translate into differences in availability bias for an aerial survey. Inside the Antarctic sea ice zone, for example, minke whales are often clearly identifiable underwater, so availability is not limited to surfacing. The calmer waters inside sea ice areas allow animals to be seen that are deeper in the water than might be seen outside of sea ice, where the sea state is typically higher. Also, in heavier pack conditions, spy-hopping minke whale can be quite conspicuous. The flipside of this, however, is that reflected light from the chunks of ice oftentimes creates too much visual contrast to allow detection of subtle colour changes and movements of a cueing minke whale. In summary, we are unwilling at this stage to try to even estimate the direction of changes in availability bias across different ice types and concentrations, let alone the magnitude of that change. Furthermore, this is even before we consider changes in minke whale diving behaviour across different sea ice habitats.

Considering that during the aerial survey in East Antarctica, and given aircraft speed, altitude and window size, observers probably had, on average, around five seconds to see a minke whale in their field-of-view (unpublished data; c.f. the just over two second window for which the availability bias of North Atlantic minke whale was estimated Heide-Jorgensen et al. (2010)), an estimate of availability bias of around 0.11 is possibly an the extreme lower bound. Applying this lower bound availability bias to our uncorrected estimates (Table 2) gives an upper bound point estimate of 14900 whales (CV=0.41) in sea ice regions between 93 and 113° in late January 2010.

IDCR/SOWER encounter rates

Estimates of primary (IO) effort encounter rates of Antarctic minke whales during the years the IDCR/SOWER vessels were operating adjacent to the aerial survey region (i.e., IWC MA IV) are given in Table 3. Encounter rates were estimated for the region south of 63°S for all IDCR/SOWER years as effort for the 2007/08 and 2009/10 seasons was constrained to the southern stratum (see Figure 7); estimated encounter rates up to 60°S are included for completion. With the uncertainty around the encounter rates over the various seasons, the IDCR/SOWER encounter rates during CPII, CPIII and the seasons aerial survey were operating are similar, indicating that there was nothing exceptional about the two seasons the aerial surveys were conducted. Therefore, it is probably appropriate to consider estimates of abundance and density from the aerial surveys in East Antarctica in the context of considering biases for IWC MA IV.

Comparisons between aerial and IDCR/SOWER results

The total abundances in open water of minke whales in IWC MA IV, during CPII and CPIII, are given in Table 3 of this paper (but see IWC (2013) for more details and results). With a fairly linear coastline in IWC MA IV, and assuming uniformity in sea ice extents in the 1988/89 (CPII) and 1998/99 (CPIII) survey years, and a reasonably linear relationship between encounter rates and abundance estimates, a pro rata abundance estimate for the 2009/10 season, in open water within 93-113°E, would be around 13696. To judge the proportion of total abundance of Antarctic minke whales within 93-113°E in late January 2010 (i.e., inside ice whales + outside ice whales), the uncorrected abundance for the corresponding within sea ice area was multiplied by a range of potential values of availability bias (not propagating any error in availability bias), see Figure 8. For the upper bound point estimate of 14900 for minke whales within sea ice 93-113°E, this corresponds to a proportion of around 0.54 (i.e., that would indicate there were more whales in sea ice than outside of it) in the summer of 2009/10 in the event that average availability bias was as low as 0.11. However, without availability bias estimates, the range of possible proportions of animals inside ice regions of East Antarctica, 0.54 down to 0.11 (Figure 8), is a conclusive as we can be at this time.

In future it may become possible to estimate availability bias, across a range of different sighting conditions and sea ice types, for Antarctic minke whales. Two things would be needed: information on time-at-depth results across a range of ice conditions (including actual surfacing events, but also with depth profiles accurate to a metre or two at least near the surface); and information on the *visibility* of minke whales from the air as a function of depth and water clarity. Now that Antarctic minke whales have been successfully satellite-tagged (Friedlaender et al. *accepted*), the first is likely to arrive in the next few years (provided that the tags are able to record depth and are programmed to transmit the appropriate data summaries). The second might be harder to resolve. At least in principle, though, it could addressed as a gigantic Secchi disk experiment, using a whale-shaped target moored underwater at known depth and over-flights from a fixed-wing, helicopter, or drone aircraft, presumably somewhere close to an Antarctic land base.

Broader implications for IDCR/SOWER results and beyond

Circumpolar-level variations in productivity aside, given that the aerial surveys in East Antarctica were not able to explore relationships between minke whale distribution and latitudinal gradients in sea ice concentration, these results are probably limited in their capacity to predict for patterns of minke whale distribution in larger embayments, such as the Weddell or Ross Seas (but see Williams et al. (2014)). However, broadly speaking—but noting the GAM analyses in this paper were not optimised for explanatory modelling—minke whale densities decreased steadily with increasing satellite sea ice concentrations. Furthermore, there may be some evidence for minke whale densities varying somewhat within and between summers, independently of sea ice concentrations, but with limited replication in this study, it is difficult to draw a strong conclusions.

