Strategies to obtain a new circumpolar abundance estimate for Antarctic blue whales: survey design and sampling protocols

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ABSTRACT

During the twentieth century, some 330,000 Antarctic blue whales were killed, first by shore-based operations and then by the pelagic catcher and factory ships. Close to extinction, in 1964 the International Whaling Commission banned the hunting of blue whales, although they were still caught by illegal Soviet whaling operations until 1973. Last year, a paper was presented to the Scientific Committee that described a feasibility study of methods to obtain a new estimate of circumpolar abundance of Antarctic blue whales. Further to this we address issues and include improvements to this paper that were suggested during the 2011 meeting of the IWC Scientific Committee. We expand on previous work that demonstrated that a line-transect approach alone is not a realistic option to obtain a precise circumpolar abundance estimate of Antarctic blue whales. We use simulations to test a mark-recapture approach in tandem with techniques to boost encounter rates. These techniques include using the seasonality and location of historical sightings, acoustic detections, and catches to target 'hotspots' that may have higher densities of Antarctic blue whales. We also review recent developments in acoustic tracking that could yield increased encounter rates over visual survey alone. We demonstrate that in order to be viable, mark-recapture surveys should target alleged hotspots and make use of passive acoustic tracking to increase encounter rates. In light of all of these results, it appears that a series of mark-recapture surveys could provide a viable estimate of abundance over the next decade.

KEYWORDS: IWC-SOWER, MARK-RECAPTURE, SPATIAL MODELLING, PASSIVE ACOUSTICS, SORP

INTRODUCTION

The blue whale is an iconic species. Reaching over 30m in length it is the largest animal to have existed on Earth. Currently, there are two subspecies recognised to occur in the Southern Hemisphere: the Antarctic (or true) blue whale (*Balaenoptera musculus intermedia*), and the pygmy blue whale (*B. m. brevicauda*). The pygmy blue whale tends to be smaller (maximum length around 24 m) and predominantly remains in lower latitudes throughout the year. During the austral summer, Antarctic blue whales feed in the krill (predominantly Antarctic krill, *Euphausia superba*) rich waters close to the Antarctic continent. It is generally assumed that most of the population of Antarctic blue whale is expected to be south of 60ºS during the summer months (Branch 2008).

During the twentieth century, some 330,000 Antarctic blue whales were killed, first by shore-based operations and then by the pelagic catcher and factory ships. Close to extinction, in 1964 the International Whaling Commission banned the hunting of blue whales, although they were still caught by illegal Soviet whaling operations until 1973 (Branch *et al.* 2004). Our understanding of the impact of the whaling era on Antarctic blue whale population is predominantly based on two sources of information: catch data derived from the logbooks of whaling vessels and from circumpolar cetacean sightings surveys. Circumpolar sighting surveys were initiated in 1978 as the International Decade of Cetacean Research (IDCR) and later Southern Ocean Whale Ecosystem Research (SOWER) initiatives (Branch and Butterworth 2001), henceforth SOWER.

The SOWER surveys were largely funded by the Japanese Government but operated under the direction of the International Whaling Commission. These programmes usually involved two ships conducting line-transect surveys between the Antarctic ice-edge and 60^{o}S. There were three circumpolar surveys (CPI (1978/79-1983/84), CPII (1985/86-1990/91) and CPIII (1991/92-2003/04)) that were completed in 2004, although further regional surveys went on until 2010. Each season, the surveys generally ran from late December and mid- to late February. While whaling data can provide yearly catch distribution and magnitude, as well as often detailed information on the animals caught (including size, sex, pregnancy status, stomach contents etc.), the data from sighting surveys can generate estimates of circumpolar abundance, trends and distribution.

Using Bayesian population analysis methods, (Branch 2008) estimated the minimum abundance of Antarctic blue whales to be as low as 395 (with a credibility interval of 235-804) in the early 1970s, which is around 0.15% of the pre-exploitation level. On completion of CPIII Branch (2008), using only the SOWER sightings data and a maximum likelihood approach (Branch *et al.* 2004), estimated the rate of increase to be 8.2% per year (95% CI 1.6-14.8%) with point abundance estimates for the mid-year of each circumpolar survey to be 453 (CV = 0.4), 559 (CV = 0.47) and 2,280 (CV = 0.36) for 1981 (CPI), 1988 (CPII) and 1998 (CPIII) respectively (Figure 1). The associated sightings rate (number of groups per 1000 n.mile of sighting effort) reflected this increased abundance from 0.44 (CPI) to 0.67 (CPII) to 1.48 (CPIII). However, these circumpolar abundance estimates are considered to be negatively biased as some animals may be north of 60ºS during the IDCR/SOWER surveys; some may have been in sea ice areas, away from where vessels could traverse; and a small number of animals may have been missed on the trackline (Branch 2008). Although the magnitudes of these biases are difficult to assess, Branch (2008) estimated they may be around 20-30%.

Since the suspension of the SOWER surveys in 2009/10, there are now no large scale, formal cetacean sightings surveys operating in Antarctic waters and there is no strategy to monitor the recovery or otherwise of Antarctic blue whales. The loss of such surveys is of great concern given the predicted climatic and ecological changes in the Antarctic sea ice ecosystem (Nicol *et al.* 2008) and the recent and very rapid expansion of the Antarctic krill fishery (e.g., Nicol *et al.*, 2011; Trathan and Agnew, 2010). Clearly these processes and activities may impact on all cetacean species that predominantly feed within the Antarctic ecosystem but arguably Antarctic blue whales are most vulnerable, given the magnitude of depletion and their slower rate of recovery compared with other baleen whales (Branch *et al.* 2004).

In 2009, the Southern Ocean Research Partnership (SORP) program was initiated within the International Whaling Commission to promote collaborative cetacean research through coordination, cooperation and data sharing between research groups and national Antarctic programs (SORP 2009). Several projects have now been initiated under the SORP banner including: studies focussing on the acoustic monitoring of fin and blue whales; niche portioning among baleen whales; and mixing of humpback whale stocks in Antarctic waters (Bell 2012). The Antarctic Blue Whale Project, a new programme within SORP, aims to undertake research to better understand Antarctic blue whale recovery from near extinction in the early 1970s. The project will do so by developing survey protocols and analysis methods that will lead to circumpolar abundance estimates and provide an insight into the general ecology of Antarctic blue whales in the post-exploitation period. The project will also improve our understanding of population structure, explore linkages between breeding and feeding grounds, and characterise behaviour on the feeding grounds. The SORP Antarctic Blue Whale Project is now the only programme that can provide the high-investment, multinational initiative that would be required to deliver a new abundance estimate for Antarctic blue whales.

Last year, a paper was presented to the Scientific Committee by Kelly *et al.* (2011) that described a feasibility study of methods for estimating the circumpolar abundance of Antarctic blue whales. The feasibility study was an initial step in developing a framework for survey design and sampling protocols for the Antarctic Blue Whale Project; and was presented to the Scientific Committee for comments, suggestions for improvement, and expressions of interest in collaborations. In particular, this study used predictions (as reported in Branch 2008) of how the Antarctic blue whale population might have changed since the last circumpolar survey of the SOWER series (and could change in the next decade or so). The predictions provide the basis to estimate how much survey effort would be required to produce an abundance estimate with a desired degree of precision from future circumpolar line-transect and/or mark-recapture surveys. One of the major conclusions of (Kelly *et al.* 2011), and one that was generally agreed within the Scientific Committee (IWC 2012), was that there were not likely to be sufficient resources available to complete a standard line-transect survey in order to derive a circumpolar abundance with enough precision to be useful in a status assessment, i.e., one with CV below 0.4. An alternative abundance estimation method, mark-recapture, was applied in a basic way in (Kelly *et al.* 2011), to provide minimum sample sizes required to generate useful abundance estimates. In recognising that required sampling effort for a conventional mark-recapture approach would still be prohibitively high, (Kelly *et al.* 2011) also presented an analysis of past Antarctic blue whale densities in order to identify regions where encounter rates would be highest, i.e., hotspots, to maximise the number of samples collected to ensure adequate sample sizes.

In response, the following recommendations were offered from the Committee (IWC 2012):

1. use more sophisticated mark-recapture models and to consider of some of sampling biases that can be problematic in generating abundance estimates using this method;
2. that techniques in directional passive acoustics (i.e., directional sonobuoys) be developed and tested for increasing encounter rates of Antarctic blue whales in the Southern Ocean.
3. explore the option of retaining line-transect methods, at least for some geographical regions, with a photo-ID and biopsy component in order to contribute to a mark-recapture study; and
4. consider developing methods to combine information from different catalogues (i.e., photo-identification (henceforth photo-ID) and genetic) to increase effective sample size for a mark-recapture analysis;

This paper addresses the first three recommendations and develops further the framework for survey design and sampling protocols for the Antarctic Blue Whale Project. The paper does not cover the recommendation to combine information from different photo-ID and genetics catalogues; such work will form part of the work-plan for the Antarctic Blue Whale Project in the coming year.

In simple terms, we consider the minimum sample sizes required to return useful estimates of circumpolar abundance of Antarctic blue whales using a mark-recapture approach, how to go about collecting as many samples as possible, and how to collect these samples to ensure the resulting abundance estimates are unbiased. This is achieved via a combination of meta-analysis of existing and recent studies, models of different survey methodologies, and simulations of potential voyage scenarios. We welcome feedback and suggestions for improvement for the analyses and recommendations reported here. Finally, to put all this work into practice, there will be a SORP voyage in early 2013 which will focus on Antarctic blue whales, and the plan for this is outlined in (Wadley *et al.* 2012).

METHODS AND BACKGROUND

To address the desire for more sophisticated mark-recapture models, simulations were used to explore the precision of mark recapture methods over a range of different sample sizes. These simulations were based on photo-ID histories provided by Olson (2010) and the assumption that circumpolar abundance of Antarctic blue whales is increasing at similar rates described by Branch et al. (2008).

Next, we address not only the use of passive acoustics, but also other promising methods to increase encounter rates for a mark-recapture survey. This involved using SOWER sighting data, weather conditions, results from prior acoustic studies, and a new analysis of historical whaling data (de la Mare 2012) to explore the distribution of different densities of Antarctic blue whales in the Southern Ocean and to find the most promising survey locations in order to maximise opportunities for photo-ID and biopsy sampling. We also make use of results from recent SORP voyages (Miller et al. 2012) that investigated the use of directional sonobuoys to find blue whales (Miller 2012), as well as a simulation exercise to extrapolate those results to an Antarctic context (Peel et al. 2012).

In addition, we use a model to test the feasibility of the combining a traditional design-based line transect survey with closing on each Antarctic blue whale sighting for collection of biological samples and identification photographs to go towards a circumpolar mark-recapture study.

Mark-recapture

As concluded by Kelly et. al (2011), and generally agreed upon during the meeting of the Scientific Committee of 2011 (IWC 2012), a mark-recapture (henceforth, MR) approach, using photo-ID and individual matches from genetic samples, is likely to be the most feasible method with which to obtain a circumpolar abundance of Antarctic blue whales. Contributing to this decision was the likely constraints on vessel-availability, and a subsequent desire to take advantage of non-science operations in the Antarctic (i.e., land station resupplies and tourist trips) to gather samples. In a general sense, sampling for MR methods do not require strict survey design, such as randomly located transects evenly spread through a study region. Also they do not require unbiased sampling, that is sampling can target only high whale density regions. They would also not necessarily need adherence to a uniform sampling protocol, beyond ensuring proper record keeping, quality photography techniques and appropriate handling of genetic samples. The current proposal is for a multi-year sampling strategy. This provides an opportunity for interim review of results which could improve sampling strategies to minimise heterogeneity in sampling and increases the number of 'marks' in the population and, hence, recaptures, too.

To ascertain minimum required yearly sample sizes for this study, predicted population trajectories of Antarctic blue whales presence and capture histories were simulated, from which mark-recapture-based estimates of abundance and growth rate were derived. These were then used to explore the effect of sample sizes on the CV and bias of estimates.

The population trajectories were based on estimated circumpolar abundance in 1998 (CPIII), and a range of potential annual rates (r) of increase of 8.2%, with the 95% CI of 1.6-14.8%; from (Branch et. al. 2008). From this trajectory, presence histories were simulated using annual survival probabilities provided in (Branch et al. 2004). From the presence histories, capture histories were derived using random sampling, with replacement, each year, with a nominated sample size. As relatively little is known about potential population structure in Antarctic blue whales, no constraints were placed on random sampling of individuals from the presence history. It was also assumed there was no error in matching individuals. Sampling was conducted each year for 10 years, from the 2013 summer season, with the same number of samples each year.

To the simulated capture history, a likelihood based closed-population mark-recapture model was fitted to estimate N_0 and r. From the likelihood model, variances were estimated numerically using the inverse of the negative Hessian matrix. This whole process was repeated, thus producing average estimates of the variance (and hence CV) on the abundance for the middle year of the survey and the yearly growth rate, $\hat{r}$, for a range of population rates and annual sample sizes. Further details of the simulations/mark-recapture model are in Appendix A.

The model/simulation framework allows the inclusion of photo-ID catalogues existing at the nominal start of the survey study. Photo-identification data has been collected for Antarctic blue whales since 1987/88 with some 219 individuals identified from the 225 whales photographed. Most of the data have been collected in the last decade or so, with 185 new individuals photographed since 2001/02 (Olson 2010). In addition to photo-identification data, biopsy samples have also been collected from 218 individuals, with again most of the data being gathered since 2001/02 (Sremba et al 2012).

