Appraisal of methods and data to estimate abundance of Antarctic minke whales within sea ice covered areas of the Southern Ocean

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Abstract
One hypothesis put forward to explain the putative drop in abundance of Antarctic minke whales, as derived from the IDCR/SOWER programme, between CPII (1984/85-1990/91) and CPIII (1991/92-2003/04) was that the animals were distributed more within sea ice regions during the CPIII period (i.e., away from survey transects). There is no way to test this hypothesis in a strict sense, but with new estimates of density of Antarctic minke whales (from aerial surveys) in particular areas of sea ice (Weddell Sea and east Antarctica), and model-based abundance methods which allow extrapolation, there is an opportunity to compare bounds and magnitudes of abundances to at least judge how likely the 'moved-into-sea ice' hypothesis is. In the first instance, it is recommended that comparisons of inside/outside abundances be made for areas and years where the aerial surveys were conducted. If these analyses are inconclusive, there is a recommendation to extend the analysis to estimating circumpolar densities, and extrapolating back over the period of CPII and CPIII, with full consideration given to how variable minke whale densities can be over space and time. However, until estimates of availability bias are produced, absolute abundance estimates for areas and seasons over which the aerial surveys were conducted will not be possible. Finally, in the event that large numbers of minke whales are in fact to be found in sea ice regions, there may be a case to undertake more aerial surveys in order to produce truly unbiased estimates of circumpolar minke whale abundances from any post-CPIII era survey efforts.

KEYWORDS: Model-based abundance estimates; availability bias; aerial surveys; sea ice edge; IDCR/SOWER

Introduction
In the years between 1978/79 and 2003/04, the IDCR/SOWER programme completed three circumpolar surveys in the Southern Ocean (IDCR from 1978/79 to 1995/96; IWC-SOWER 1996/97 to 2009/10; complete programme henceforth SOWER), focussing on areas outside of the sea ice zone, up to 60ºS (Branch 2006). A series of experimental cruises were conducted from 2004/05 to 2009/2010. Although sighting data were collected for a range of cetacean species, the primary focus of the SOWER programme was the Antarctic minke whale (*Balaenoptera bonaerensis*; henceforth, minke whale); the SOWER programme has provided the best data available with which to estimate circumpolar abundance of minke whales (Branch 2006). The minke whale is highly adapted to sea ice habitats (Ainley *et al.* 2007), and there is a history of this species being observed in a range ice concentrations (Ensor, 1989; Naito, 1982; Ribic, *et al.*, 1991; Taylor, 1957; Thiele and Gill, 1999). During the summer months, when sea ice extent—across the circumpolar region—is at its least, ice coverage can be up to 3-4 million km^2 in area (Gloersen *et al.* 1993), providing a large area of potential sea ice habitat for minke whales. As the vessels conducting the SOWER surveys did not access these ice covered regions, they will have missed a proportion of the circumpolar minke whale population; and the magnitude of that proportion remains unknown.

Initial analyses of data from the second and third SOWER surveys (CPII (1984/85-1990/91) and CPII (1991/92-2003/04)) indicated considerable differences in circumpolar abundances of minke whales south of 60ºS (Branch and Butterworth 2001; Branch 2006). This change has now also been defined at the level of IWC Management Areas, with preliminary analyses returning statistically significant decreases detected for Areas I, II and V (IWC 2012); but these results await revision and further consideration at this meeting of the Scientific Committee of the IWC. A number of hypotheses have been proposed to explain at least some of the change in abundance estimates; the most recent summary of these is given Murase and Bravington (2012). One hypothesis suggests that substantial numbers of minke whales moved into sea ice regions—areas difficult to survey or are completely inaccessible to survey vessels—during summer months throughout the CPIII period (Branch 2006), producing a negative bias in abundance estimates. (The mechanism for this would be either that the animals actively moved into sea ice regions, or that large-scale changes in the concentrations and extents of sea ice have shifted around where minke whales prefer to distribute themselves. Either way, there is no suggestion that the biology of the animals has changed over a number of decades, but that their preferred habitat may have become less accessible to survey vessels during the CPII to CPIII period.) The movement could also be related to increasing number of large baleen whales as well changes in environmental condition between CPII and CPIII, as indicated by Murase *et al.* (2011). Naturally, we cannot produce quality retrospective estimates of *absolute* or *relative* numbers of minke whales in sea ice regions during CPII and CPIII to correct abundance estimates currently under consideration. Instead, we could look to estimating likely boundaries or magnitudes of abundances of minke whales inside sea ice regions, to allow us to consider whether it is likely that the 'moved-into-sea ice' hypothesis is at least tenable. In the first instance, it is possible to use estimates of the current proportion of minke whales in certain sea ice regions (i.e., throughout areas where recent inside-ice surveys have been undertaken) as an indicator. That is, if the estimated number of minke whales in ice regions, during recent times, is small compared to the rest of the population outside the ice edge (for instance, as derived from recent SOWER surveys or portions of those within-sea ice surveys that may have extended into open water), then, on balance, the 'moved-into-sea ice' hypothesis is not likely to fully explain the drop in abundance estimates between CPII and CPIII. Alternatively, if the number of minke whales inside ice regions is of a similar magnitude to the putative drop outside, which has to be accompanied with the underlying assumption that minke whales were not in ice regions in substantial numbers during CPII, then this hypothesis must remain on the table, however ecologically unlikely, to be dealt with using an extended analysis approach. The other possibility is that densities of minke whales in sea ice region could be comparable between CPII and CPIII but abundances could be different because of change in sea ice condition (e.g., sea ice area). Such extensions would involve producing estimates of the numbers of minke whales inside the ice boundary (either current or, if quality sea ice concentration data is available for previous decades, retrospective), across all IWC Management Areas, by extrapolating results of recent surveys inside sea ice regions. Work to complete these extended analyses is not trivial, and should only be considered if the first, less formal analyses fails to dismiss the 'moved-into-sea ice' analysis. It should not be forgotten, however, that there have been many years between the timing of the within-sea ice surveys and the last time the SOWER vessels were in the respective areas (i.e., included in the CPII and CPIII abundance calculations); this time lag should be factored into any interpretation of the contribution of these results towards understanding the differences between CPII and CPIII abundance estimates (e.g., Murase *et al.*, 2009). Finally, regardless of how these general 'bounding' analyses progress, efforts towards estimating absolute abundance of minke whales in ice, in regions where aerial surveys have been undertaken, should continue in order to both develop that survey method and to make full use of those data.