How can these results help the Committee interpret the change in circumpolar abundance of minke whales between CPII and CPIII? Given the overall design of the aerial survey programme, we were able to estimate not only uncorrected minke whale densities within sea ice regions of East Antarctica, but also to estimate how these densities might be varying through time and over various tens of degrees of longitude. Under the assumption changes in minke whale densities inside sea ice areas might either mirror, or certainly influence, the distribution of animals outside of the ice zone, then there may be information for new estimates of additional variance.

Using an extrapolated (from studies of Northern Atlantic minke whales) lower bound in availability bias for aerial surveys in Antarctic sea ice, we have presented some evidence that there could be up to around 50% of the total number of minke whales inside sea ice in East Antarctica. Given the limited longitudinal extent of the aerial surveys, we are not willing to extrapolate this finding beyond the IWC Management Area level, let alone to the circumpolar region. However, as we have found the encounter rates during CPII and CPIII to be similar to those of SOWER survey in 2009/10, there is some evidence that between 10 and 50% the population may have been within ice all over those longitudes over the summer of 2009/10. So we can conclude that the proportion of minke whales in ice regions is probably considerable, and will be an influence on biases on abundance estimates for open water regions. But, as to whether these biases are predominantly a product of animals moving en masse into ice regions over decadal scales, or perhaps whether the vagaries of the dynamic marginal ice zone influence the opportunities of vessels to find (or miss) high densities of minke whales (Williams et al. 2014), remains to be explored.

Regardless of any of these discussions, it is clearly important that funding be allocated to begin to estimate availability bias across a range of sea ice and open water habitats. Without this parameter, final abundance estimates of minke whales in sea ice regions can take on a large range of values. However, even at higher values of availability bias, this probably represents a substantial proportion of the total minke whale population.

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Tables

Table 1 Survey effort (≤ Sea state 4) and Antarctic minke whale sightings for 2008/09 and 2009/10 aerial surveys. (Sightings include those that were beyond the truncation distance for the distance analysis.)

Polynya/region	**Dates surveyed**	**Area (km^2)**	**Realised effort-double platform (km). (SS≤3 in brackets)**	**Realised effort – single platform (km) (SS≤3 in brackets)**	**Transects (n)**	**Sightings-minke (total animals)**	**Sightings-'like' minke (total animals)**
Vincennes Bay+Cape Poinsett	11 Dec-31 Dec 2008	17 668.1	5 295.0 (4731.9)	405.8 (405.8)	24	44 (63)	5(6)
Vincennes Bay+Cape Poinsett	16 Dec-27 Dec 2009	16 238.3	3 259.6 (3 220.5)	95.9 (75.4)	23	2 (3)	-
Davis Sea	29-31 Dec 2009	9 808.7	1 698.1 (1 584.1)	37.3 (34.0)	22	6 (9)	-
Shackleton+SOWER follow	31 Dec 2009-16 Jan 2010	4 478.3	665.2 (637.6)	2.2 (2.2)	8	5 (11)	1(1)
Vincennes Bay+Cape Poinsett	31 Jan-5 Feb 2010	25 013.9	4 082.2 (3 906.4)	34.3 (25.2)	20	8 (8)	2(2)
Totals			**15 000.1 (14 080.5)**	**575.5 (542.6)**	**97**	**65 (94)**	**8 (9)**

Table 2 Estimates of uncorrected abundance (with CVs) and densities (with 95% CI) of Antarctic minke whales in various aerial survey regions, for dates these predictions are relevant for.

	Dates	**Area of prediction grid (km^2)**	**Uncorrected abundance (CV)**	**Mean uncorrected density--animals per km^2 (95% CI)**
Vincennes Bay+Cape Poinsett Dec 2008	28 Dec 2008	55 937.5	1 198.0 (0.23)	0.021 (0.016, 0.029)
Vincennes Bay+Cape Poinsett Dec 2009	22 Dec 2009	55 937.5	137.2 (0.35)	0.002 (0.001, 0.004)
Davis Sea	30 Dec 2009	33 790.2	312.4 (0.51)	0.009 (0.004, 0.017)
Shackleton+SOWER follow	7 Jan 2010	20 368.7	543.9 (0.60)	0.027 (0.012, 0.057)
Vincennes Bay+Cape Poinsett	5 Feb 2010	55 937.5	176.8 (0.36)	0.003 (0.002, 0.005)
Inside sea ice, 93-113°E	22 Jan 2010	162 674.5	1 635.5 (0.41)	0.010 (0.006, 0.017)

Table 3 Length of primary effort, minke whale sightings and encounter rates for IDCR/SOWER surveys in the IWC Management Area IV. Encounter rates for results constrained by latitude and longitude.