Methods to boost encounter rates

Historical Sightings

The distribution of Antarctic blue whale sightings and survey effort was considered for all years of SOWER unless otherwise stated. As these data are not going to be used to compute an abundance, all effort that might yield a sighting of an Antarctic blue whale has been included. Sighting rates of animals are based on the 'best' size estimate in the SOWER sightings database. Because the ultimate quality of an abundance estimate using the MR approach is based on the number of individual animals encountered and subsequently identified, not sightings of groups, as line-transect methods are, we consider the sighting rate of animals, not groups (where $n \geq 1$). Animal-wise sighting rate will be a basic proxy for Antarctic blue whale density.

Mean sighting rates were estimated throughout each SOWER survey and subsequent surveys for 10º longitude bands (starting at 180º W and ending at 180ºE) in order to characterise the circumpolar distribution of animal-wise sighting rates and, hence, density. Where there are two survey years represented in a single 10º longitude band, a weighted average sighting rate was used, where the weight depends on the amount of effort for each survey in that band. According to the observation that most sightings have been made close to the ice edges, the sighting rates have been further delineated based on distance from the ice edge, and averaged within bands 0-200 km and 200-500 km from the ice edge.

The success of any survey to locate and sample higher densities of Antarctic blue whales will also be influenced by the local weather. During SOWER voyages, weather observations were taken every hour. For the purposes of judging the circumpolar distribution of weather favourable to sighting surveys, 'good' observing weather is considered to be Beaufort sea state of 4 or less, and a sightability score of 2 or more. The amount of time with 'good' weather was divided by total amount of time of weather observations, and the result was used as a general indicator of the proportion of 'good' weather expected. This calculation was performed for all weather observations over the period of late December through mid-February. Despite there being some evidence of drift in how the sightability variable has been assessed over the three decades of the IDCR/SOWER programme (Peel *et al.* 2011), we assume the definitions of the weather variables to have remained constant throughout.

The SOWER sighting survey series provides a wealth of information regarding the distribution of baleen whale species in the Southern Ocean. However, it is subject to one flaw: the sheer magnitude of the task of surveying an area as large as that between 60ºS and the dynamic summer ice boundary. Because the SOWER vessels surveyed single regions (between 20º and 70º of longitude), then moved along to another region the following year, there was no opportunity to quantify the inter-annual variation in whale abundance and distribution. This is known, amongst other things, as 'additional variance' (Kitakado and Okamura 2009). When additional variance is unknown, there is no way to judge if whale distributions observed in a given season are representative of an average abundance and density or if they are influenced by unusual environmental features for that season, such as high or low Antarctic krill abundance. Therefore, it is difficult to judge how representative sighting rates might be for a given region.

Fortunately, after the completion of the third circumpolar survey, the SOWER voyages were able to undertake repeat surveys of two different regions in Areas III and IV. Furthermore, the last 3 years of the third circumpolar survey targeted adjacent longitudinally narrow areas between 130ºE and 170ºW. It should be noted, however, that none of the repeat surveys are a perfect match to each other, either in longitudinal extent or survey method. For instance, the survey undertaken in 2004/05 used standard line-transect methods and covered 0-70ºE, while the surveys in 2005/06 and 2006/07 largely followed the sea ice boundary, and only covered 0-20ºE. Therefore, the mean sighting rates, and associated variances, should be treated as indicative and not absolute estimates to characterise inter-annual variation.

Acoustics

Understanding broad scale trends in blue whale acoustics provides another means to locate 'hotspots' of high blue whale density, but it is also important to understand how acoustics might be used to increase in-situ encounter rates over medium and small spatial scales (Figure 2). Here we present a brief summary of literature relevant to Antarctic blue whale acoustics. Primarily we focus on broad seasonal and spatial variation in vocalisations, but we also consider whether acoustic behaviours measured in other blue whale populations are applicable to Antarctic blue whales. We looked at SOWER sonobuoy deployments, the results of long-term acoustic moorings, and a pilot-study of a real-time acoustic tracking system in order to investigate the potential for passive acoustics to enhance abundance estimation.

BACKGROUND

Blue whale vocalisations have been recorded worldwide in every ocean, and it has been hypothesized that different populations of blue whales each have characteristic 'songs' (McDonald et al. 2006). It is unclear whether the production and function of blue whale 'song' is comparable between populations, but in addition to 'song', blue whales make short frequency modulated sounds of variable frequency and variable duration of up to 5seconds. These short-duration sounds are sometimes referred to as ‘D’ calls, and appear to be common to many, if not all, blue whale populations worldwide (Thompson et al. 1996, Stafford et al. 2001, Rankin et al. 2005, Oleson et al. 2007b, Gavrilov et al. 2011).

The function of blue whale vocalisations is largely believed to be communication rather than echolocation. Oleson et al. (2007a) investigated the behavioural context of 38 blue whales on a California feeding ground through the use of acoustic recording tags, tissue sampling, and visual observation and found that ‘song’ was produced only by males, while ‘D’ calls were produced by both sexes. ‘D’ calls were produced during foraging commonly from individuals in groups, while ‘song’ fragments were produced by pairs of whales. However, the number of observations for each case was small, and some whales made no sounds at all, so it is still unclear whether these patterns apply to Antarctic blue whales.

Oleson et al. (2007c), not only found seasonal variation in calling rates, but also seasonal variation in call type over four years of recording blue whales off a California feeding ground. ‘D’ calls were present earlier and also absent earlier than B-calls (i.e., ‘song’). Off the coast of California, ‘D’ calls appear to be more suitable as an index of whale abundance than ‘song’ calls (Oleson et al. 2007a). More general seasonal trends in other blue whale populations have been reported, though these reports only make use of ‘song’ calls rather than ‘D’ calls (eg. Stafford et al. 2001, Oleson et al. 2007, Gavrilov et al. 2011).

Antarctic blue whales, like these other populations, appear to follow similar annual trends in calling. Širović et al. (2004) report a peak in calling through March-April in the Western Antarctic Peninsula. Gedamke et al. (2007) and Širović et al. (2009) report a peak in acoustic energy at Antarctic blue whale frequencies in Eastern Antarctica from April-June, and Širović et al. (2009) reports a peak in Antarctic blue whale calling at a site in the Ross Sea over March. Gedamke et al. (2007) reports a peak in acoustic energy at Antarctic blue whale frequencies off southwest Australia over April-September, and Stafford et al. (2004) reports detection of Antarctic blue whale calls at low latitude sites in the eastern tropical Pacific and Indian Oceans from May-September with peak calling in July. Again, these studies have only reported seasonal trends in ‘song’ calls, as ‘D’ calls could potentially be associated with any blue whale population.

Oleson et al. (2007) as well as Wiggins et al. (2005) found diel patterns in blue whale ‘song’ with peaks at dusk and dawn and a relative absence of ‘song’ during daylight. Oleson et al. also reports lesser peaks at dusk and dawn for D calls with most D calls occurring during daylight. It is unclear if these diel trends also apply to Antarctic blue whales, especially because underwater at those at high latitudes where diel variation in daylight depends on the a.

In addition to daylight, both the ambient noise and the attenuation of sound in the deeper waters around Antarctica are likely to be less than those at lower latitudes, especially over the range of frequencies used by Antarctic blue whales. Therefore, it is expected that acoustic detection ranges of blue whales around Antarctica will be greater than or equal to those measured at lower latitudes. Very cursory comparison of the reported localisation ranges reveals ranges of 120-200 km for blue whales in the Antarctic (Samaran et al 2010; Sirovic et al. 2007 respectively) and 8 km for those described around Australia (Gavrilov et al. 2011), which supports this assertion. However, the localisation methods and models are not consistent among these studies.

Finally, there is some evidence that only a small number of whales in a given group will be vocalising at any given time. This has been documented by Rankin et al. (2005) around Antarctica, Oleson et al. (2007b, 2007a) off California, and off the Southern coast of Australia (Miller 2012). Acoustic tracking of Antarctic blue whales would provide additional opportunities to link visual and acoustic observations of blue whales, which may in conjunction with long-term recording stations yield long term estimates of blue whale density (Bell 2012, Annex 1, Section 5).

ANALYSIS

In order to look more closely at spatial variation in whale calling, data from sonobuoys deployed during SOWER voyages, between 1999 and 2009. During each sonobuoy deployment, the presence of whales, including Antarctic blue whales, was recorded. The proportion of sonobuoys which registered an Antarctic blue whale call was considered to be a crude estimate of local blue whale density.

In January and March 2012 the Australian Marine Mammal Centre conducted two voyages in the Bonney upwelling to further develop and field test passive acoustic methods for tracking blue whales (Miller *et al.* 2012). A result of these voyages was the validation of a real-time acoustic tracking system for locating and encountering blue whales which is described in detail in (Miller 2012). It should be noted that these field trials were conducted in temperate waters along the south coast of Australia, and that these trials were conducted on pygmy blue whales rather than Antarctic blue whales. Thus, there is a need to consider differences in the physical environments, as well as differences in vocalisations between pygmy and Antarctic blue whales.

To get an idea of the plausible encounter rates expected from acoustic-assisted tracking of Antarctic blue whales, (Peel *et al.* 2012) described a discrete-time individual-based simulation. A large number of parameters fed into the analysis, covering acoustic properties (e.g., acoustic range, bearing error), whale biology (e.g., whale density, swim speed, proportion of vocalising groups) and vessel operation (e.g., vessel tracking decision rules, time to mark animals). Some of these parameters could be taken directly from SOWER data (in particular, blue whale specific experiments) and others from the recent Bonney Upwelling pilot survey (see Miller *et al.* 2012).

The main assumptions were: 1) a uniform 8.2% population increase has occurred across all areas since CPIII, and 2) that 50% of all whale groups contain a singer. Overall, the assumptions and parameters were set cautiously to give conservative estimates. As a check the simulation was applied to the Bonney Upwelling data and gave estimates comparable to the number of whales observed. For the Antarctic, the simulation was applied to 10 degree longitudinal regions (180°W to 180°E) between 0 - 200km of the ice edge. The only distinction between regions as far as the simulation is concerned is whale density and the proportion of days lost due to poor weather conditions.

Historical Catch

Historical catch data provide information about where whales were distributed, at least at the time of exploitation. This data can be a little misleading as there is no guarantee that animals will have returned to where they were distributed many decades previously (e.g., many species of baleen whales have failed to return to historic feeding grounds near South Georgia). However, whaling data may be helpful in identifying potential areas of higher and lower densities to support other analyses of the spatial distribution of Antarctic blue whales for the purposes of selecting study sites. Apparent densities of blue whales were calculated in terms of catch per catcher searching day worked (C/CSW) by 1° of latitude by 1° of longitude using only data from pelagic whaling expeditions. Densities were calculated by month and across a number of years using the method given in (de la Mare 2012). This method corrects for the effect of daylength, handling time and the number of unrecorded days on which catches were taken, although for the latter this is only possible if at least one whale was taken of any species.

Mark-recapture/line-transect model

A mark-recapture/line-transect (MR/LT) hybrid would involve traversing a standard line-transect survey design, like the zig-zag transect configuration used during the later phases of the SOWER programme, but with closing mode for every suspected Antarctic blue whale sighting. Unlike a pure MR survery, tracklines for the MR/LT survey would be predefined. As such, any modelling for this survey design needs to consider how many Antarctic blue whales are expected to be encountered along a randomly located transect in a given area (i.e. the animal-wise sighting rate), how long it might take to photograph and biopsy the animal(s) in the sighting, the success rate of photographing and biopsying (i.e., the proportion of animals that allow such sampling to occur), and the total amount of survey time available, as informed by historical weather records from a given region from IDCR/SOWER data. Weather records were taken from CPI, CPII and CPIII, and the subsequent IWC-SOWER voyages up to 2009/10 season. We also assume that there has not been any significant shift in regional weather (i.e., as a function of altered sea ice dynamics, etc), over the three decades. Given the number and scope of the various assumptions applied in the analyses below, the results are approximate and intend only to provide a general picture of likely outcomes.

In testing the feasibility of the MR/LT survey model, we are concerned with the encounter rate of individual animals and associated CV for a line-transect based abundance estimate for the 2013 season. We must also consider, not just encounter rate, but also the number of animals expected to be photographed and biopsied. Two areas with relatively high Antarctic blue whale densities (as judged by encounter rates from SOWER sighting data) were selected: 0-30ºE and 135-173ºE. For each case study region, two general strata were considered: 60-65ºS and 65-70ºS, to allow for an overall summary of sighting conditions expected as a function of distance from the ice edge. These strata delineations were used to be in keeping with the SOWER approach.

Using the assumption that sighting rates will scale linearly with any increase in circumpolar abundance, sighting rates from CPIII have been multiplied by the relative increase, as predicted by the annual rate of increase estimated by Branch (2008), in order to account for any effect in the rise in densities between when a given region was last surveyed and 2013. As indicated in Figure 1, there are large intervals around the predicted population trajectory. These intervals have also been included in the case study analyses to account for this uncertainty in predicting future sighting rates.