A number of surveys, both aerial and ship-based, have been undertaken over the past two decades (with one more planned for the coming summer) which could help with the problems of: 1) estimating current relative abundance of minke whales in certain sea ice regions (i.e., in order to informally check whether animals are present in large enough numbers to start to explain 6n the putative drop in abundance between CPII and CPIII); 2) beginning to produce regional estimates of minke whales in sea ice *if* estimates of the current number of minke whales inside the ice edge is large enough to warrant taking analyses to this next step; and 3) to help understand their habitat preferences. However, some of these datasets have very limited coverage and/or methodological issues which might force subsequent analyses to be constrained or not worth the effort at all. The aims of this paper are to describe data from these surveys; to explore the pros and cons of each platform, and to discuss how these will influence estimating abundances; to consider the utility of each survey dataset in estimating abundances, and whether these data should be considered at all; to outline data requirements to achieve absolute abundance estimation in sea ice regions; and to speculate about a possible future survey and tagging programme to study minke whales in sea ice regions that may be required in the event that substantial numbers are in fact present.

Existing and planned surveys

Details concerning existing and planned ship-based (i.e., icebreakers) and aerial surveys inside sea ice regions are given in Table 1.These are surveys which have focussed some or all sighting effort inside sea ice regions (and the data from which would be readily available to members of the Scientific Committee (i.e., results from these surveys have been presented within SC or regular members of SC have analysed)). There are also a number of surveys, mainly using icebreakers, for cetaceans inside the sea ice zone, including minke whales, although these surveys did not follow standard line transect methods; the details have been included here for completion; see Table 2 of Ainley *et al.* (2012). We are also aware of a number of SO GLOBEC surveys conducted in autumn and winter, but the ownership of these data is unclear at this time.

There are two basic types of cetacean surveys that have been undertaken in sea ice regions around Antarctica: ship-based (i.e., icebreakers) and aerial surveys, using helicopters (operating from an icebreaker) or fixed-wing aircraft. Both types have pros and cons, which have been outlined in Table 2. Basically, sighting surveys undertaken on icebreakers are not considered appropriate for the purposes of estimate abundance due to the unknown attraction/repulsion effects of the ship upon minke whales (these animals can be attracted to the leads opening up behind the ship, particularly in heavy ice concentrations, yet possibly repulsed by the noisy engines and icebreaking). Furthermore, it is very difficult to maintain a straight transect while navigating heavy ice fields (Hedley *et al.* 2007). There may be some scope, however, to use these data to infer minke whale-environment relationships, which is expanded upon below.

Compared to ship-based surveys in ice regions, aerial surveys are considered the positive alternative for the purpose of estimating abundance, as aircraft can access considerably larger areas in much shorter periods of time; and there is not likely to be much or any animal reaction to the presence of aircraft flying overhead. However, aerial surveys are usually subject to imperfect coverage of the trackline (bubble windows help, but can be expensive to obtain and install) and as aircraft move so fast, there is a great chance that animals are missed because they were not available in the short period of time observers have to scan a given patch of water (although this can be accounted for if availability bias is known; see below). Helicopters do have the capacity to travel at much slower speeds, and to hover if necessary, but there would be a tension between maximising sighting effort and minimising availability bias this way. Furthermore, aerial surveys using fixed-wing aircraft require the presence of airstrips/skiways, from which to operate; these are quite rare in Antarctica. So, with fixed-wing surveys, at least, the region of sea ice that could be surveyed within a single season will always be quite limited (perhaps 10-15 degrees of longitude). The helicopter surveys undertaken from the *Polarstern* are a compromise between the two extremes in that it has the benefits of being able complete transects at speed but, being based on a ship, can operate over large areas, such as the Weddell sea. Helicopters are, however, subject to special constraints given the flight distances imposed due to safety requirements.

Particular features of existing survey data that could be exploited in further analyses

Ship-based surveys

Sighting surveys based on *Aurora Australis* (BROKE and BROKE-West surveys)

- Collected a suite of underway environmental covariates
- Broad longitudinal range (covering 30-150ºE, over two surveys, 10 years apart)

Sighting surveys based on the *Polarstern*

- There have been 4 surveys
- Collected a suite of underway environmental covariates, including sea state, well, ice coverage, cloud cover, glare.
- Same track between Capetown and Neumayer in 2006, 2008, 2010 and 2011
- Broad longitudinal range

Sighting surveys based on the *Shirase*

- Collected a suite of underway environmental covariates
- Covering 40-50ºE and 73-85ºE in 2004/05

Aerial surveys

Helicopter surveys operating from the *Polarstern* in the Weddell Sea and the tip of the Antarctic Peninsula

- Long, reasonably linear tracks through the sea ice region, from open water through to Neumeyer Station, a distance of around 700 nautical miles (calculated informally from a map, see Kock *et al.* (2009; SC/61/IA11)). This particular trackcombined with other survey tracks along the ice edge of the Weddell Sea will allow analysis of the distribution of minke whales along spatial gradients (i.e., from the coastline (or fast ice, at least) out into open water), see Williams et al. 2011.
- Afore mentioned ship track between open water and Neumayer Station has been repeated a number of times, so that might help with exploring inter-year variation in minke whale distribution and densities across a latitudinal gradient.
- Equally spaced, pre-planned transects around Elephant Island, west of the Antarctic Peninsula, Larsen A and B (which is to be repeated in 2013). Exploration of this data would probably warrant separate (i.e., local) study, particularly given the large changes in ice sheet configurations the Larsen B area.