Season (longitudinal ext)	Total distance primary effort	Sightings *n*	Enc rate--sightings per 100 km (CV)	CNB Abund. Ests for MA IV[#] (CV)
1988/89 (70-130°E, up to 60°S.)	9 973.126	312	3.13 (0.15)	51 241 (0.39)
1998/99 (80-130°E, up to 60°S.)	5 659.091	244	4.14 (0.17)	55 899 (0.49)
1988/89 (80-120°E, up to 63°S.)	3 946.516	131	3.32 (0.19)	
1998/99 (80-120°E, up to 63°S.)	3 467.93	260	7.49 (0.16)	
2007/08 (105-120°E, up to 63°S.)	1 127.52	44	2.36 (0.31)	
2009/10 (97-114°E, up to 63°S.)	1 899.6	36	3.19 (0.34)	

[#] As reported in IWC (2012).

Figures

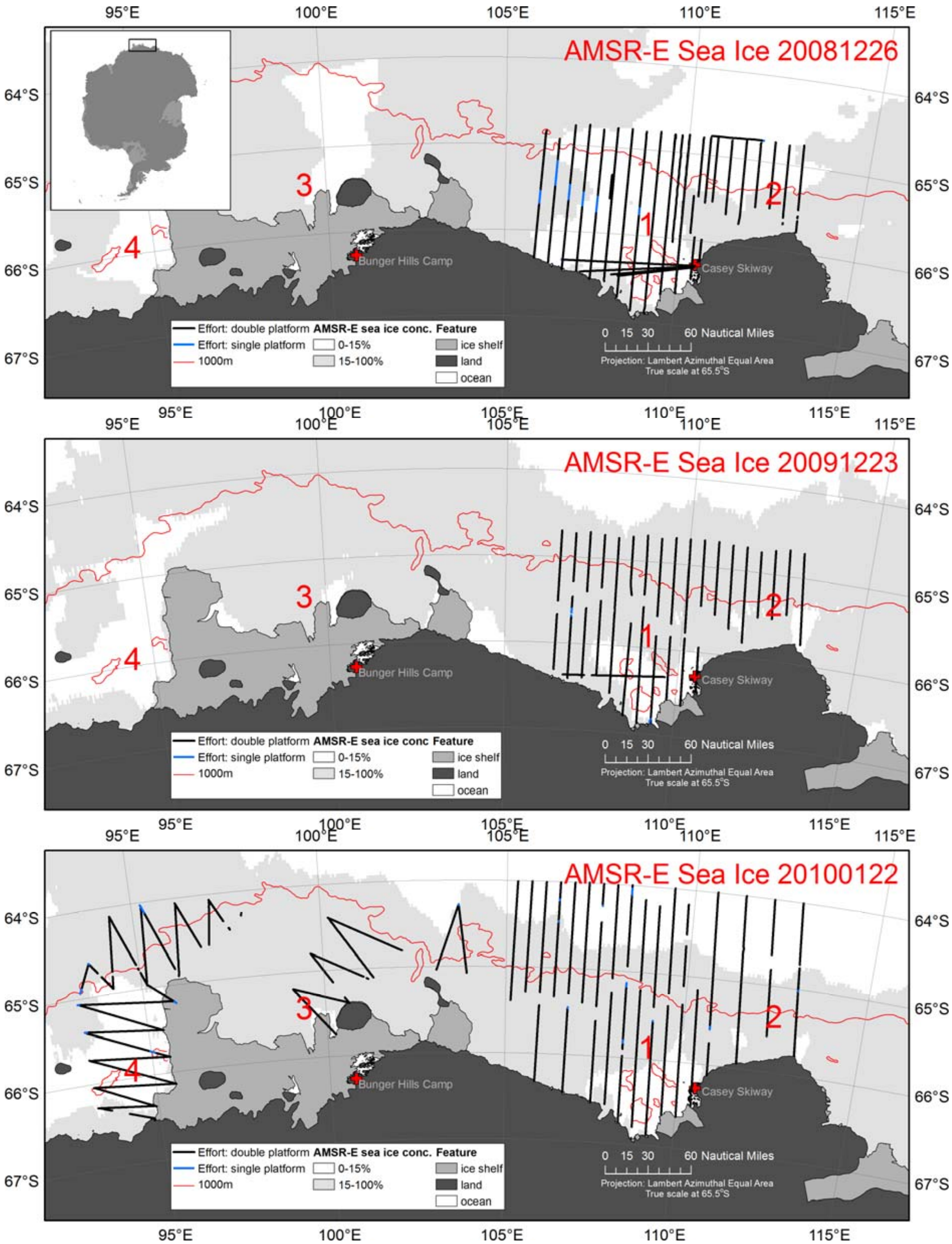

Figure 1 Realised survey effort for Beaufort Sea state <5 during the first survey season in December 2008 (top panel); the first phase of the second aerial survey in December 2009 (middle panel); and the second phase of the second survey in January/February 2010 (lower panel). Red numbers indicate polynya locations: 1, Vincennes Bay; 2= Cape Poinsett Polynya; 3, Shackleton Iceshelf Polynya; 4, Davis Sea. Dates the sea ice coverage apply for are given in the maps.