To emulate a SOWER survey, effort was spread equally between the north and south strata. Given the duration of past SOWER voyages, an average of 45 days would be a reasonable average survey length. Like SOWER voyages, we are assuming here that a survey voyage with a single vessel would operate between the hours of 0600 and 1800. Good sighting conditions are judged to be those with both a sightability rating of 2 or more and a Beaufort sea state of 4 or below. Vessel speed is assumed to be 11.5 knots. From records kept during the 2004/05, 2005/06 and 2006/07 SOWER voyages (e.g., Ensor *et al.* 2005; Ensor *et al.* 2006; Ensor *et al.* 2007), it is estimated the average amount of time it takes to locate a blue whale and attempt to photograph and biopsy it after it is first sighted is around 1.51 hours (regardless of how many animals in single sighting). The success rate of photography and biopsy from the 2004/05-2006/07 SOWER voyages was around 0.92 and 0.6, respectively (i.e., of all blue whales approached, 92% could be adequately photographed and 60% could be biopsied). Furthermore, the average within season re-sight rate (i.e., blue whales that have been photographed more than once in a single season) was around 17% (taken as the mean within-season resight rate from 2005/06, 2006/07 and 2008/09 reported in Olson 2010).

The line-transect component of a MR/LT hybrid survey can allow abundance estimation using standard design-based distance sampling methods. In order to judge the likely success of the line-transect component of a MR/LT survey design (where 'design' relates, in simplest terms, to the total amount of effort), we can use the abundance estimate and related precision from previous surveys, i.e., abundance estimates and associated CVs for given years/regions of the SOWER programme, as reported in (Branch 2008). The total amount of time available to complete transects will depend on the sighting rate of individual animals (i.e., taking out time to close on sightings and attempt to photograph and biopsy).

Estimates of the effort and sighting rate of individual animals for Antarctic blue whales in the 0-30ºE area were provided by the SOWER survey undertaken in1992/93. There were SOWER surveys in this area after the completion of CPIII, however, the survey in 2004/05 only surveyed between the ice edge and 64ºS. The next two surveys, in 2005/06 and 2006/07, focussed almost exclusively along the ice edge (with the exception of the fin whale study area north of 61ºS in 2005/06). Given that area along the ice edge have historically been areas of high densities of Antarctic blue whales (Branch *et al.* 2007) the sighting rates from these two SOWER voyages are likely to be overestimates for expected sighting rates for north-south (generally speaking) oriented, randomly located transects.

Estimates of the effort and sighting rate of individual blue whales in the 135-175ºE area were provided by the SOWER surveys undertaken in2001/02-2003/04. Again, only sightings within the longitudinal extent of these three surveys were considered. The representative year from these three surveys was taken to be 2003.

The proposed survey regions for 2013, and those in the comparative SOWER surveys, do not correspond perfectly in space. It is assumed, however, there is some spatial correlation in sighting rates expected between adjacent survey regions.

In order to estimate the success of the line-transect component of the MR/LT survey model, expected group-wise sighting rates and total survey effort from each case study was compared to those in previous by-season SOWER abundance estimates given in (Branch 2008), who used standard line-transect abundance estimate methods. All things remaining equal, the precision of a survey will be related to the total amount of effort and the abundance, or density, of the study animal (i.e., for two surveys of the same amount of effort, one survey in a lower density region will yield a lower precision for the abundance estimate than the survey in a higher density region by virtue of the fact that fewer sightings will occur). We can use simple arithmetic to relate abundance, survey effort and resultant precision.

Assuming sighting rates scale linearly with abundance (i.e., there are no effects on spatial distribution from increasing abundance), and that surveys were conducted in similar conditions (i.e., methods, sighting weather, time of year etc.), the effort required in survey 2 to achieve the same CV as derived in survey 1 would be:

$$Corrected\ sample\ size\ survey\ 2 = Sample\ size\ survey\ 1 \times \left(\frac{Abundance\ 1}{Abundance\ 2}\right)$$

Then, by assuming, *a priori*, some abundance difference in the time between survey 1 and survey 2, an effort level for survey 2 can be calculated in order to return an abundance estimate with a similar CV to that of survey 1.

$$Sample\ size\ required\ \ for\ survey\ 2 = Sample\ size\ survey\ 1 \times \left(\frac{CV1}{CV2}\right)^2$$

which rearranges to,

$$CV2 = \frac{CV1}{\sqrt{\frac{Sample\ sizesurvey\ 2}{Sample\ size\ survey\ 1}}}$$

When combining survey abundance estimates, the associated mean sighting rate is weighted by amount of effort in each SOWER survey region and the associated CV is,

$$CVcomb. = \sqrt{\frac{(CV1 \times abund1)^2 + (CV2 \times abund2)^2}{(abund1 + abund2)^2}}$$

RESULTS

Mark-recapture

The simulation/mark-recapture analysis was ran 500 times, for a range of population rates of increase (1.6, 8.2 and 14.8%), and a range of annual sample sizes (10-500). To quantify the benefit of including pre-existing individual identification data in our analysis, we constructed two simulation scenarios: one assumed that there was no existing photo-ID catalogue and marking commenced in 2013, and another used capture histories from the existing Antarctic blue whale photo-ID catalogue (which were incorporated into the capture history simulation step). The results of these simulations are given in Figure 3 and Figure 4. We use the abundance estimate from the middle year of the study and our yearly growth rate, *r*, as our key indicators.

Examining the Figures, there is some obvious positive bias occurring in the estimation. To investigate this further we fitted the model to capture histories based on a closed population with no mortality, and the bias was greatly reduced (see Figure 5).

From the results, if we deemed an acceptable CV as below 0.2, under the assumption that Antarctic blue whale population is growing at around 8.2% per year, then, we will require around 50 samples per year. However, if we consider potentially higher growth rate this would rise to about 90. Conversely, the required number of samples per year is lower for an assumed annual rate of increase of 1.6%, at around 25 samples. Considering the presence of some bias at smaller sample sizes, a slightly larger sample size may be warranted.

Looking to the scenario of utilising the pre-existing photo-ID catalogue, as expected, having pre-existing data confers some benefit (decreasing the required sample size to 25 per year). Sampling at a rate of 50 samples per year would give an estimated standard deviation of 0.4 on the annual rate of increase (0.3 if existing catalogues are used), see Figure 4.

We now consider the feasibility of attaining 50 samples per year. Peel (2012) described a discrete-time individual-based simulation to determine potential encounter rates from acoustic-assisted tracking of whales. The simulation was applied to 10 degree longitudinal regions (180°W to 180°E) between 0 and 200km of the ice edge (see Figure 12). The result depended heavily on region but for higher density regions predicted encounter rate ranged from 1 to 4 whales per planned survey day.

Forty-five planned days of survey would correspond to 45 to 180 whales encountered annually. It should be noted that the higher values in the range would not be sustainable for a full 45 days. We can extrapolate to number of animals by taking a conservative average group size of 1.4. Two more issues now come into play, firstly, not all animals can be successfully photographed, and some of the encounters will be re-sights from within the season. Estimates of these quantities are discussed in the Line Transect-Hybrid section (0.92 for photo-success and 17% in-season recapture rate). This results in an estimate of between 48 and 192 individuals. Even though, there are many assumptions and approximations this indicates that the required sampling effort is feasible.

Methods to boost encounter rates

Historical Sightings

For reference, all sightings of Antarctic blue whales throughout the SOWER programme (i.e., 1978/79-2009/10) are given in Figure 6, along with survey effort.

Figure 7 shows the mean sighting rates[1] calculated for each SOWER survey, and the years after the third survey finished, for 10º longitude bands (i.e., starting at 180º W and ending at 180ºE). As expected, there is a general trend of increasing sighting rates with CP survey, but with somewhat higher sighting rates in the regions 20ºW-30ºE, 40ºE-10ºE and 130ºE-170ºW. The red lines on Figure 6 represent sighting rates for surveys undertaken after the last circumpolar survey. The large red spike around 20ºE represents SOWER surveys undertaken 2005/06 and 2006/07 where, instead of following the traditional zig-zag line transect design, the survey instead followed the ice-edge; so, this result cannot be directly compared with the others. Furthermore, with the exception of the larger sighting rates in the 20ºW-70ºE region, the remaining areas of the Antarctic have a fairly uniform distribution of sighting rates across a scale of many 10s of degrees of longitude.

The distribution of sightings and total numbers of animals, from the ice edge out to a distance of 750 km, is given as a function of distance in Figure 8. While the majority of sightings have been made within 200km of the sea ice edge, when corrected for actual survey effort within each distance-from-ice band, the relative density of Antarctic blue whales further

[1] Sighting rates of animals are based on the 'best' size estimate in the SOWER sightings database. Furthermore, as these data are not going to be used to estimate an abundance (e.g., restrictions of which effort type was used in Branch, T. A. (2008). Abundance of Antarctic blue whales south of 60ºS from three complete circumpolar sets of surveys. *Journal of Cetacean Research and Management* **9**(3): 253-262.), all effort that might yield a sighting of an Antarctic blue whale has been included.

out actually increases slightly (see two dashed lines in bottom panel of Figure 8). While 90% of the SOWER sightings were made within 200 km of the sea ice edge, when corrected for survey effort, it comes to represent around 60% of the number of Antarctic blue whales, assuming sighting rates scale linearly with densities. However, with approximately 60% of Antarctic blue whales within 200 km of the ice edge at any one time, the best strategy would be to target this area in order to boost sighting rates compared to the average found south of 60ºS.

Various sighting rates for these repeat survey regions are given in Tables 1-3. The CV of sighting rates varies from around 0.4 to nearly 2.0. Any decision to use these regional sighting rates in selecting areas to survey for Antarctic blue whales should consider the possibility that the coming survey year could return low to zero sighting rates, as indicated by the 95% confidence intervals on the various sighting rates in Tables 1-3. However, high encounter rates observed during SOWER surveys in 2005/06 and 2006/07 suggest that this may be less of a problem if survey effort targets the region of 0-200km from the ice edge.

The proportion of time recorded as 'good' weather clearly decreased as a function of distance from the sea ice boundary (see Figure 9). In Figure 10, the proportion of time recorded as 'good' weather is given for various regions south of 60ºS. In accordance with results in Figure 10, most of the coastal regions have 40-60% of the time or higher as 'good' weather. Considering all areas south of 60ºS, the problematic regions would be the more northern regions, and areas such as the Antarctic Peninsula, the marginal ice zone around the Weddell Sea, near the Getz Ice Shelf (130ºW) and the top of the Ross Sea.

Acoustics

Locations of sonobuoys deployed during SOWER cruises are given in Figure 11 along with the distribution of the proportion of sonobuoys in each 10º longitudinal band that detected vocalisations from Antarctic blue whales. These data have so far only undergone limited analyses, but these are sufficient to demonstrate that the longitudinal distribution of blue whale vocalisations is far from uniform. The region 0-20ºE again seems to have a higher density of vocalising Antarctic blue whales, as compared to other regions.

The simulations of an acoustically-assisted survey (i.e. Peel et al. 2012) also revealed encounter rates that were heavily dependent on the region (Figure 12). Due, to the amount of uncertainty on some of the key parameters and the assumptions made, the results of these simulations should be taken too literally. However, they do provide a general idea of the order of magnitude to expect from an acoustic assisted survey. For example, generalising from Figure 12, in dense regions we would expect at least 1 whale per planned day. Furthermore, we would find it very unlikely that acoustics would provide more than 4+ whales per planned voyage day (see Peel et. al 2012).

Historical Catch

Charts showing apparent densities of blue whales in terms of catch per catcher searching day worked (C/CSW) by 1° of latitude by 1° of longitude using only data from pelagic whaling expeditions are given for month and across a number of years, in Figures 14-17. Each chart covers a block of years by each month. Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey. Land station data are not used, and it should be recalled that in the western South Atlantic intensive whaling from South Georgia and the South Orkneys would have a substantial impact on the blue whale populations found there. Thus the absence on these charts of any high blue whale densities in this sector should not be interpreted as an indicating historical low densities there. Outside this region blue whale densities were high in the regions centred on 15°W (0-30°W), 30°E (70°E-110°E), 90°E (75°E-110°E) and 180° (160°E to 160°W). Densities in the 'Sanctuary' (70°W to 160°W) were not particularly high when it was opened in the 1955/56 season. This could be either that blue whales were never abundant there, or that blue whales ranged more widely than the size of the Sanctuary and thus were already depleted by being caught elsewhere.

Mark-recapture/line transect hybrid model

Table 1 shows the comparison of expected sighting rate of individual whales and sighting rate of whale groups predicted for 2013 using a MR/LT survey model. It also shows the resultant number of photograph and biopsy samples that was predicted for the two case study areas for a 45 day survey in 2013. In the area 0º-30ºE an average of around 15 blue whales are predicted to be sighted, of which, 13 would be available for photographic identification and 9 available for biopsy samples. In the 135º-175ºE region the same 45 day survey is predicted to yield around 17 blue whales, 14 of which would be available for photography, and 9 which would be available to be biopsied.

The CV of the abundance estimate of the line-transect component for the 0º-30ºE area would be around 0.59, and around 0.88 for the 135º-175ºE area (Table 2). A check of these predictions can be obtained by considering the sighting rate from the 2004/05 SOWER voyage in the same area (i.e., 0-30ºE, 65ºS to the ice edge), which was 1.2×10^{-3} per n.mile.