Helicopter surveys operating from the *Shirase* in east Antarctica

- A limited amount of sighting effort was allocated in each site in 2004/05.
- Three short flights (2-3 hours) were conducted between 38°45'E and 43°57'E in December and February.

Fixed-wing surveys in east Antarctica

- Almost even coverage between coastline out into open water, between 93º and 113ºE (for 2009/10 season, at least), covering or partially covering the Vincennes Bay, Cape Poinsett, Shackleton and Davis Sea polynyas.
- Will enable exploration of small-scale inter-annual variation in minke whale distribution and densities as transects were flown in and around Vincennes Bay in December 2008, and December 2009, with some qualitative information collected in January 2008, as well.
- Will enable exploration of small-scale intra-annual variation in minke whale distribution and densities as transects were flown in and around Vincennes Bay in December 2009 then again in late January and early February.

Methods for abundance estimation

General approach

Given the difficulties in obtaining even spatial coverage, or complete transects for that matter, for both aerial or ship-based surveys, design-based methods are may be difficult to implement for the purposes of generating estimates of abundance of minke whales inside sea ice regions. This leaves model-based methods, such as those outlined in Hedley and Buckland (2004), and used in studies such as Herr *et al.* (2009), Bengtson *et al.* (2011) and Williams *et al.* (2011). In particular, these methods use generalised additive models to describe the way in which sightings of animals—density, to be more specific—vary with space or explicitly defined environmental covariates. These relationships can then be used to interpolate or extrapolate from the survey area (across a reasonable region, the definition of which dependent on application of results), depending on the extent and quality of the environmental covariates, in order to estimate an integrated abundance. A method to produce a more inclusive estimate of the variance of the integrated abundance has also recently been developed by Hedley and Bravington and described in Williams *et al.* (2011).

Informal local analyses

As outlined in the introduction, the first step to testing the 'moved-into-ice' hypothesis would be to estimate relative abundances of minke whales in areas around where aerial surveys have been conducted and to compare these to either: 1) recent or older SOWER data (depending on when and where particular SOWER voyages were), with accompanying assumptions about ranges of availability bias that might have been present, and to additional variance of abundances produced using SOWER data, given surveys were not synoptic across all regions of the Southern Ocean; or 2) to aerial survey sighting results outside the ice edge, where substantial amounts of effort was completed.

Fixed-wing survey in east Antarctica

Given the fixed-wing aerial surveys covered areas, in a reasonably even fashion, from just beyond the ice edge to the coast, there is probably little risk in extrapolating between these latitudinal extremes to estimate relative abundance of minke whales. Although many hours of effort outside the ice region where conducted during the 2009/10 season, there were only six sightings that would be considered in 'open water', north of the ice edge (see Kelly *et al.* (2010SC/62/IA8) for further details).As such, it is not valid to use this data for an inside/outside ice comparison. However, the last two years of the SOWER programme coincided in season and rough location with the fixed-wing aerial survey (particularly the 2009/10 season); see Table 3 for how the two programmes overlapped. Therefore, direct comparison with SOWER, with appropriate caveats concerning how availability bias was dealt with for the aerials survey data (see below), results remains the only way in which to make inside/outside comparisons with the fixed-wing area survey data.

Unfortunately, absolute abundance estimates for minke whales have yet to be produced for the 2008/09 and 2009/10 SOWER seasons. Therefore, a comparison of encounter rates for these last seasons, and with those that do have existing abundance estimates (i.e., 1995 for Area IV-W (70º-100ºE) and 1999 for Area IV-E (100º-130ºE)), will have to suffice in order to provide crude multipliers between these encounter rates and absolute abundance, corrected for weather conditions and sightability. Naturally, if model-based methods are applied to the last few seasons of SOWER to produce minke whale abundances for the respective areas, these should be used instead.

As outlined in Kelly *et al.* (2011; SC/63/IA3), relative abundance estimates for minke whales inside the ice have been produced for Area IV-E (i.e., 100º-130ºE), using AMSR-E sea ice data from late January, 2009 and 2010, respectively (dates selected to be reasonably representative of the seasonal date that both the aerial surveys and the SOWER voyages were underway). A rough conversion to absolute abundance, using availability results from common minke whales (e.g., Heide-Jørgensen *et al.* (2009)), was also presented (with the caveat that the availability bias of common minkes is probably much lower than Antarctic minke whales, so this absolute abundance estimate would be at best an upper bound, at worst, a gross overestimate). Any subsequent analysis and interpretation of the density and abundance results from the fixed-wing aerial survey should be accompanied by a sensitivity analysis based on a range of potential availability biases. Finally, in creating these rough absolute abundance estimates, there should also be scope for adding intra-and inter-seasonal variation, as observed across the 93º-113ºE area in the 2008/09 and 2009/10 surveys.

In summary, these suggested analyses will allow comparison of crude absolute abundance estimates of minke whales inside-ice (actually, a range of values) for late January, with both the estimated drop in abundance between CPII and CPIII for Area IV-E and with (currently) crude minke whale abundances outside of the ice edge, as estimated from 2008/09 and 2009/10 SOWER data. This comparison needs to be accompanied with the consideration that, according to preliminary analyses, Area IV was not one in which a significant change in minke whale abundance seems to have occurred (IWC 2012).