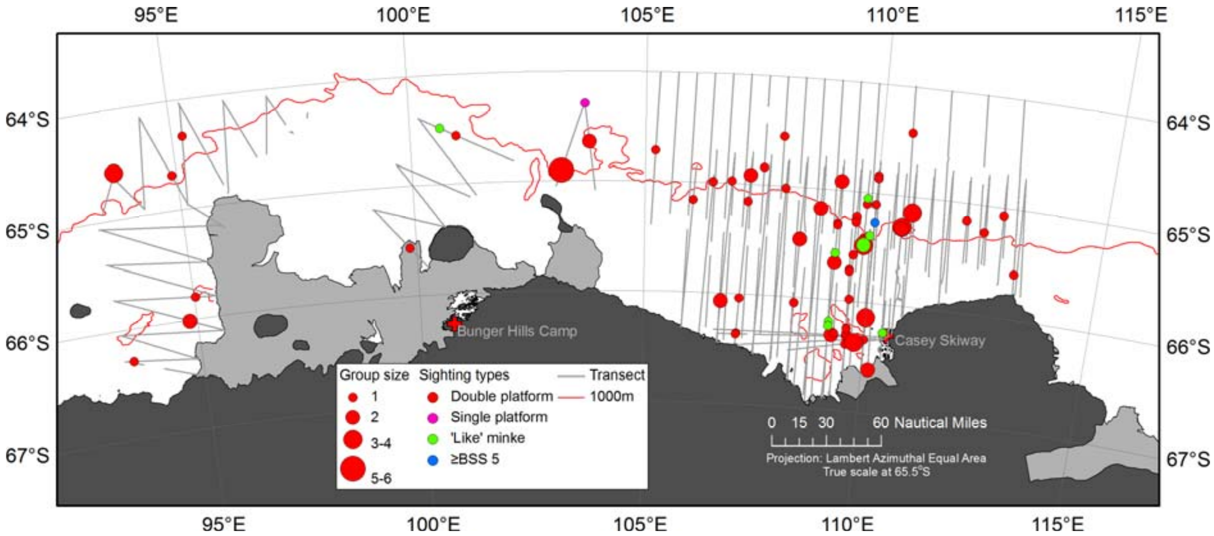

Figure 2 Distribution of sightings of Antarctic minke whales during all survey effort during 2008/09 and 2009/10 survey seasons.

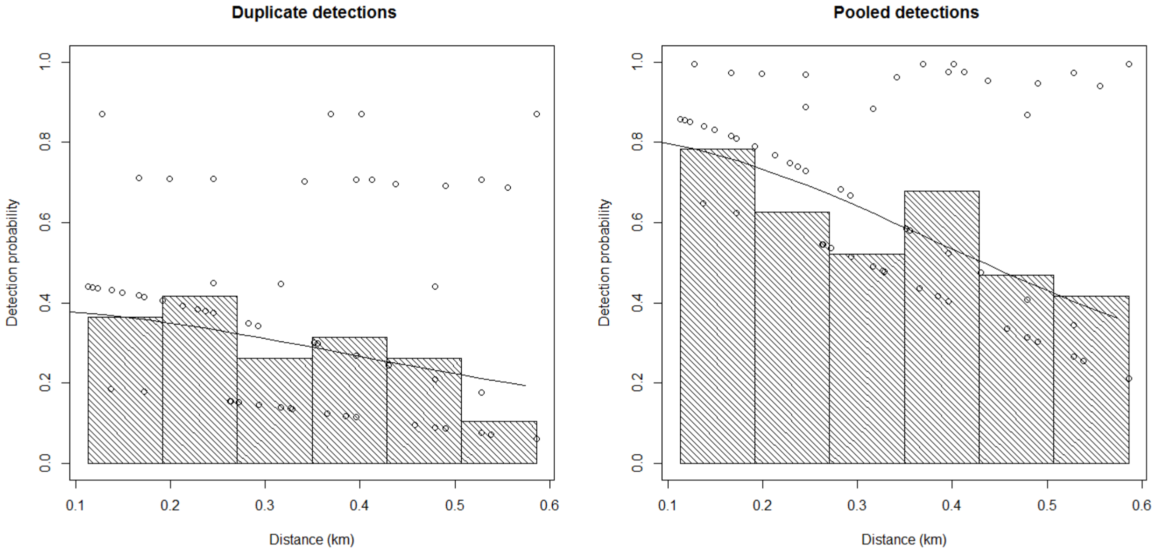

Figure 3 MRDS detection function fits. Circles are the probability of detection for each sighting given its perpendicular distance and other covariate values. Lines are the fitted models. In the pooled detection plot (right), the line is a smooth function fitted to the points. (Please note the x-axis does not start at 0 km.)