An equivalent 'predicted' sighting rate[2] would have been 1.1×10^{-3} per n.mile (0.5×10^{-3}, 2.4×10^{-3}), which is in good agreement.

DISCUSSION

Mark-recapture

The required sample size assessment for mark-recapture gave promising results showing that the required sample size was around 50 animals per year, and furthermore that this was indeed a feasible number to encounter given a 45 day planned survey. The CVs of the estimates were generally very reasonable. It should be noted the abundance CVs reported are for the estimated abundance of the middle year of the study. Since the likelihood ties the individual years together via the population trajectory, in effect, this estimate draws information from the full ten years of recaptures (so for a yearly sample size of 50, 500 samples contribute). So in that respect it is not surprising the CVs are small. One consequence of this model is that an estimate with this CV would only be expected once the full survey is complete.

These results only consider the mark-recapture data in isolation, i.e. we did fit to existing SOWER abundance estimates). However, it is possible to incorporate the SOWER-based abundance estimates into the likelihood framework to inform the model. This should reduce the variance further, but at the expense of reducing the models responsiveness to more recent changes in population growth, i.e., the growth estimate will be representing growth over 20+ years, and so it will be more difficult to detect deviation from constant growth.

Within the mark-recapture calculation, we have only focused on one method of individual identification (photo-identification). It is possible to combine population estimates derived from multiple sources (e.g. genetic and photo-ID mark-recapture programs) and methods are in development.

The relatively simple approach/model we used makes many assumptions about the study population such as equal probability of capture (sighting) for all individuals in each sampling session (zero heterogeneity of capture), and no births or deaths between sampling sessions (i.e. a closed-population). Given the long-term nature of any likely survey effort for Antarctic blue whales (i.e., over many summer seasons), and the possible inclusion of the existing photo-ID catalogue, the assumption of a closed population is not likely to be appropriate (Pollock *et al.* 2002). In an 'open population', where there is turnover in individuals present over the duration of the study, the fundamental assumption of MR methods-that the number of marked animals present at a given sample point is known- is far less reliable. For some studies these assumptions will not greatly bias the population estimate but for many cases more sophisticated models are required to account for deaths, births, immigration, emigration, heterogeneity of capture and so on (Hammond 2010).

In the assessment of the MR strategy we have largely ignored the issue of population structure. Currently it is not known if there are distinct Antarctic blue whales populations (Branch *et al.*, 2007) but from the distribution of lower latitude catch data during austral winters it seems plausible that separate breeding populations may exist. Even so, any such structure may be mitigated to some extent by the large longitudinal movements reported for Antarctica blue whales both within and between seasons derived from Discovery tag data (Branch *et al.*, 2007). Regardless, population structure cannot be ignored and any MR would require a wide distribution of effort to reduce potential bias (Hammond, 2010).

Methods to boost encounter rates

Historical Sightings and Catch

Antarctic blue whales are distributed continuously around Antarctic coastline, which is known from SOWER sightings (Branch 2008), whaling records (Branch *et al.* 2007; de la Mare 2012), the Discovery mark programme (Branch *et al.* 2007) and acoustic moorings (Sirovic *et al.* 2004; Stafford *et al.* 2004). Like all baleen species in the Southern Ocean, patterns of movement of Antarctic blue whales around the Antarctic coastline remain largely undescribed.

Discovery marks (Branch *et al.* 2007), genetics analyses (Sremba *et al.* 2012) and photo-ID (Olson 2010) suggest evidence of both regional fidelity (i.e., returning to the same area every summer) and medium to large-scale movement over a number of seasons (i.e., up to 180º of longitude movement). Most individuals resighted were done so within a single season (probably within around 60º of longitude) indicating that Antarctic blue whales will generally remain within a region within a single season. The next most common resight type in the Discovery, genetic and photo-ID data was within a single region between seasons. Finally, a small number of Antarctic blue whales were observed to have moved up to 180º after two or more seasons after first being marked, including a female that travelled 131 degrees on longitude over four years (Sremba *et al.* 2012).

After imposing *a priori* boundaries based on the IWC Management Areas (Donovan 1991) in their clustering analyses, (Sremba *et al.* 2012) found evidence of population structure in Antarctic blue whales from 218 biopsy samples collected

[2] Increasing from an estimated circumpolar abundance of 1540 in 1993, up to an estimated abundance of 3960 in 2005.

from all Management Areas during SOWER surveys between 1990 and 2009. However, (Sremba *et al.* 2012) concede that with imposed *a priori* geographic boundaries, no indication about how these structures might apply to breeding grounds, a small sample size and "relatively weak levels of differentiation in molecular markers", interpretation of these results in terms of population structure cannot proceed much further. However, these results must be considered in the context of formulating a circumpolar strategy for mark-recapture analyses for a circumpolar abundance estimate for Antarctic blue whales. If these putative population structures are ignored, the resultant mark-recapture abundance estimate will be negatively biased.

Acoustics

There are still a large number of unknowns regarding the acoustic behaviour of Antarctic blue whales, but the existing evidence suggests broad similarities in acoustic behaviour between Antarctic and other blue whale population. (e.g., similar source levels and frequency range, similar annual variation in 'song' detection, and the production of 'D' calls). These broad similarities and the success of the real-time tracking system during the two trial voyages reported in (Miller 2012) suggests that acoustic tracking may be able to increase the total number of whale encounters, thus making more efficient use of expensive ship time around Antarctica, and thus supports the use of acoustics as a key tool in determining the circumpolar abundance of blue whales in the Southern Ocean.

One caveat to using DIFAR sonobuoys around Antarctica arises from proximity to the South magnetic pole. The spatial variation in magnetic declination and the magnitude of the magnetic dip in the Southern Ocean are much greater than at lower latitudes and increase as a function of proximity to the South magnetic pole. The acoustic methods proposed in (Miller 2012) require DIFAR sonobuoys that, in-turn, depend on a magnetic compass to obtain directions to the whales. At some point near the magnetic pole the horizontal component of the magnetic field will be smaller than can be measured by the magnetic compass in the sonobuoys. Data from the 2010 Antarctic Whale Expedition (SC/63/SO13) indicate that DIFAR sonobuoys are still functional with a horizontal component of the magnetic field as small as 4200nT (B. Miller unpub.). The region outside the circle on Figure 16 denotes the area where DIFAR sonobuoys are expected to provide accurate bearings to whales.

While it is presently unclear whether DIFAR sonobuoys will provide reliable bearings near the South pole (i.e. 64°S, 137°E), it is expected that clarity on the issue will be resolved shortly (e.g. the minimum magnetic field required for DIFAR compass can be measured in a laboratory setting or at the very least specified by the manufacturer). Near the South pole, bearings to whales could potentially be obtained using the time differences of arrival among multiple sonobuoys, however this technique requires deploying more sonobuoys in logistically more complex patterns to achieve the same results as DIFAR sonobuoys. While such techniques are not ideal, their use could also help to mitigate any disruptions to the supply of affordable (i.e. free) sonobuoys. In the interim, a conservative approach would be to assume that passive acoustic tracking would have reduced performance around the south pole (Figure 13) and thus increases in encounter rates resulting from this method would be reduced in that area.

Mark-recapture/line transect hybrid model

It is certainly possible to complete line-transect surveys for given regions of the Southern Ocean, in a similar fashion to SOWER. Furthermore, studies have shown that model-based abundance estimators (spatial smoothers) can be used to account for bias associated with sampling hotspots, and generate density-based abundance estimates from surveys that were designed primarily for photo-identification or biopsy (e.g.,Williams *et al.* 2011). Although valuable in a regional sense, both approaches will be potentially limited in the extent to which they could contribute to a circumpolar abundance estimate using mark-recapture methods, depending on the numbers of photo-ID or genetic samples are yielded.

General Discussion

In principle, there are other considerations when adopting a survey strategy than effort alone. There may be reasons to invest more in a high-effort strategy if it can deliver additional outcomes than those considered here. An IDCR/SOWER-type survey would provide data not only on blue whales but all other cetacean species encountered in that region. Indeed such data are the basis of population or regional abundance estimate for Antarctic minke and fin whales as well as Antarctic blue whales (e.g. Branch and Butterworth 2001; Bravington and Hedley 2010). Also if an SOWER circumpolar survey was repeated then arguably the estimates would be considered more comparable to the previous estimates. Similarly, structured line-transect surveys would also provide improved information for other studies such as habitat modelling and for calibrating long-term acoustic monitoring data of several cetacean species relative to regional abundance estimates.

However, one major drawback of an SOWER-type survey is their complexity and the need for uniformity of protocols between vessels. Such surveys generally require a full dedicated voyage. As much of this future work is likely to rely upon an integration of whale research with broader polar research programs, then opportunities may be more restricted to work that can occur along with other research (such as oceanography, sea-ice experiments etc). If future abundance estimates are to be derived from multinational efforts then the coordination and delivery of the strict experimental protocols and track lines of an SOWER-type survey will be a significant practical and logistical hurdle that may be difficult to overcome.

In contrast to line-transect surveys the MR approach, through the collection of biopsy samples and photographs, presents a much more simple approach to derive an abundance estimate for Antarctic blue whales. Little standardisation is required between vessels and potentially the effort can be spread over many years. However, as can be seen from the calculations above there are significant advantages to marking a reasonably large number of individuals early in the study as this reduces the later effort required to deliver a precise abundance estimate. This is essentially a ‘legacy model’ where investment in effort now will continue to pay dividends for many years or decades to come. Importantly, given the relaxed survey protocols, any vessel operating in Antarctica could potentially generate data for this project if they can deliver photographs of sufficient quality for photo-identification. Indeed this may be an opportunity to engage Antarctic tourism vessels and station supply vessels in important data delivery if managed appropriately although it is clear there will need to be dedicated survey vessels to ultimately provide the magnitude of sightings required.

In this paper we have not attempted to predict what effort can be delivered; that is, the number of vessels that could be provided by the international community for an endeavour such as this. Access to vessels for polar research is managed through a variety of mechanism in different countries with determinants including the excellence of the research, the relevance to national priorities and political aspects of regional and international engagement. It is obvious that any strategy, even one requiring less than ten vessel-seasons over several years, represents a significant investment in Antarctic research and will require considerable buy in from many Governments and their polar programs. Although ambitious, funding such an initiative is achievable if sufficient planning and collaboration occur. The SORP, which includes at least 12 nations with active polar programs, is an ideal mechanism for a project of this scale. A focused effort on understanding the current status and behaviour of the Antarctic blue whale builds well on the legacy of the multi-decadal SOWER cruises which made a significant contribution to non-lethal whale research in the Southern Ocean (International Whaling Commission, 2009).

In our analyses and simulations, we have assumed that the population of Antarctic blue whales is increasing at around 8.2% per year, according to results given in (Branch 2008). It should be recognised, however, this trajectory many not continue to be true in the future, and, as such, there must be mechanisms in place to monitor this population. However, if the population rate of increase is lower than expected, a survey design formulated to return a circumpolar abundance estimate with a useful level of precision for a population increasing at 8.2% will also be adequate for the lesser population trajectory.

Future Work

In terms of future work, some further development is required on mark-recapture methods. In particular, a method to handle the multiple catalogues (photo-ID and genetic biopsy). As well as further investigation on the effect of the closed population assumption, i.e., an investigation into using (or developing) an open mark-recapture model (such as POPAN). Given its effect of Mark-recapture methods, it is also important to examine the implications of heterogeneity; particularly heterogeneity arising from population structure and acoustic sampling bias. In the case of population structure it may be beneficial to conduct a simulation study to quantify it effects. Alternatively, satellite tagging may help our understanding of the spatial structure of the population by providing missing linkages between feeding and breeding grounds. For acoustic sampling bias, further work is needed to determine if the use of passive acoustics to find whales is gender biased. If this is the case the development of methods to take this into account would be needed (e.g. the use of acoustic archival tags).

Another strategy to address heterogeneity would be to ensure reasonably even distribution of survey effort around the Antarctic on an annual basis. However, to maintain an adequate annual sample size, areas of historically higher densities of Antarctic blue whales need to be surveyed reasonably frequently, if not every year. However, sampling these higher density areas every year will also yield information concerning site fidelity. By recommending that surveys remain within 200 km of the ice edge in order to stay within the highest densities of Antarctic blue whales, we have to do so under the assumption that there is no heterogeneity across animals near the ice edge and across those further north.

Conclusions

We have thoroughly considered existing datasets, sophisticated models, and recent developments relating to the circumpolar abundance of Antarctic blue whales. In light of this, the most practical approach for obtaining a new circumpolar estimate of abundance appears to involve all of the following:

- A mark-recapture survey methodology
- Using passive acoustic tracking to increase encounter rate
- Targeting ‘hotspots’ that are expected to have higher densities of whales
- Repeating surveys annually (or at least as frequently as possible)

- Ensuring that targeted areas are representative of circumpolar whale distribution

The work in this paper suggests that by combining all of these methods, a precise circumpolar abundance estimate for Antarctic blue whales could be achieved over the next decade.

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TABLES

Table 1 Results of mark-recapture/line-transect hybrid model case studies, estimating the numbers of animals expected to be encountered, photographed, biopsied and identified for the two case study areas.