Helicopter surveys north of Dronning Maud Land, across the Weddell Sea and tip of the Antarctic Peninsula

The idea of delineating representative areas (that is, a contiguous area that contains the geographical location and the range of sea ice concentrations represented across all survey effort, throughout which it would be reasonable to interpolate/extrapolate estimated densities) was more problematic for the helicopter surveys, given coverage was largely comprised of small-scale rectangular transect configurations distributed somewhat irregularly across vast areas north of Dronning Maud Land, around the Weddell Sea and the top of the Antarctic Peninsula. Latitudinally, the surveys never ventured deep into the Weddell Sea embayment, but rather tacked along its upper reaches as the *Polarstern* accessed Neumayer Station and moved across toward the tip of the Antarctic Peninsula (Scheidat *et al.* 2011). Therefore, a representative area would not reach down as far as the more southern regions of the Weddell Sea, which includes the polynyas that open up near the Ronne Ice Shelf and Halley Bay (Barber and Massom 2007). One benefit of the helicopter survey data are many hours of effort over open water outside of the putative ice edge. So, one idea might be to consider the representative area for the helicopter surveys to be 500 km on either side of the putative ice boundary in the Weddell Sea region (i.e., defined as a smoothed line connecting the 15% sea ice concentration, according to the AMSR-E sea ice data), between longitudes 62ºW and 11ºE. This would take into account that a range of sea ice concentrations were surveyed, but most of the survey effort was within 500 km of the location of the ice edge on the day given transects were flown. Furthermore, on average, over the January period, 500 km either side of the ice edge generally represents a substantial proportion of the marginal ice zone and nearby open water in the Weddell Sea region. Therefore, any abundance estimates derived using this representative area will likely capture a large proportion of the available minke whale sea ice habitats in the Weddell Sea region.

Using the same assumptions about applying estimates of availability from common minke whales, rough 'absolute' abundance estimates could be estimated from these helicopter surveys, across the described representative area, both inside and outside the putative ice edge. However, this will only provide a rough estimate of abundance inside ice areas, and it will have a negative bias to some degree given that the area does not represent polynyas further south in the Weddell Sea region. But the platform does offer data to provide some estimate of intra- and inter-year variation minke whale densities along the tracks into Neumayer Station which would be helpful in placing bounds on the ranges of abundances expected in the region. There may be some information regarding inter-year variation, albeit it with a number of intervening years, in the Larsen A and B region when that area is surveyed again in 2013.

In summary, these suggested analyses will allow comparison of crude absolute abundance estimates of minke whales inside-ice (actually, a range of values) for January, with: 1) the estimated drop in abundance between CPII and CPIII for Management Area II (there is also a slight overlap into Area I); 2) with minke whale abundances outside of the ice edge, also estimated from the helicopter survey data; and 3) with SOWER estimates for Area II from 1998. This comparison needs to be accompanied with the consideration that Area II (and I) was one in which a significant change in minke whale abundance seems to have occurred (IWC 2012).

Extended analyses

If the informal analyses suggested in the previous section fail to dismiss the 'moved-into-ice' hypothesis in explaining the differences between minke whale abundances estimated for CPII and CPIII, there might be reason to consider extrapolating the model-based estimates of densities from both aerial survey programmes to all Management Areas, and perhaps even back over the period of CPII and CPIII. Again, this would be an exercise in considering boundaries and magnitudes, not comparing quality absolute abundance estimates. Changes in abundance estimates between CPII and CPIII, by Management Areas (the scale at which SOWER abundance estimates are currently being produced), could be compared, in a general sense, to any changes in the crude estimates of 'within-sea ice' abundances. This may (or equally, may not, depending on values of bounds and magnitudes) be helpful in deciding whether the 'moved-into-ice' hypothesis remains tenable, or can be removed from consideration.

Extrapolating results from the aerial surveys will require extended modelling of the relationship between minke whale density and a range of environmental covariates, such as sea ice concentrations or bathymetry, to name a few potentially influential variables. Modelling of minke whales in open sea by using SOWER could also be helpful to understand nature of habitat of minke whales. The variability in minke whale densities predicted circumpolar, and back through time, are likely to be primarily dictated by sea ice concentrations and, to a lesser degree, by positions along latitudinal and longitudinal gradient (assuming that variability in sea ice concentration explains the largest proportion of variability in minke whale densities. Therefore, retrospective estimates of minke whale abundance in sea ice areas will depend on the quality of sea ice data which are available during seasons covered by CPII and CPIII, and how well these sea ice data (see Murase *et al*. (2012; SC/64/IA3) for further discussion about the range and quality of sea ice data available). A particular issue to be addressed in selecting quality sea ice data is the location of the operational ice edge, inside of which SOWER vessels rarely, if ever, ventured to survey for minke whales. In areas and years where SOWER vessels were surveying, operational ice edges were recorded. These recorded ice edges could be used, in parallel with satellite sea ice data, to delineate and characterise the ice habitat region for the purposes of estimating densities and abundances (i.e., for that year and area). In the absence of SOWER-observed ice edges, satellite data must be used to delineate the ice habitat region, which may underestimate the total sea ice area (see Murase *et al*. (2012; SC/64/IA3) for further details). However, given the large errors already associated with extrapolating minke whale densities derived from aerial surveys throughout all Management Areas, and back through time, the magnitude of the effect of the position of the operational ice edge may be relatively small. At the very least, sensitivity analyses could be undertaken to check the effect of changing the location of the operational ice edge upon estimated densities and resultant abundances.