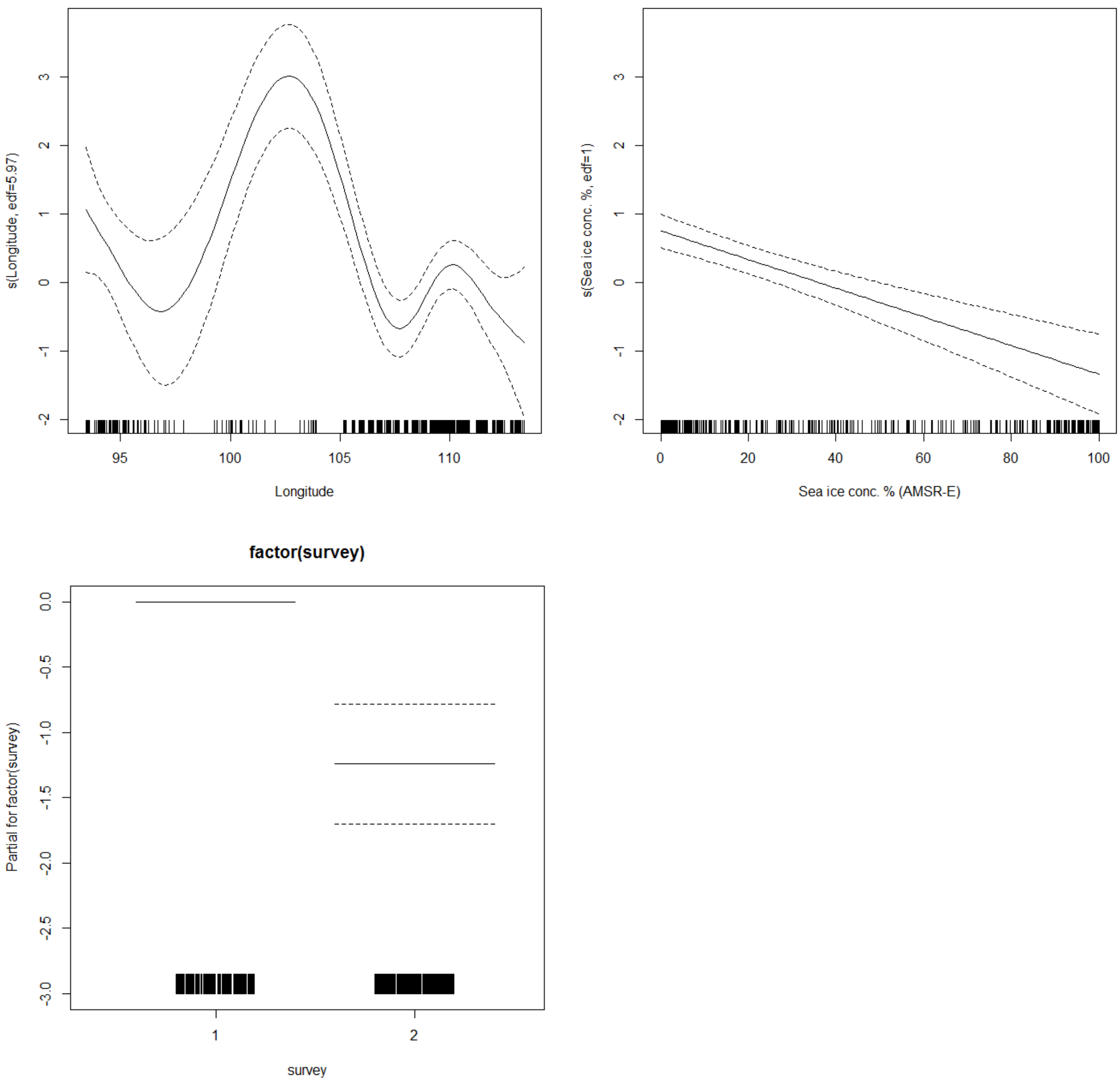

Figure 4 Effect of how minke whale density changed with longitude (upper left) and sea ice concentration (AMSR-E satellite; upper right), as modelled with GAMs; effect of survey season (1=2008/09 and 2= 2009/10) given in lower right plot. The rug ticks at the bottom indicate we have reasonable coverage of longitude between 93 and 113°E, and good coverage across all sea ice concentrations. The *y* axis in these plots is on the scale of the log-link function. Dotted lines indicate the 95% confidence band.