Case study area		Last SOWER survey year and extent	Prop. good sighting weather	Total hours available for 45 day survey	Sighting rate when case study area was last surveyed	Number of years since last surveyed and 2013	Mean group size	Predicted sighting rate (per n.mile) in 2013 (with 95% prediction interval)
0º-30ºE	60º-65ºS	1992/93 (0-40ºE)	0.474	127	0.0×10^{-3}	20	-	0.0×10^{-3}
	65ºS-ice edge		0.641	173	2.03×10^{-3}	20	2.0	9.8×10^{-3} (2.9×10^{-3}, 28.3×10^{-3})
135º-175ºE	60º-65ºS	2001/02 (130-150ºE), 2002/03 (150-170ºW), 2003/04 (170ºE-170ºW)	0.362	97	1.11×10^{-3}	10[1]	2.1	2.4×10^{-3} (0.7×10^{-3}, 7.1×10^{-3})
	65ºS-ice edge[2]		0.486	131	2.03×10^{-3}	10	2.8	4.5×10^{-3} (1.3×10^{-3} , 12.9×10^{-3})

[1] 10 years from 2002/03 season, used as the middle year for the 2001/02-2003/04 SOWER surveys covering the 135-175ºE
[2] Either the ice edge or 70ºS, whichever comes first when moving south.

Table 4 continued.

Case study area		Predicted animal-wise sighting rate (per n.mile) in 2013 (with 95% prediction interval)	Mean time (hrs) to find an animal	Predicted total number of animals sighted (with corresponding 95% PI)	Predicted number of animals to be photographed (with corresponding 95% PI)	Predicted number of animals to be photographed (with corresponding 95% PI)	Predicted number of individuals (with corresponding 95% PI)
0º-30ºE	60º-65ºS	0.0×10^{-3}	-	-	-	-	-
	65ºS-ice edge	10.6×10^{-3} (5.8×10^{-3}, 56.6×10^{-3})	8.2 (1.5-15.0)	15 (9, 38)	13 (8, 34)	9 (5, 22)	10 (6, 28)
135º-175ºE	60º-65ºS	5.0×10^{-3} (1.5×10^{-3}, 14.9×10^{-3})	17.4 (5.8, 58.8)	13 (3, 24)	11 (4, 22)	7 (3, 14)	9 (13, 18)
	65ºS-ice edge	12.6×10^{-3} (3.6×10^{-3}, 36.1×10^{-3})	6.9 (2.4, 24.4)	4 (1, 11)	3 (0, 10)	2 (0, 6)	2 (0, 8)

Table 2 Comparison of quality of abundance estimates from the line-transect component of the mark-recapture/line-transect hybrid model. Unlike the previous sighting rates from original SOWER voyage taken from whole of survey for that year, not just the longitudinal range of the case study area.

Case study area		Year of SOWER abundance estimate	Longitudinal extent of SOWER survey	Total survey length (n.mile) of SOWER survey- both strata	SOWER abundance estimate for that season (CV)	SOWER group-wise sighting rate (per n.mile)	Predicted group-wise sighting rate (per n.mile) in 2013 (with 95% prediction interval)
0º-30ºE	60º-65ºS	1992/93	0-40ºE	5451	74 (0.66)	1.1×10^{-3}	5.4×10^{-3} (1.48×10^{-3}, 15.4×10^{-3})
	65ºS-ice edge				-		
135º-175ºE	60º-65ºS	2001/02 +2002/03	130º-170ºE (130º-150 E; 150º-170ºE)	5809 (1899 + 3910)	283 (0.74)[2]	0.9×10^{-3}	2.03×10^{-3} (0.56×10^{-3} , 5.92×10^{-3})
	65ºS-ice edge						

[2] Combined abundance estimate and CV

FIGURES

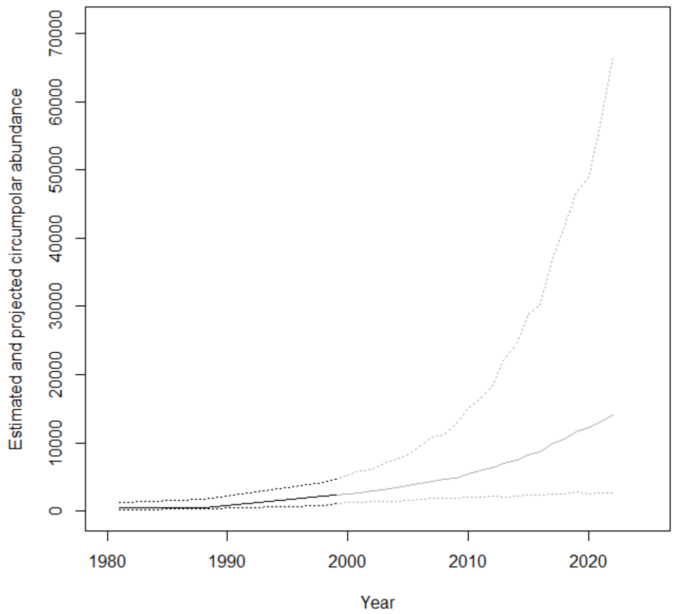

Figure 1 Estimated and projected abundance estimate for Antarctic blue whales. The black lines are circumpolar population estimates for CPI, CPII and CPIII, respectively (as in Branch 2008); dotted black lines are the upper and lower 95% confidence intervals on those estimates. The solid grey line represents the projected (simulated) abundance based on an estimated rate of increase of 8.2% per year from 1998 and the associated 95% confidence interval, derived using the quantile method (grey dotted lines).

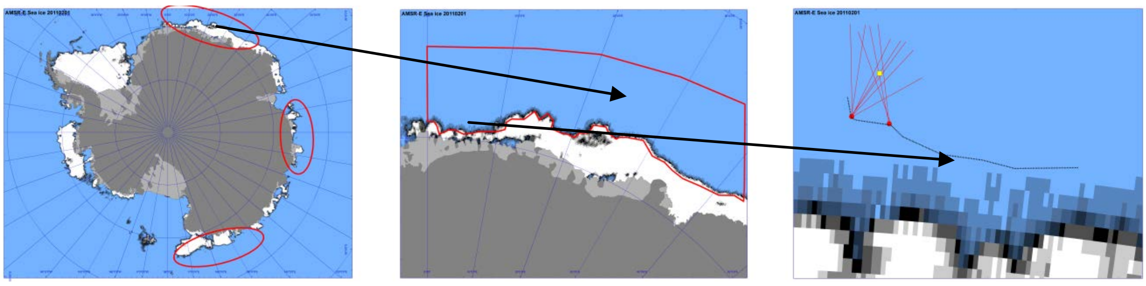

Figure 2 Geographic scales that need to be considered in order to locate Antarctic blue whales. At the circumpolar level, we can explore historical sighting and catch records to find areas of higher Antarctic blue whale densities (left panel). Within circumpolar density ‘hotspots’, at the scale of a 1000 km or so, we can use observations of feeding ecology of Antarctic blue whales to suggest that targeting the ice edge will yield relatively higher densities (middle panel). Then at the scale of 100 km or so, we can potentially use passive acoustics to target individual animals or groups.

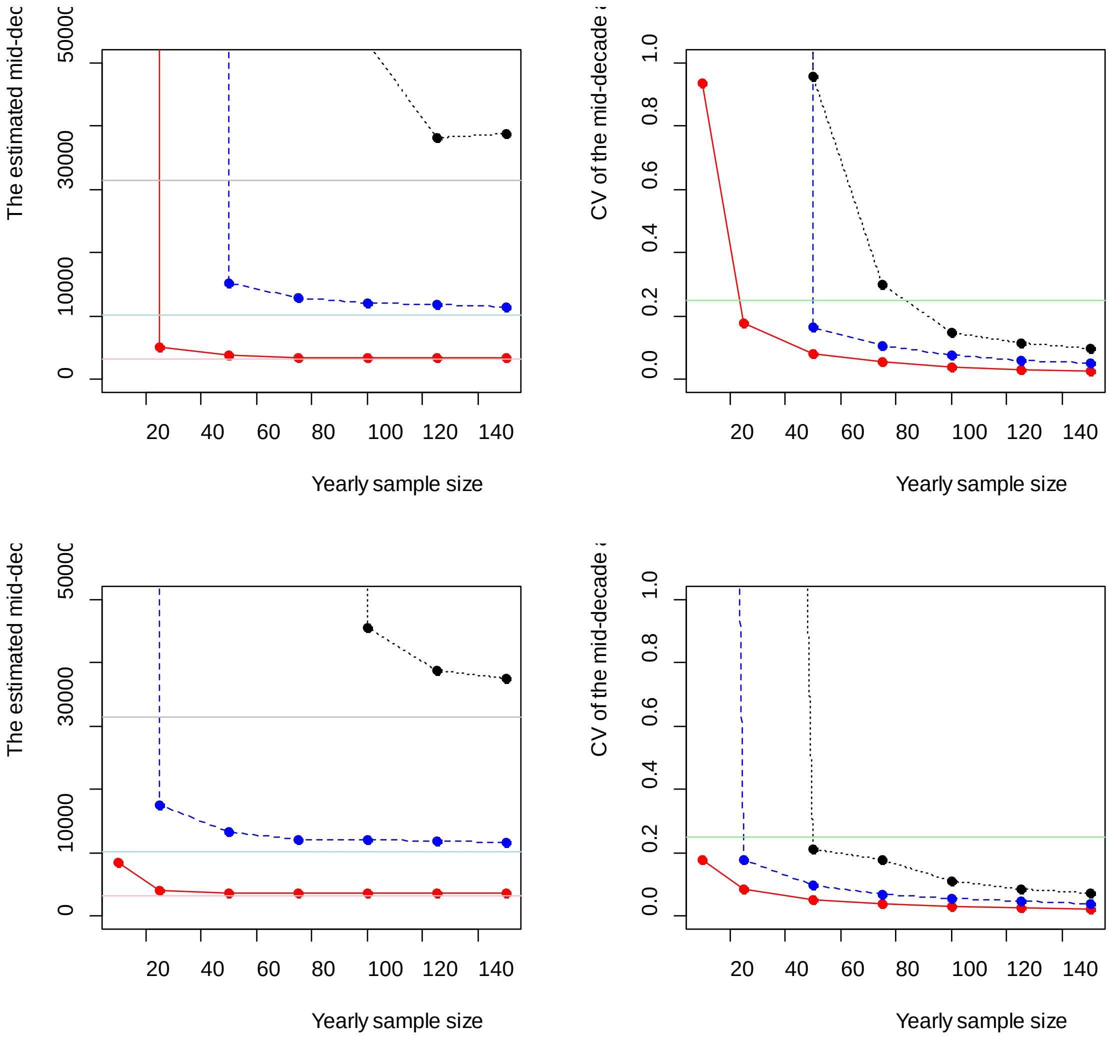

Figure 3 Simulation results with no mortality. Left panels: the maximum likelihood estimate of the mid-decade (2018) abundance, estimated from mark-recapture for 2013-2022, from simulated presence and capture histories for a range of different rates of increase (black = 14.8%; blue = 8.2%; and red = 1.6%), for a range of different yearly sampling levels for mark-recapture component. The solid lines denote the true values. Right panels: CV of maximum likelihood estimate of annual rate of change, with the green line denoting our target CV. Upper panels: where mark-recapture sampling (either biopsy or photo-ID) starts in 2012/13. Lower panels: for presence/capture history simulations involving pre-existing photo-ID data, and subsequent sampling starting in 2012/13.