Recognising the limitations of icebreaker-based surveys in terms of collecting data for estimating abundance, perhaps the associated sighting data could be used to explore general relationships between minke whale presence/absence or basic densities estimates with a suite of environmental covariates, both underway, remotely sensed (sea ice, chlorophyll *a*, etc) or inferred from oceanographic models (i.e., Orsi *et al.* (1995)). These relationships could be explored using machine learning methods such as classification and regression trees (CART) (De'ath and Fabricius (2000); and see Scheidat *et al.* (2011) for an example), boosted regression trees (De'ath 2007) and the maximum entropy (Phillips *et al*, 2006). Any minke whale-environment associations may then be used to select environmental covariates to be tested and used within model-based abundance estimation using aerial survey data. The BROKE and BROKE-West cetacean sighting and effort data are in a reasonable format to proceed with these analyses, but there is the overhead of getting the remotely sensed data.Ice, oceanographic and other environmental data were also recorded in the *Shirase* survey; environmental observations pertinent to cetacean observing conditions were collected from the Polarstern.

Even though the helicopter surveys were across a large embayment, effort did not extend sufficiently wide enough to represent likely minke whale densities across that area. Therefore, caution is required when extrapolating the results of the helicopter and fixed-wing surveys across areas such as further south into the Weddell Sea. This will apply even more in the Ross Sea area, an area known to have high densities of minke whales (i.e., far beyond densities observed in either aerial programmes) and dynamic sea ice patterns (Ainley 2010). Furthermore, the bounds of abundances must also include some of the intra- and inter-season variability observed with the aerial programmes, particularly the fixed-wing surveys (i.e., not all polynyas have similar densities of minke whales, and these can also vary both within and between years).

Looking into the future: estimating availability bias

Again, although there are currently seven aerial surveys (two in eastern Antarctica and five in the Weddell Sea and surrounding areas), none can be used to generate an absolute abundance in their respective areas due to a lack of information regarding availability bias. Availability bias (*sensu* Marsh and Sinclair (1989)) helps correct for the proportion of animals that are too far beneath the surface of the water (actual depth will depend on turbidity of the water and ambient light levels and angles) to be seen by observers as they travel past. At present, estimates of availability bias are not available for minke whales (or many other cetaceans, for that matter). Also, although visibility from the front of the helicopters used in the aerial surveys around the Weddell Sea allow good coverage of the trackline (i.e., g(0) is certainly closer to 1 than the fixed-wing surveys), there does need to be some attempt to estimate perception bias for this platform. As such, the abundance estimates offered in Kelly *et al*. (2011; SC/63/IA9) and Williams *et al*. (2011; SC/63/IA14) can only be considered as valid for near-surface components of the water. Furthermore, availability biases are likely to be heterogeneous across different observing conditions (Thomson *et al.* 2012). For example, hypothetically speaking, turbidity and ambient light levels may be similar both inside and outside of the ice, but presence of ice may influence minke whale surfacing to some degree; so, the availability biases may be very different (other influences on availability might be time of day and the presence and amount of prey). Therefore, for the purposes of estimating absolute abundance, not only does there need to be some attempt to estimate availability bias for aerial surveys minke whales in the Southern Ocean, but there also needs to be consideration as to how different environments will influence those estimates. If, however, if the aim is to estimate relative abundance inside sea ice areas to compare with relative abundance estimates outside of the ice edge, then the need for an estimate of availability bias may disappear (but only if sighting data comes from a single survey type (i.e., aerial) and that one is willing to assume that the bias is the same inside and outside of sea ice regions). It is hoped that estimates of availability bias for minke whales will become available in the near future, which could then be applied to fixed-wing and helicopter aerial survey data in order generate absolute abundance estimates for the respective survey regions and years the surveys were undertaken.

In order to get at the problem of availability bias, one needs to consider the range of cue types displayed by a given species at a given location. For instance, if only blows and bodies at the surface of the water are visible, then time-at-the-surface (i.e., the type of data that might come from a wet/dry switch on a satellite tag) or visual dive times would probably yield a reasonable estimate of availability. If, however, low turbidity and ambient levels enabled bodies to be seen some distance down, then there would also be the need to estimate at what depth animals cease to visible, and the amount of time they are below that depth. For the latter situation, it is theoretically possible to take the approach of Pollock *et al.* (2006) to estimate availability. They used fibreglass model of dugongs to judge at what depth below the surface animals would not be visible, given turbidity levels. (Pollock *et al.* 2006) then coupled this with time-depth recorder (TDR) data from real dugongs to estimate the amount of time the animals were spending beneath that depth. Though comprehensive, this approach would not be appropriate an Antarctic context. Other options include: 1) go to TDR-type tags to estimate surfacing characteristics and depth profiles, and then estimate how likely it is that whale bodies would be to see in the near-surface region; or 2) use high-definition video or photographs (taken from above, i.e., from a slower moving aircraft or helicopter) of surfacing events to estimate how long animals are visible; a method described in Heide-Jørgensen *et al.* (2009). Although high-definition video and digital stills were taken during the fixed-wing aerial surveys around Vincennes Bay in eastern Antarctica (Kelly *et al.* 2011; SC/63/IA), the aircraft were moving too fast to capture whole surfacing events (typical amount of time a given patch of water was visible would be around 3-4 seconds). In addition, there was a video camera mounted to the bottom of the helicopter during the 2006/07 survey, which may be worth assessing, although the camera was not high-definition. Also, there is the potential to use video recordings from the dive experiments undertaken during SOWER surveys (Ensor *et al.* 2007; Ensor *et al.* 2008; Ensor *et al.* 2009) to estimate surfacing rate, but that does not get at how long animals spend at the given depths, or how turbidity or ambient light levels might affect the relationship between depth and visibility, which is fundamental component in estimating availability. There is also the possibility of using diving and surfacing information collected for common minke whales (*Balaenoptera acutorostrata*), such as those reported in Øien *et al.* (2009) or Heide-Jørgensen *et al.* (2009). For instance, Heide-Jørgensen *et al.* (2009) report an average inter-surfacing period of 76.6 seconds; this coupled with a surfacing length of around 1.52 seconds, represents an availability of around 0.052, using a non-instantaneous correction developed by Laake *et al.* (1997). However, as it has been suggested that cue characteristics from the two species are somewhat different (D. Pike, *pers comm*.), and these estimated values may not be suitable or, at least, represent a minimum bound. Another option might be to consider that where there is no visibility into water (which was often observed in heavy pack ice in overcast weather conditions during the fixed-wing surveys), dive-time based estimates (i.e., from SOWER experiments), combined with the duration that a patch of water is scanned by observers (a maximum of around 7 seconds on the fixed-wing aerial surveys), would give a reasonable estimate of availability. This result may then be extrapolated to areas where whale bodies could be seen at depth by estimating the number of underwater sightings followed by a surfacing and blow during those 7 or so seconds. Then, if TDR or dive-pattern data become available for different ice conditions, this would provide an estimate of the respective availability biases which are independent of observers and judgements about sighting condition.