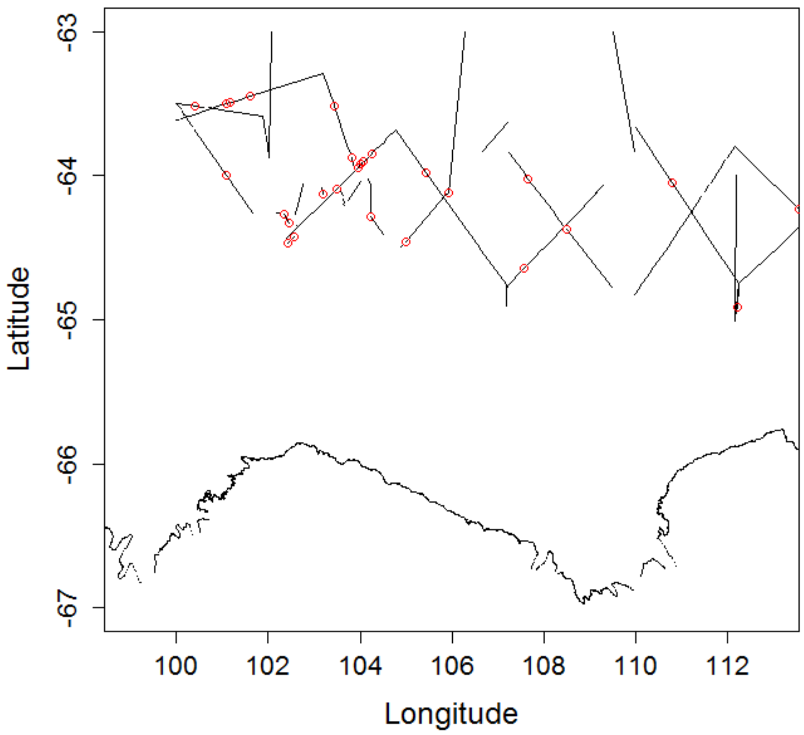

Figure 5 Distribution of Antarctic minke and 'like' minke whale sightings (red circles), and primary effort achieved (sightability score of 3 or better) during SOWER survey in 2009/10. Effort achieved between 9 Jan and 6 Feb 2010.