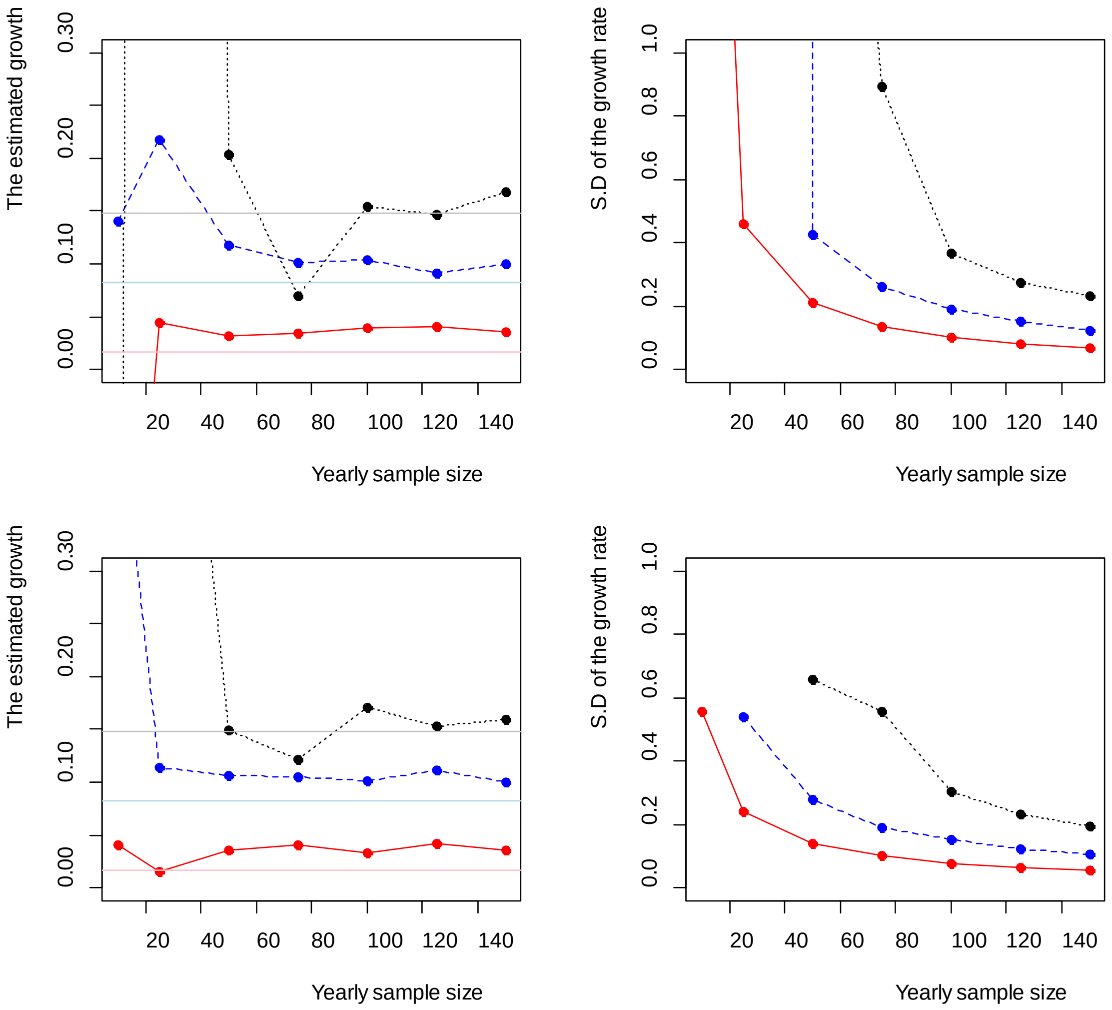

Figure 4 Simulation results with mortality. Left panels: the maximum likelihood estimate of annual rate of change, estimated from mark-recapture for 2013-2022, from simulated presence and capture histories for a range of different rates of increase (black = 14.8%; blue = 8.2%; and red = 1.6%), for a range of different yearly sampling levels for mark-recapture component. The solid lines denote the true values. Right panels: CV of maximum likelihood estimate of annual rate of change. Upper panels: where mark-recapture sampling (either biopsy or photo-ID) starts in 2012/13. Lower panels: for presence/capture history simulations involving pre-existing photo-ID data, and subsequent sampling starting in 2012/13.

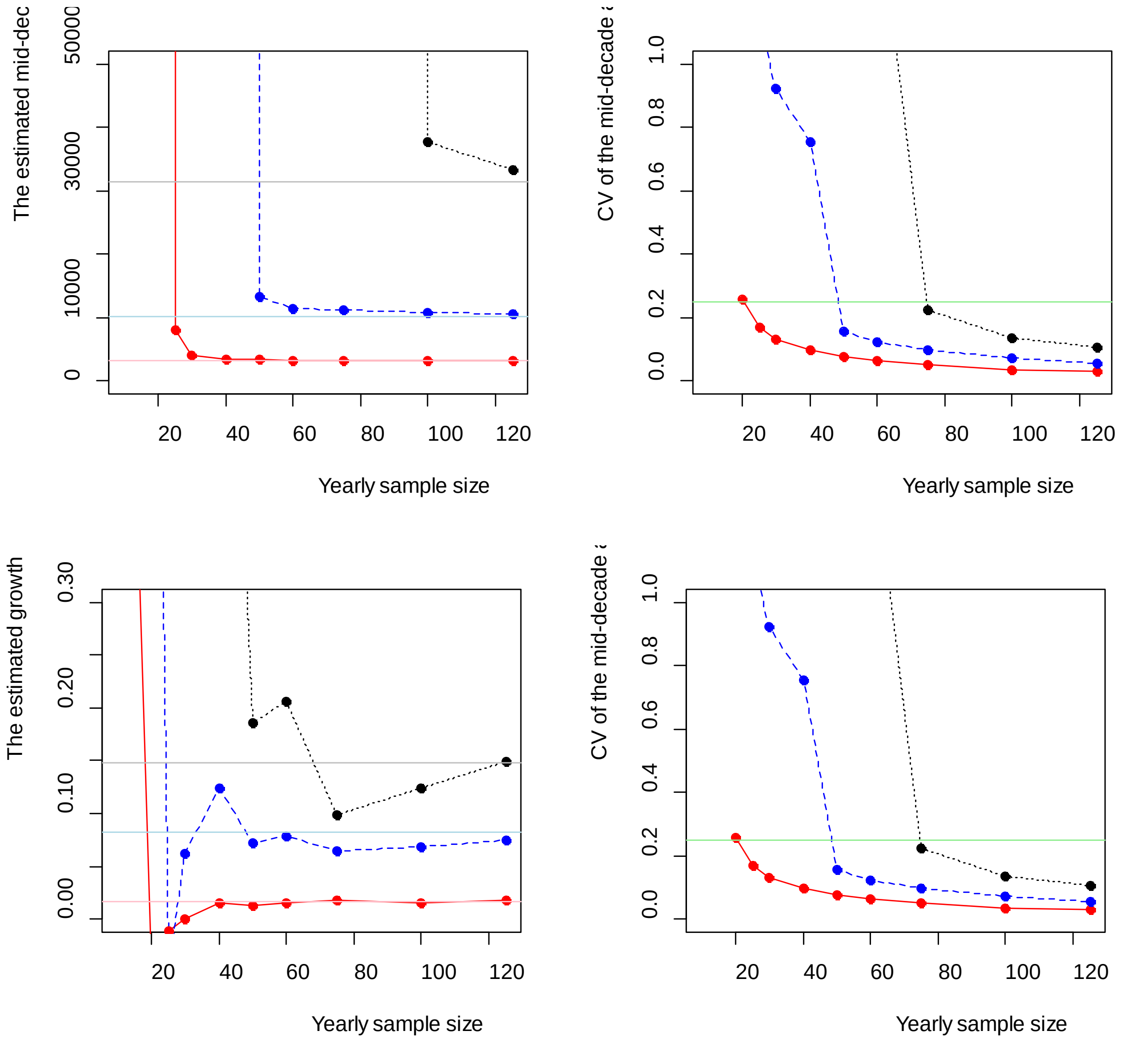

Figure 5 Simulation results with no mortality or pre-existing photo-id data. Upper panels: the maximum likelihood estimate of mid-decade (2018) abundance (left) and its associated CV (right). Lower panels the maximum likelihood estimate of annual rate of change (left) and its standard deviations (right). Derived from simulated presence and capture histories for a range of different rates of increase (black = 14.8%; blue = 8.2%; and red = 1.6%), for a range of different yearly sampling levels for mark-recapture component.

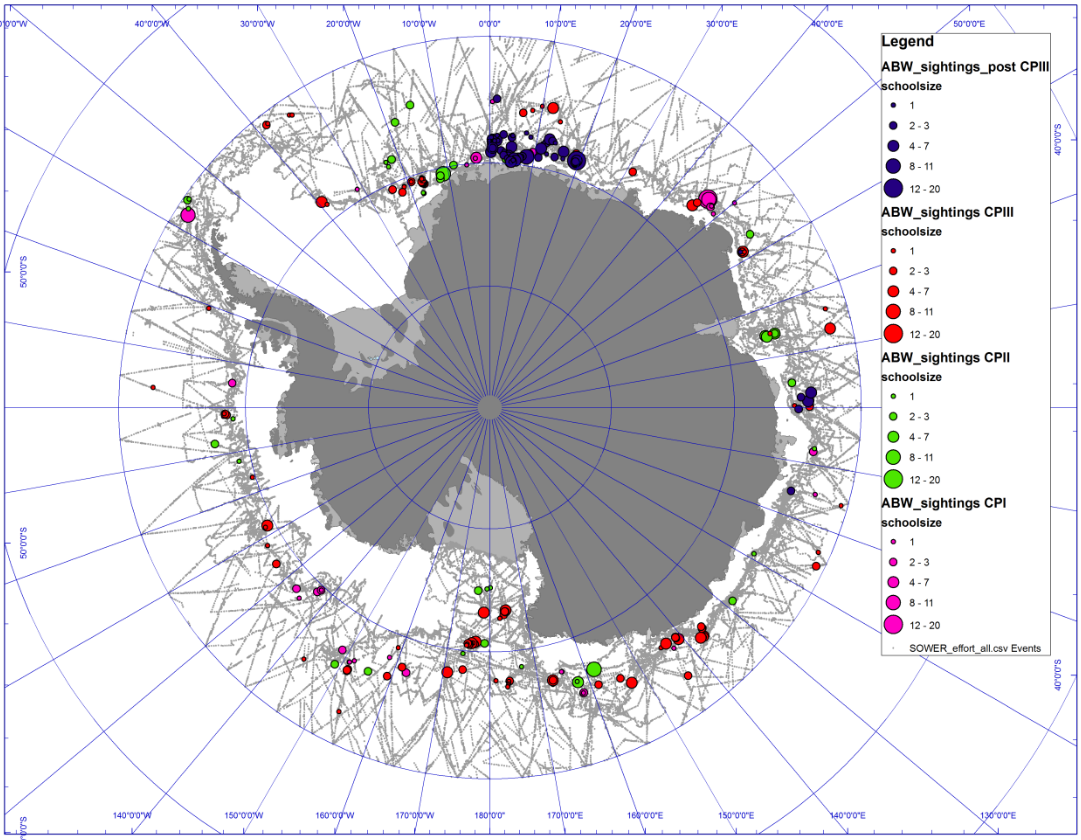

Figure 6 All sightings of Antarctic blue whales throughout the IDCR/SOWER programme (1978/79-2009/10). Sightings are presented as circles, colour and size indicating which CP survey and group size, respectively. Grey lines indicate survey effort.

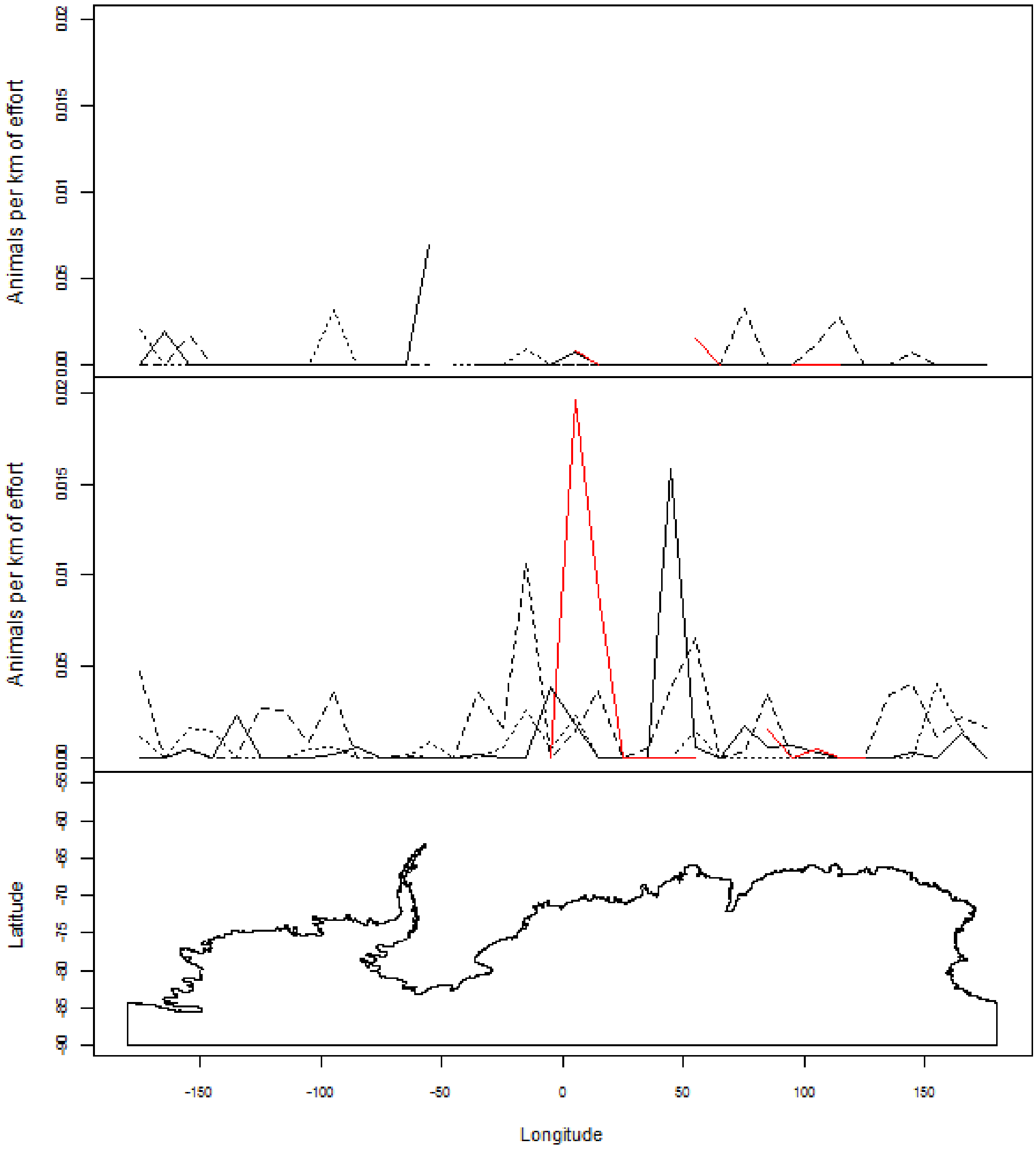

Figure 7 Sighting rates per animal (i.e., all animals within sightings) per 1000 km of effort, by CP survey, and averaged within 10 degree longitude bands. Upper panel indicates sighting rates in the band 200-500km from the local ice edge; the middle panel indicates sighting rates in the band 0-200km from the local ice edge. Solid line indicates sighting rates for CPI; dotted line for CPII; dashed line for CPIII; and red line for survey effort undertaken after the completion of CPIII (i.e., between 2004/05 and 2009/10).