Looking further into the future: replacement for SOWER and more aerial surveys

As the SOWER survey programme suspended (in 2009/10), there will need to be some sort of survey effort in the future in order to monitor the status of Antarctic minke, and other, whales. In the event that the extended analyses of aerial survey data, as suggested above, indicate substantial numbers of minke whales within sea ice there may be a case to undertake further aerial surveys over sea ice regions in order to produce representative, unbiased estimates of circumpolar abundances from any future survey effort. The success of aerial survey programmes, both fixed-wing and helicopter, has already been demonstrated (Kelly *et al.* 2011; Scheidat *et al.* 2011). However, given the problem of limited longitudinal extent, in a circumpolar context in these existing surveys, any future survey programme will need to be spread effort around the Antarctic coastline. The map given Figure 1 outlines the locations of various skiways/airfields around the coastline of Antarctica that do or could support flights for aircraft such as CASA-212s or Twin-Otters (details of locations are given in Appendix 1). (We can make no statement about the quality of the skiways/runways at each of these locations, nor whether the associated nations would be interested in participating in this research; information has been added to this paper in order to facilitate discussion.) The black circles indicate the average range that could be expected from a CASA-212 aircraft. Coupled with ice-breaker helicopter surveys (other marine mammal examples of which include Bengtson *et al.* (2011) and Southwell *et al.* (2008)), there are very few sea ice areas that could not be covered to some degree. Even if aerial surveys are conducted around all the skiways/runways, it is expected that spatial and temporal coverage is still limited. Naturally, SOWER-type shipboard surveys which can cover from 60°S to ice edge would also be necessary to estimate absolute abundance of Antarctic minke whales.

Finally, no discussion about future aerial surveys over sea ice would be complete without mentioning unmanned aerial vehicles (UAVs) or drones. One point that is obvious to anybody involved with aerial surveys over remote sea ice areas is the massive associated cost of ensuring personnel health and safety. In particular, any accidents are likely to lead to loss of life for all onboard. Although the concept is far from being operational in an Antarctic context, UAVs certainly present a potentially cheaper and safer alternative for aerial surveys (see Koski *et al.* (2009a) and Koski *et al.* (2009b)) for an Arctic perspective) and to study availability bias via aerial focal follows (i.e., monitoring the diving behaviour of single animals or groups for extended periods of time; as demonstrated by the recent success of using UAVs for focal follows of migrating humpback whales along eastern Australia (A. Hodgson, *pers.comm.*)). Cost effective UAVs for use in polar region are also under development (Funaki *et al.*, 2008). Though nobody has attempted, use of the sub-metre resolution optical image obtained by satellite sensors such as GeoEye and WorldVeiw could also be an option.

Conclusions

With a combination of data from a number of aerial surveys—helicopter and fixed-wing—over ice regions around Antarctica, and development of methods for model-based abundance estimation, there is now an opportunity to test, in an informal way (i.e., considering upper/lower bounds and magnitudes), whether the 'moved-into-sea ice' hypothesis is at least a reasonable explanation for the drop in minke whale abundances between CPII and CPII. However, given the potentially large amount of work required to estimate minke whale densities and abundances within ice areas, both circumpolar and retrospectively over the period of CPII and CPIII, smaller, more tractable analyses are suggested, at least in the first instance. Either way, attempts to estimate availability bias of Antarctic minke whales should be encouraged to facilitate estimation of absolute abundances in sea ice regions. Finally, in the event that large numbers of minke whales are in fact to be found in sea ice regions, there may be a case to undertake more aerial surveys in order to produce truly unbiased estimates of circumpolar minke whale abundances from any post-SOWER era survey efforts.

Acknowledgements

Thank you to Mark Bravington and David Peel for invaluable comments on an earlier draft. NK undertook most of the background research and writing of this paper, with assistance from the other authors.

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Table 1 Cetacean surveys which have focussed some or all sighting effort inside of sea ice region (and the data from which would be readily available to members of the Scientific Committee (i.e., results from these surveys have been presented within SC or regular members of SC have analysed)).