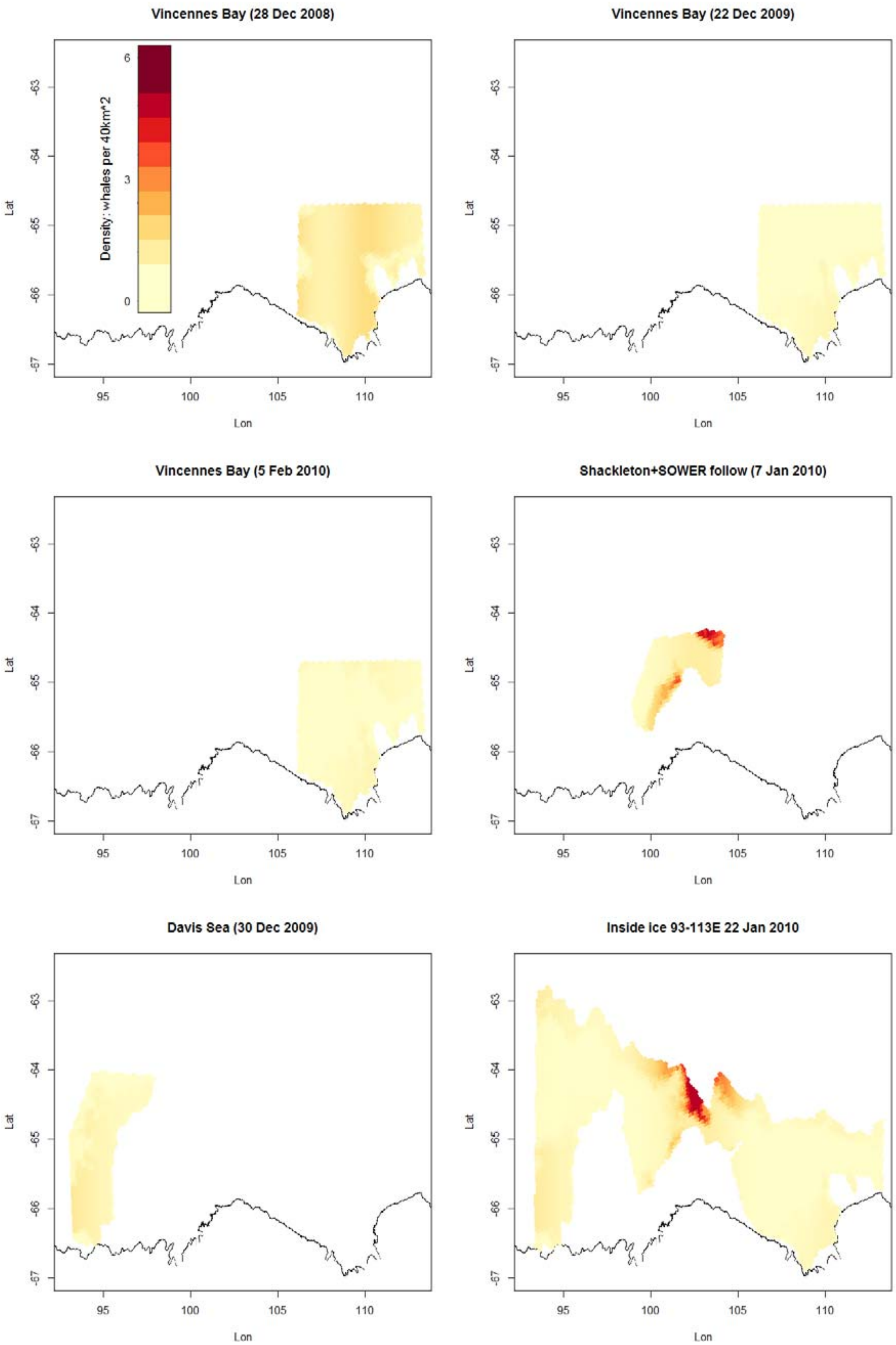

Figure 6 Densities of Antarctic minke whale throughout various survey areas, between 93 and 113°E (see density scale in upper left plot).

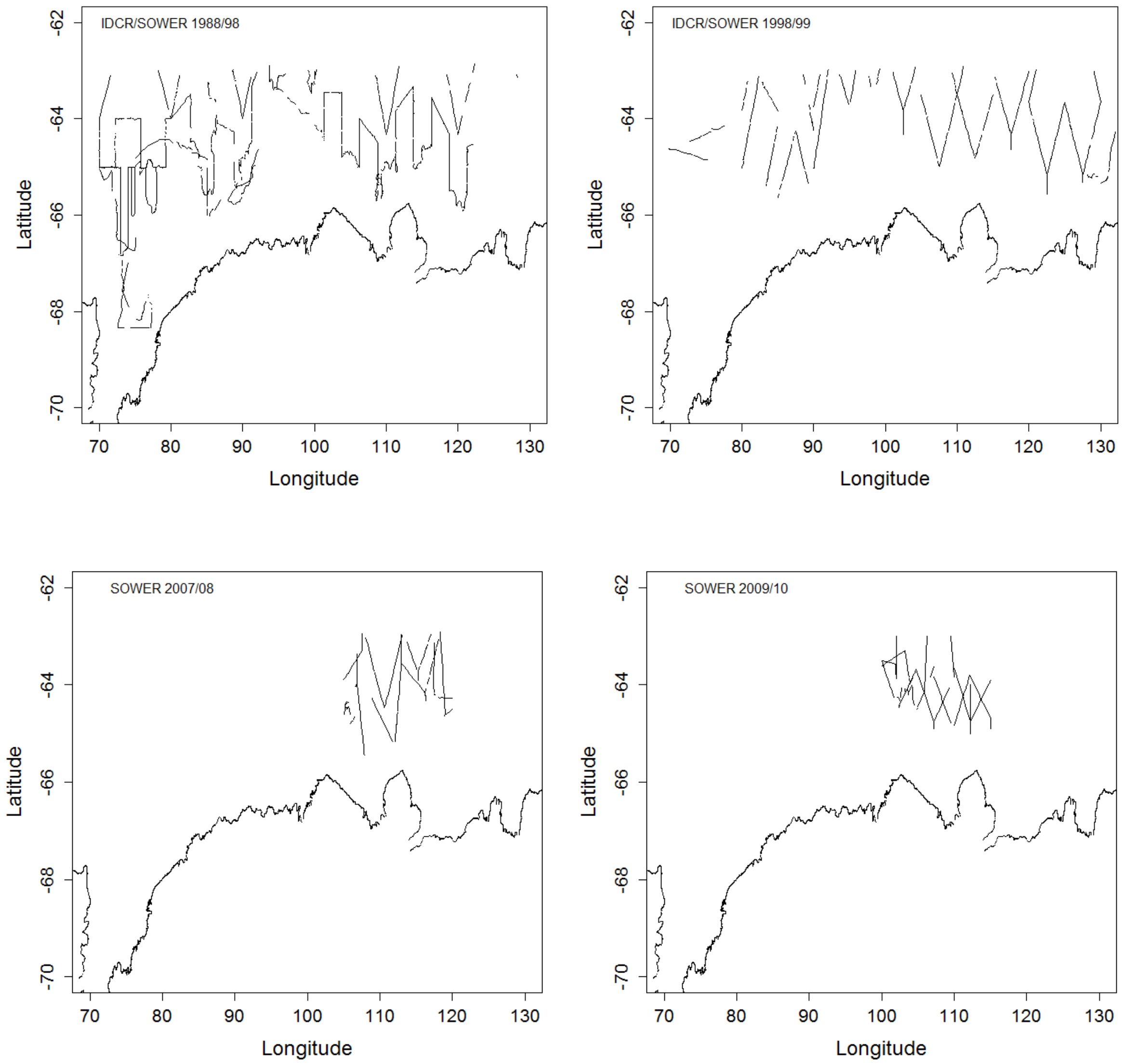

Figure 7 Primary effort (black lines) for IDCR/SOWER surveys in the IWC MA IV area; survey season indicated in plots. Only effort used to estimate encounter rates is shown.