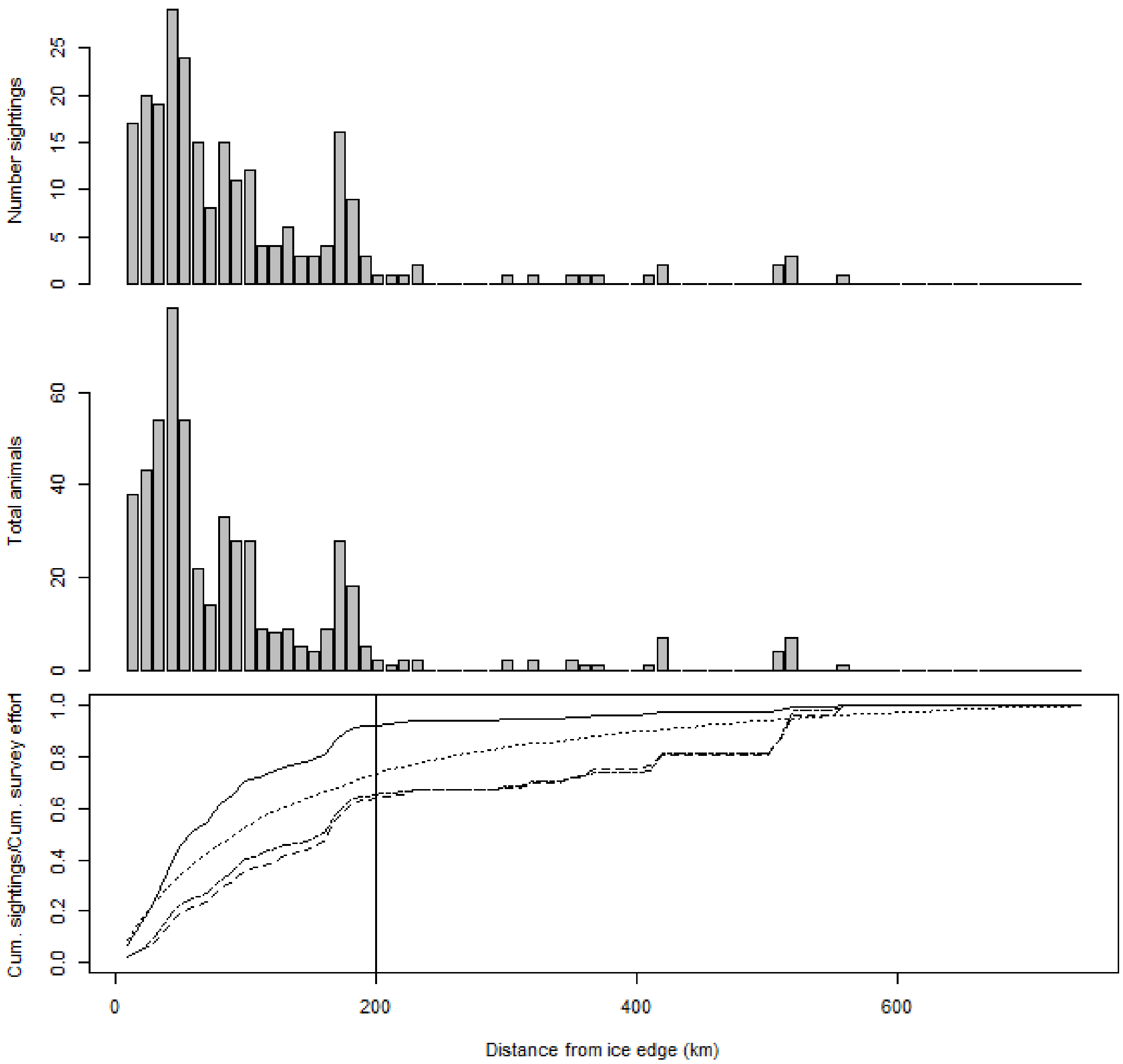

Figure 8 Distribution of all Antarctic blue whale sightings during CPII, CPIII and subsequent SOWER surveys 2004/05-2007/08 (upper panel) and total numbers of animals observed (middle panel) as a function of distance from local ice edge (position of ice edge as observed and recorded during surveys). Bottom panel indicates the proportion of all blue whale sightings (solid black line); survey effort (dotted line); and sightings (dashed line) and total animals observed (two-dash line), both standardised against the survey effort at each distance, within a given distance from the ice edge.

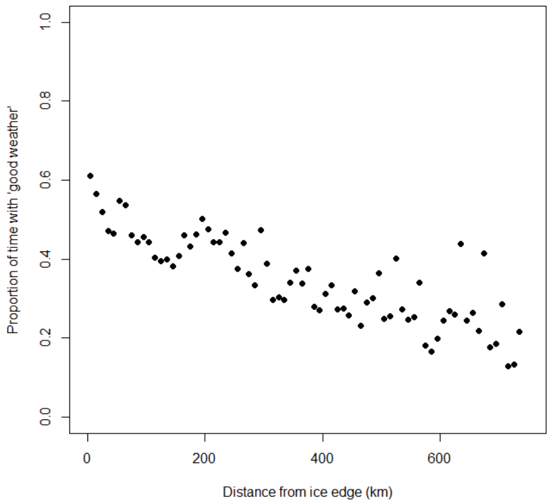

Figure 9 Proportion of good weather (i.e., hours where sighting conditions were Beaufort sea state ≤ 4 and sightability ≥ 2), as a function of distance from a SOWER defined ice edge (i.e., that observed from vessel), out to a distance of 750 km. Proportion has was calculated as the amount of 'good observing' time divided by total time spent in each 10km distance bins; weather observations were taken from CPII, CPIII and the non-CP survey years 2004/05, 2005/06, 2006/07 and 2007/08.

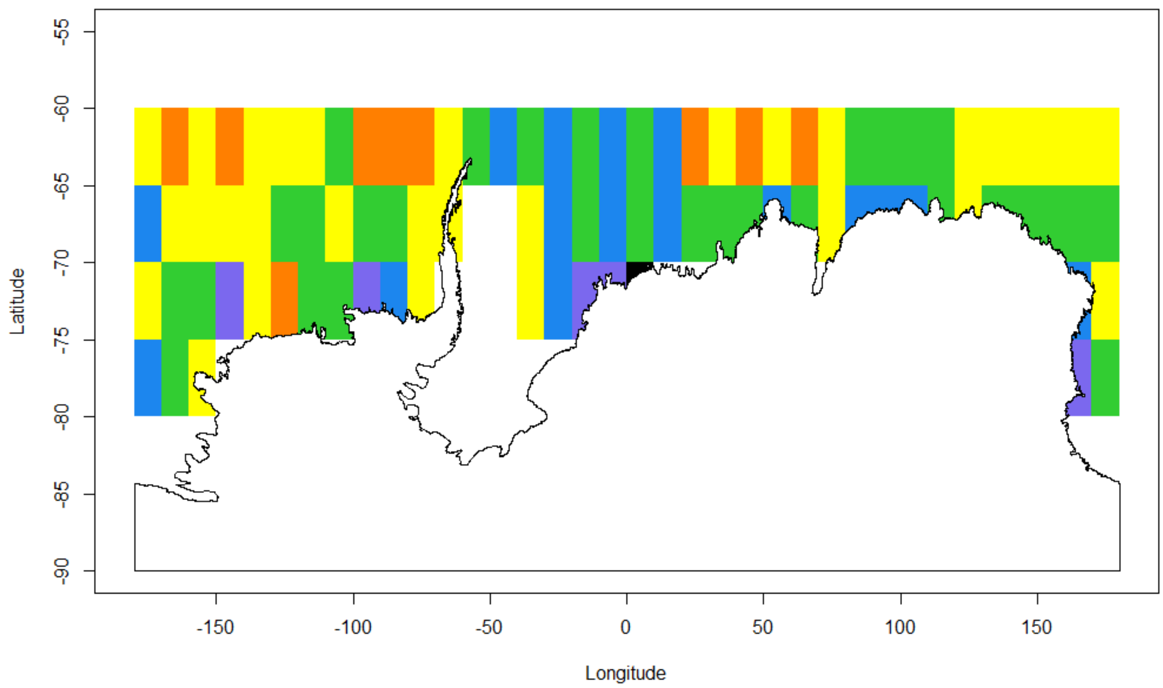

Figure 10 Proportion of time in each 10º longitude × 5º latitude cell that IDCR/SOWER surveys recorded good observing weather (i.e., Beaufort sea state of 4 or below and a sightability score of 2 or above) for CPII, CPIII and the non-CP survey years 2004/05, 2005/06, 2006/07 and 2007/08. White cells indicate no effort was recorded; black indicates that no good observing weather was recorded; orange indicates 0-20% of the time was good observing weather; yellow, 20-40%; green, 40-60%; blue, 60-80%; and purple indicates 80-100% of the time was good observing weather.

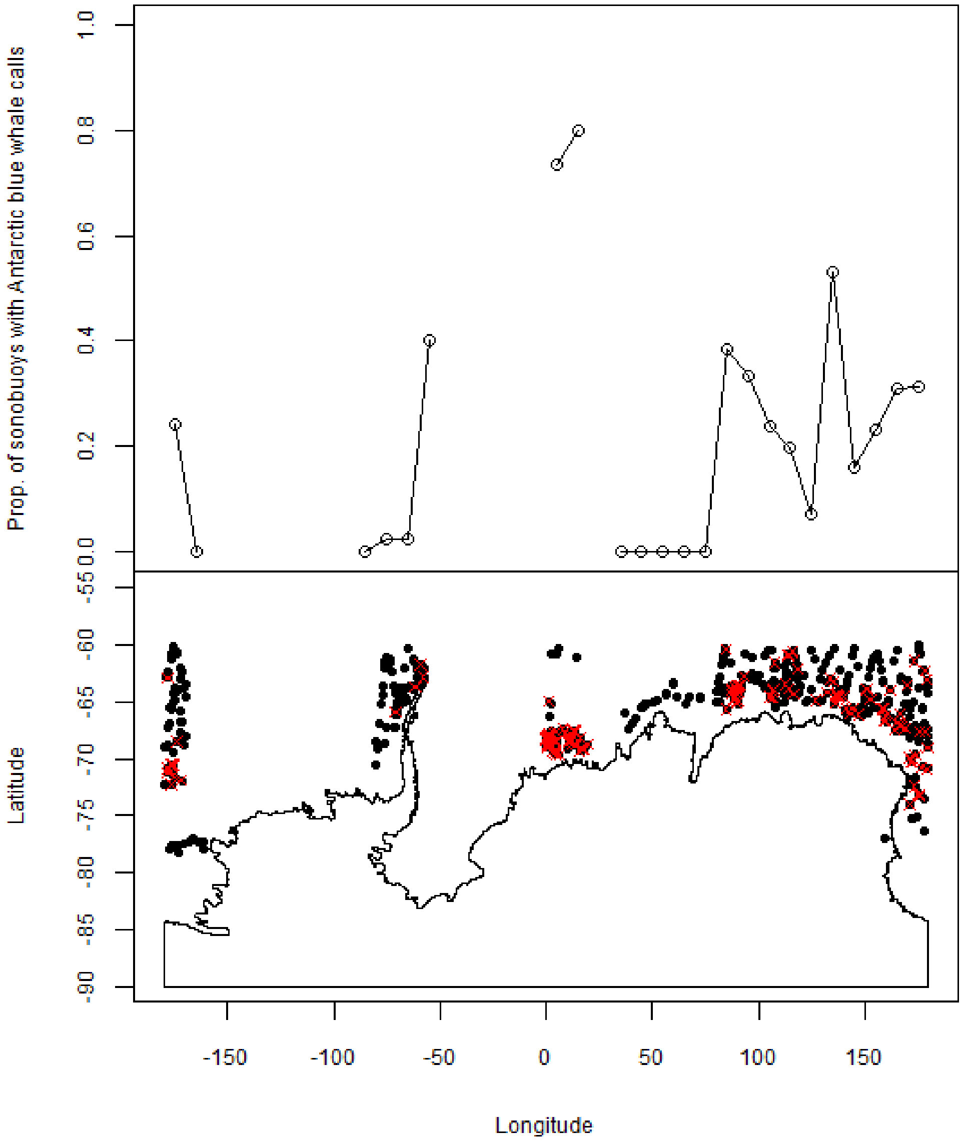

Figure 11 Proportion of sonobuoys deployed south of 60ºS on SOWER voyages between 1999 and 2009, with which Antarctic blue whale calls were heard (upper panel). Positions of sonobuoys points deployed given with black dots (lower panel). Those registering an Antarctic blue whale call are also marked with a red cross.