	General Description	**References**	**Region Covered**	**Dates (dates inside sea ice zone for voyages).**	**Survey effort (nm)**	**Number minke whale sightings**	**Data custodians**
Ship-based surveys							
	BROKE undertaken on *Aurora Australis*	Thiele *et al*. (2000)	80-150°E	30 Jan-21 Mar 1996	1452	30	Government of Australia
	Survey from icebreaker *Shirase*	Shimada and Kato (2005; SC/57/IA7)	40-50°E and 70-82°E	10-15 Feb 2005; 3-5 Mar 2005 (specifically, for inside ice component of survey)	(127 + 239[1])	19	Authors of the reference
	BROKE-West, undertaken on *Aurora Australis*	Tarzia *et al*. (unpublished)	30-80°E	20 Jan-3 Mach 2006	3300	71	Government of Australia
	Sighting survey from deck below crow's nest of *Polarstern*	Kock *et al* (2010; SC/62/O15)	Through MIZ to Neumeyer Station; along ice edge of Weddell Sea to tip of the Antarctic Peninsula (both east and west); 62°W-11°E	27 Nov 2006- 18 Dec 2006, 6 -24 Jan 2007	633	21	German Government
	Sighting survey from crows' nest of *Polarstern*	Kock *et al* (2010; SC/62/O15)	Survey flights undertaken over open water, then through MIZ to Neumeyer Station, and out again; 10°W-15°E	12 Dec 2008-27 Dec 2008	1085	22	German Government

Aerial surveys							
	Helicopter survey, operating from *Shirase*	Shimada and Kato (2005; SC/57/IA7)	Lützow- Holm Bay and off the Kronprins Olav Coast	28 December 2004 8 February 2005	NA	19	Authors of the reference
	Fixed-wing aircraft survey, operating from Casey Station	Kelly *et al*. 2009 (SC/61/IA3)	106-113ºE, Vincennes Bay. Parallel transects flown inside sea ice zone, spaced 10 nm	11 Dec 2008 – 31 Dec 2009	3398	53	Australian Government
	Fixed-wing aircraft survey, operating from Casey Station and Bunger Hills	Kelly et al. 2010 (SC/62/IA8), Kelly *et al*. 2011 (SC/63/IA3)	93-113°E, Vincennes Bay, around Shackleton Ice Shelf and Davis Sea. Parallel and zig-zag transects flown both inside and outside sea ice.	16 Dec 2009-5 Feb 2010	4923	24	Australian government
	Helicopter survey, operating from *Polarstern*.	Kock et al (2010; SC/62/O15) Scheidat *et al*. 2011	Survey flights, in box-transect configuration, undertaken over open water, then through MIZ to Neumeyer Station; along ice edge of Weddell Sea to tip of the Antarctic Peninsula (both east and west); 62°W-11°E	27 Nov 2006- 18 Dec 2006, 6-24 Jan 2007	7086	71	German Government

	Helicopter survey, operating from *Polarstern*.	Kock *et al* (2010; SC/62/O15), Scheidat *et al.* 2011 Williams *et al.* 2011	Survey flights undertaken over open water, then through MIZ to Neumeyer Station, and out again; 10°W-15°E	12 Dec 2008-27 Dec 2008	7245	24	German Government
	Helicopter survey, operating from *Polarstern*.	To be analysed by J. Cooke.	Around Neumayer Station, Weddell Sea, western Antarctic Peninsula	Feb 2011	10 days of pre-planned, dedicated line-transect survey	T.B.A.	German Government
	Helicopter survey, operating from *Polarstern*.		Around Neumayer Station		No data collected due to bad weather		German Government
	Helicopter survey, operating from *Polarstern*.		Planned area: East side of Antarctic Peninsula, deep into Weddell Sea, as far as Larsen C.	Planned for: 20 Jan – 20 Mar 2013			German Government

[1]Survey effort just inside sea ice.

Table 2 Pros and cons of each survey method in the context of how they might affect subsequent analyses and interpretations.

	Pros	**Cons**
Ship-based surveys		
	• Slower speeds mean animals are less likely to missed if they have been unavailable for some time. • Can allow the concurrent collection of environmental covariates.	• Animals could react negatively or positively to the ship's presence; or the leads in the ice that ships create. • Given that icebreakers will often chart, where possible, existing leads and lower ice concentrations, the coverage of any sighting survey may be restricted to these types of ice habitats. • Slower speeds mean less distance covered; surveys often completed over a couple of months, suggesting surveys are not necessarily synoptic.
Aerial surveys		
Fixed-wing	• Can cover large distances in relatively short periods of time. • Usually little to no reaction from animals. • Easier to avoid patches of poor weather; can move to other less affected areas of the survey region with relative ease.	• Constrained to flight ranges from airstrips and skiways. • Missing large numbers of animals due to availability bias (this may not be an issue if one is only concerned with estimating relative density or abundance). • Not particularly suited to watching the trackline if that is a concern (i.e., if there is no bubble window); camera gear taking photographs or video footage beneath aircraft can help, but there is a big time overhead after survey to go through data.
Helicopter (from a ship)	• Can hover over groups for more complete species ID and group size estimates. • Can access more areas of large embayments, such as Weddell and Ross Seas; concurrently allows greater longitudinal spread of survey effort within a single summer season. • The front window of the helicopter should allow better searching ahead and along trackline. • Slightly slower survey speed (as compared to fixed-wing aircraft) means that animals might be less likely to be missed if they have been available for some time.	• Relatively short flight ranges, compared to fixed-wing aircraft. • Depending on OH&S requirements of given ship, the distance flown and configuration of trackline might be constrained. Furthermore, the range of weather a helicopter would be permitted to fly in is narrower than a fixed-wing aircraft. • Limited to following ship's track, which may be decided by other unrelated science programmes or station resupply commitments.

Table 3 Dates and longitudinal ranges for recent IWC-SOWER voyages and an Australian aerial survey programme in East Antarctica.