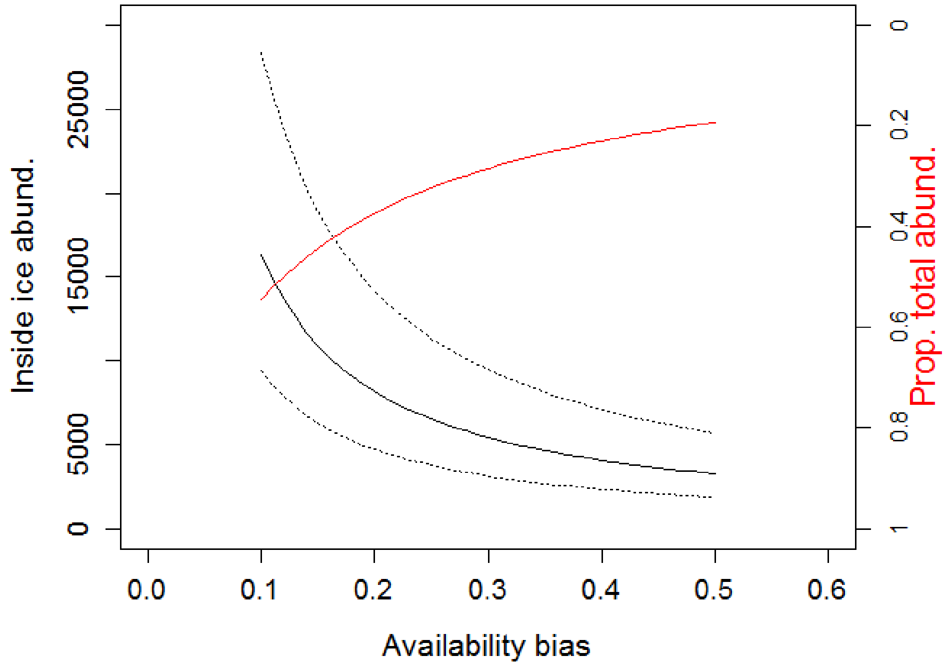

Figure 8 Estimates of corrected abundances of minke whales, 93- 113°E, for a range of availability biases (black line; dotted black lines indicate 95% confidence intervals). Corresponding proportion of total minke whale abundance, 93-113°E, up to 60°S (red line), axis on the right. (*Right y-axis reversed for clarity*.)

Appendix: Model outputs and summaries

Output from the *mrds* library for best detection function. 'size.1.2.3' is the binned group size variable, 'iceCat.mean.0.1' is the binned sea ice concentration variable (0= 0-10%, 1 = 10=100%).

```
Summary for io.fi object
Number of observations   :  67
Number seen by primary   :  55
Number seen by secondary :  45
Number seen by both      :  33
AIC                      :  137.1171


Conditional detection function parameters:
                  estimate        se
(Intercept)     -0.1975994 0.6529553
iceCat.mean.0.1 -0.9684958 0.5347139
size.1.2.3       0.9454218 0.4454509

                        Estimate          SE          CV
Average primary p(0)   0.6027847 0.07210648 0.11962229
Average secondary p(0) 0.6027847 0.07210648 0.11962229
Average combined p(0)  0.8199826 0.06788705 0.08279085


Summary for ds object
Number of observations :  67
Distance range         :  0.113  -  0.5860377
AIC                    :  -101.1886

Detection function:
 Half-normal key function

Detection function parameters
Scale Coefficients:
             estimate       se
(Intercept) -2.628589 13.76490
size.1.2.3   1.664652 13.75173

           Estimate         SE         CV
Average p 0.5742429 0.08883667 0.1547023


Summary for io object
Total AIC value :  35.92852

                       Estimate          SE         CV
Average p             0.4708692  0.08371994 0.1777987
N in covered region 142.2900514 28.49841593 0.2002840
```

Model output for density surface model (GAM) fit, as fitted in library *mgcv*. 'chunk.AMRS.cover' is the satellite sea ice concentration value for a given 30 km segment of transect; survey factor level 1= 2008/09 and level 2 = 2009/10.

```
Family: Tweedie(1.4)
Link function: log

Formula:
N.total.chunk ~ s(longitude) + s(chunk.AMSR.cover) + offset(off.set) +
    factor(survey)

Parametric coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)      -4.2903     0.1639 -26.178  < 2e-16 ***
factor(survey)2  -1.2416     0.2293  -5.415 8.87e-08 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                      edf Ref.df     F  p-value
s(longitude)        5.967  7.104 10.68 7.32e-13 ***
s(chunk.AMSR.cover) 1.000  1.000 38.03 1.25e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0489   Deviance explained = 22.1%
REML score = 256.11  Scale est. = 1.3616    n = 607
```