Summer Season	Recent IWC-SOWER Programme surveys		Aust. Aerial Survey Programme	
	Longitudes	Dates	Longitudes	Dates
2007/08	105º -120º E	31 Dec 2007 – 13 Feb 2008	105º –120º E	14 Jan – 23 Jan 2008#
2008/09	82º – 95ºE	19 Jan – 12 Feb 2009	105º –120º E	11 -31 Dec 2008
2009/10	100º –115ºE	7 Jan – 3 Feb 2010	93º –113º E	16 Dec 2009 – 5 Feb 2010

#not a proper survey; only test flights

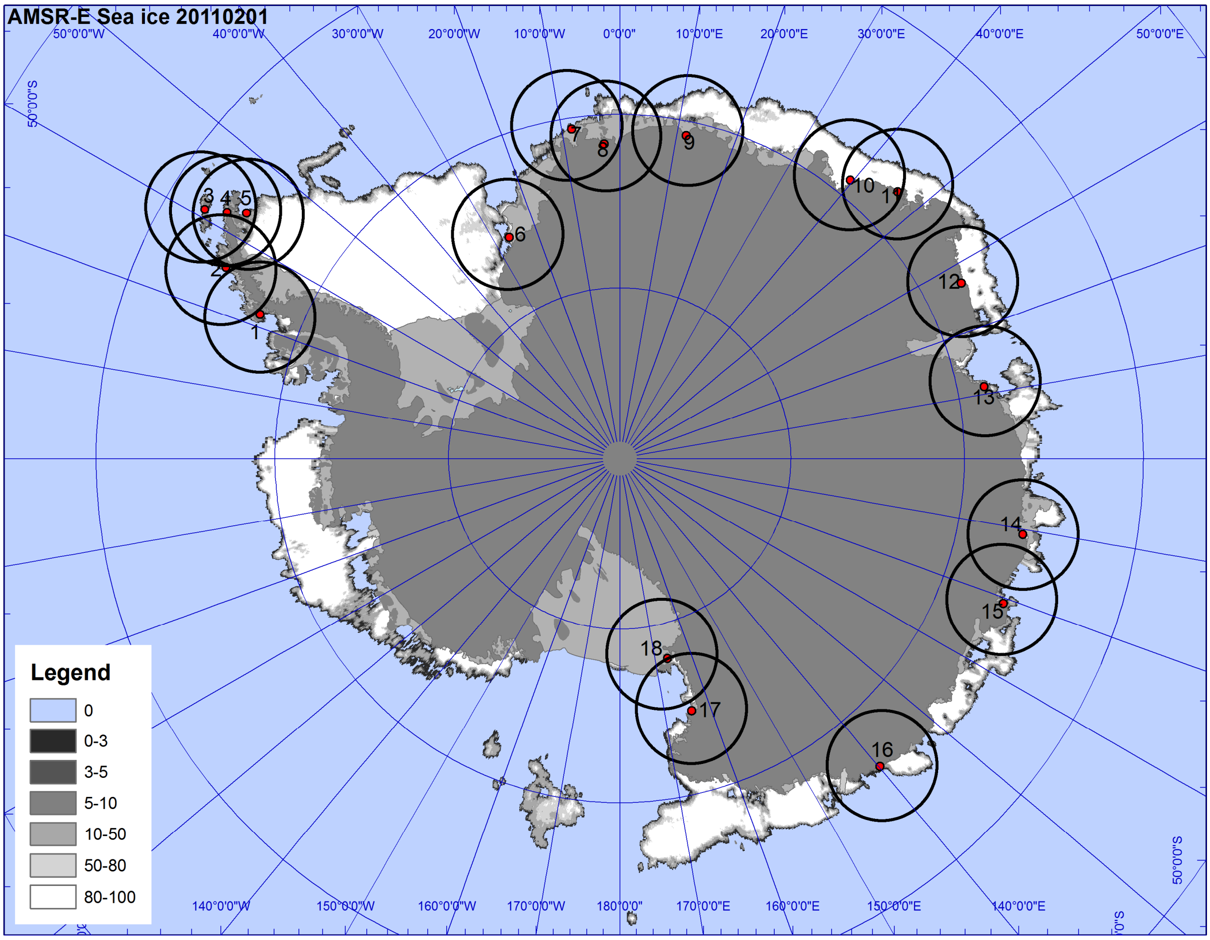

Figure 1 Distribution of airstrips/skiways around the coastline of Antarctica; numbers indicate airstrip, as described in Table 3; sea ice concentration (as derived from AMSR-E on 1 February 2011), is indicated in the legend. Circles represent a standard range of aircraft such as CASA-212 or Twin Otters. Details of each airstrip/skiway are given in Appendix 1.

Appendix 1

Table A.1 Locations and details of coastal airstrips and skiways around Antarctica

Map number	Location	Base	Nationality	Longitude	Latitude
1	Rothera Point	Rothera	UK	-68.1274	-67.5678
2	Anvers Island	Palmer	USA	-64.0531	-64.7512
3	King George Island	Presidente Eduardo Frei Montalva	Chile	-58.9867	-62.1908
4	Prime Head	General Bernado O'Higgins Riquelme	Chile	-57.8913	-63.3203
5	Seymour Island	Marambio	Argentina	-56.6308	-64.2383
6	Brunt Ice Shelf	Halley	UK	-26.5412	-75.5817
7	Ekstrom Ice Shelf	Neumayer	Germany	-8.2633	-70.6333
8	Queen Maud Land	SANAE IV	South Africa	-2.8288	-71.6737
9	Queen Maud Land	Novolazarevskay a	Russia and India	11.6395	-70.8262
10	East Ongul Island	Showa	Japan	39.5900	-69.0062
11	Thala Hills	Molodezhnaya	Russia	46.1347	-67.6828
12	MacRobertson Land	Mawson	Australia	62.7661	-67.7536
13	Davis Plateau	Davis	Australia	78.7909	-68.4696
14	Bunger Hills	Field camp	Australia	100.7469	-66.2747
15	Casey Skiway	Casey	Australia	110.7598	-66.2885
16	Terre Adelie	Dumont D'Urville	France	139.8197	-66.6680
17	Terra Nova Bay	Mario Zucchelli	Italy	164.0801	-74.6992
18	Ross Island	McMurdo and Ross	USA and NZ	166.5279	-77.9745