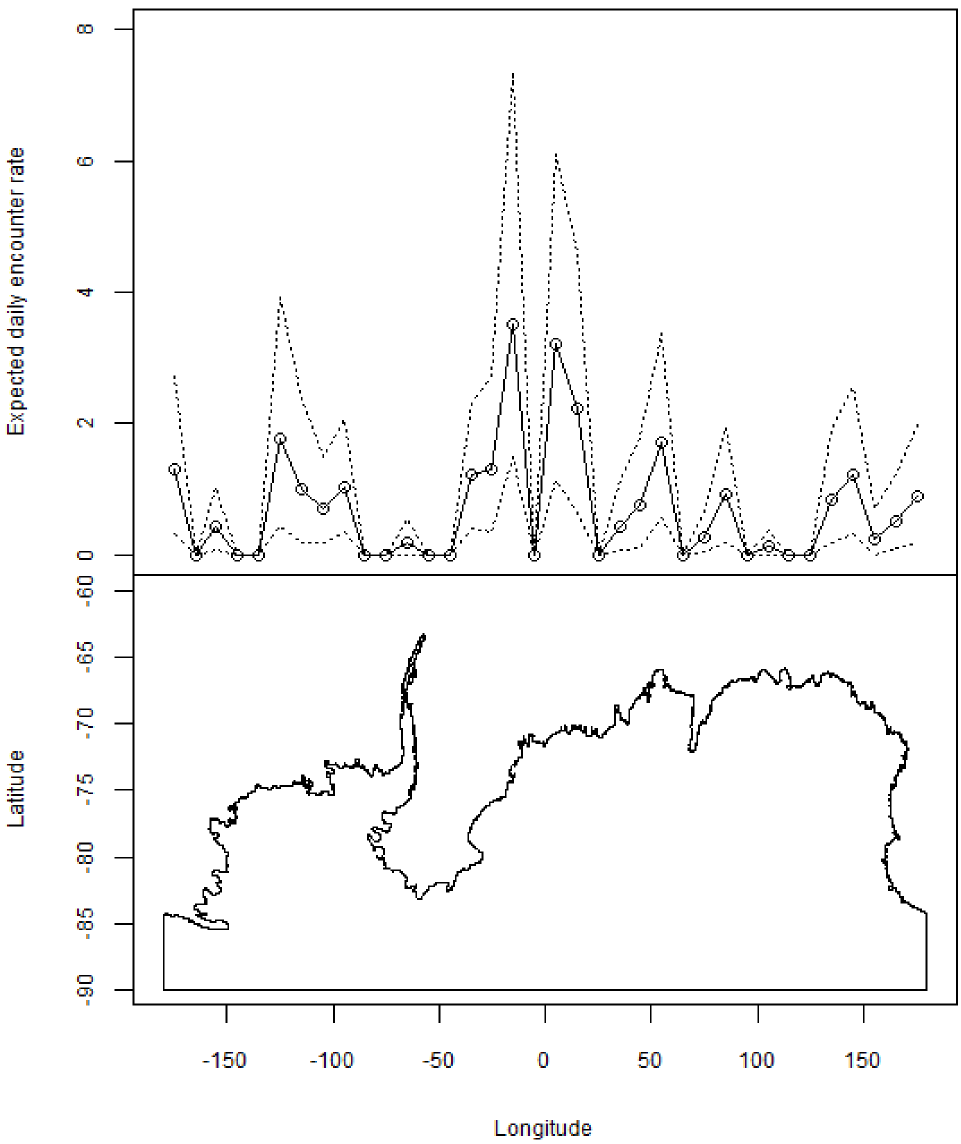

Figure 12 Simulated daily encounter rates for surveys supported by passive acoustics. Mean encounter rate given in black; dotted lines indicated upper and lower 95% confidence interval (From Peel et. al. 2012). In dense regions we would expect at least 1 whales per planned day. Furthermore, we would find it very unlikely that acoustics would provide more than 4+ sightings whales per planned voyage day.

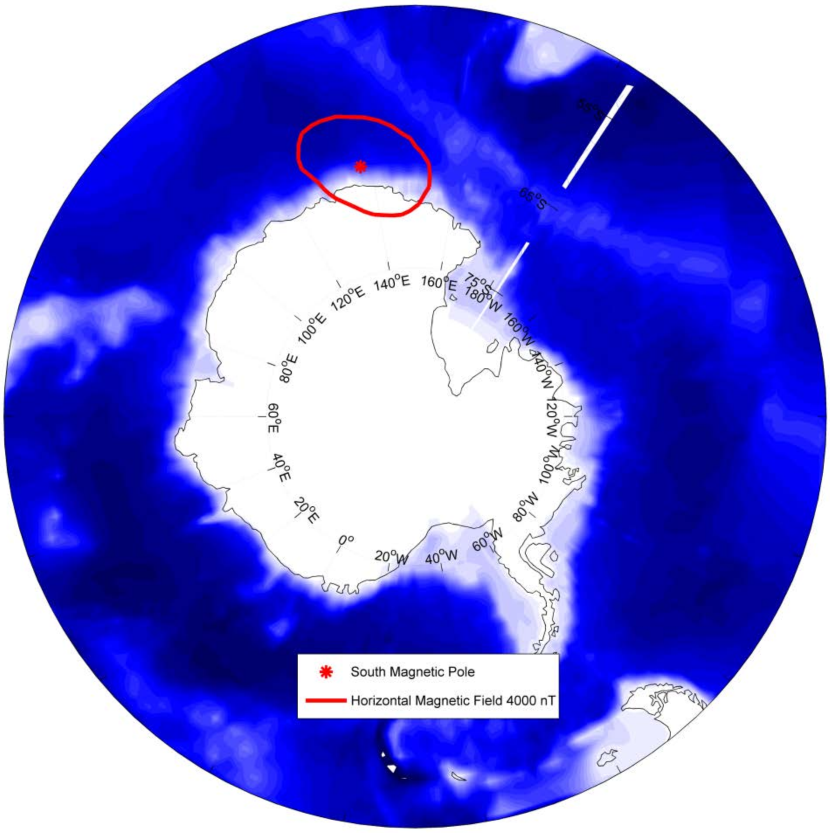

Figure 13 The region outside the red circle denotes the area where DIFAR sonobuoys are expected to provide accurate bearings to whales. DIFAR Sonobuoys deployed nearer to the magnetic pole may not provide accurate bearings due to weak horizontal component of the magnetic field which may cause the compass drift.

APPENDIX A

To investigate minimum sample sizes we looked at the sample size required to obtain a reasonable CV on the abundance estimates as well as the standard deviation of the growth rate.

The overall procedure we used to estimate variance was to 1) predict population trajectories of Antarctic blue whales, then 2) given the yearly population numbers simulate presence and capture histories and 3) from the capture histories estimate abundance and growth rate using maximum likelihood. 4) from this model we estimated the variance using the inverse hessian of the negative log-likelihood. This process was repeated a number of times for different simulated capture histories and the average variance taken.

The population trajectory was taken to be

$$\hat{N}_t = N_0 (1+r)^t, \qquad \text{(Equation A1)}$$

where t is the number of years after the starting year; N_t is the projected population at time t; N_0 is the estimated population at time 0 (i.e., at 1998, the first time point for which there is a circumpolar abundance estimate); r is the estimated annual rate of increase. On completion of CPIII Branch (2007), using the IDCR/SOWER sightings data and a maximum likelihood approach (Branch *et al.*, 2004), estimated the rate of increase to be 8.2% per year (95% CI 1.6-14.8%) with point abundance estimates for the mid-year (1998) of CPIII to be 2280 (CV = 0.36). Projecting into the future from the CPIII abundance estimate using equation A1 we can produce future population size estimates from 2007 (to cover existing photo-id catalog), and over the proposed ten year survey period from 2013.

The likelihood model we used assumed a closed population. However to incorporate, the bias introduced by this assumption into the estimates, the simulation framework includes a birth-mortality component. So in order to create the presence history, the population size must be known, in addition to any abundance trajectories, and associated birth and mortality rates.

As reported in {Branch, 2004 #3086}, there is limited information about survival rates for Antarctic blue whales. However, in their study of Bayesian methods to estimate abundance in trends {Branch, 2004 #3086} assumed $S \sim N(0.96, 0.02^2)$ with bounds [0.93, 0.99]. Although it is only strictly valid to consider birth rates as a function of the number of reproductive females, here assuming constant sex ratio, we can provide a simple estimate as a function of all animals in a population at a given time; 1.082-0.96 = 0.112, i.e., there are 0.112 births per individual, per year. Therefore, for a given time step, we can estimate how many whales were present in the previous time-step; how many of those animals will survive into the current time-step; and how many births there must have been. From this, we can create a presence history matrix containing the fates of all animals over the sampling period of interest (new animals added and others removed permanently).

So an underlying population was generated, to which the given birth and mortality rates were applied. The population can be characterised via a presence history, which describes whether an animal is present over the sampling periods of interest; animals are assigned a 1 if present, and 0 if absent. If the animal has been removed during the intervening time-step it is assigned a 0. If it has been born in the intervening time-step, it switches from a 0 to a 1. A MR sampling framework can then be applied to this presence history to create a capture history.

From a presence history we can simulate a capture history. We assume that all animals have identical sampling probabilities; any diversion from these assumptions—that is, heterogeneity in sampling—leads to biases in abundance estimates (for example, if the sampling only targets males, then the resultant abundance estimate will be negatively biased). Unfortunately, at this time, there is little information which could help quantify heterogeneity in sampling probabilities of Antarctic blue whales. Therefore, for the purposes of these simulations, no consideration has been given to animal age, gender or location; we have assumed uniformity in the probability of sampling, and the probability of an individual being sampled in a given time-step t is $s_t(1/N)$, where s_t is the sample size per sampling period and N_t is the total abundance in that time-step t.

To account for the possibility of sampling animals more than once in a single sampling period (which has been observed within the blue whale photo-ID catalogue (Olson 2010)), animals were sampled with replacement. Furthermore, the probability of an individual being sampled in a given time-step is independent of whether it was sampled previously.

We then estimated $\hat{N}_0$ and $\hat{r}$ from the simulated capture histories, using maximum likelihood. The likelihood incorporated the mark-recapture data, and the population trajectory model (eq. A1) . The model assumed there was no mortality, as this greatly simplifies the analysis. The blue whale mortality is very low but this countered by the span of the survey over many years and the use of historical photo-id catalogue. This issue should be investigated further. The fact that the simulated capture histories include mortality should mean that the effect of this assumption is represented in the estimates.

The likelihood is based on looking at the numbers of new whales found each year (n_t) in relation to the (s_t) whales that were sampled as the result of a binomial experiment. So the log-likelihood is given by

$$LogL = \sum_{t=1}^{T} \binom{s_t}{n_t} p_t^{n_t} (1 - p_t)^{s_t - n_t}$$

where p_t is the probability in year t that any given whale will be a new whale not previously seen in the running catalogue of whales. Given we have C_{t-1} individuals in the running catalogue, then p_t is given by

$$p_t = \frac{N_t - C_{t-1}}{N_t}$$

Furthermore, we can substitute N_t in the above equation with and hence our likelihood can be parameterised in terms of N_0 and r, i.e., $L(s,n;N_0,r)$.

This likelihood was maximised, using the `optim` function in R {Team, 2012 #2005}, to give estimates of N_0 and R. From here we calculated the variances numerically from the inverse Hessian of the negative log likelihood. We also examined a parametric bootstrap derived variance but these gave quite different results, which is worth investigating further.

APPENDIX B – SUPPLEMENTARY DATA FROM IWC/SOWER SURVEYS

Table B1 Summary of sighting rates for Antarctic blue whales during IWC-SOWER voyages between 0 and 20ºE, for the years 2004/05, 2005/06 and 2006/07, in the regions 0-200km and 200-500km from the local ice edge.

Region		***0-200km from ice edge***					***200-500km from ice edge***				
	Year of survey (lon. extent)	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**
0-20ºE	2004/05 (0-70ºE)	4723.4	5	33	1.06	6.99	1580.0	0	0	0.00	0.00
	2005/06 (0-20ºE)	4655.0	33	63	7.09	13.53	378.7	0	0	0.00	0.00
	2006/07 (0-20ºE)	5946.3	52	120	8.75	20.18	884.6	1	1	1.13	0.01
Mean (st. dev; CV)					5.87 (4.04; 0.68)	14.09 (6.74; 0.48)				0.35 (0.69; 1.97)	0.35 (0.69; 1.97)
95% CI					-4.16, 5.88	-2.64, 30.83				-1.36, 2.06	-1.36, 2.06

Table B2 Summary of sighting rates for Antarctic blue whales during IWC-SOWER voyages between 80 and 120ºE, for the years 2007/08, 2008/09 and 2009/10, in the regions 0-200km and 200-500km from the local ice edge.

Region		***0-200km from ice edge***					***200-500km from ice edge***				
	Year of survey	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**
80-120ºE	2007/08 (105-120ºE)	5733.9	1	2	0.17	0.35	825.3	0	0	0.00	0.00
	2008/09 (82-95ºE)	3872.9	2	4	0.52	1.03	0.0	-	-	-	-
	2009/10 (100-115ºE)	3085.5	0	0	0.00	0.0000	484.9	0	0	0.00	0.00
Mean (st. dev; CV)					0.24 (0.25; 1.04)	0.47 (0.49; 1.04)				0.00 (-)	0.00 (-)
95% CI					-0.38, 0.24	-0.75, 1.70				-	-

Table B3 Summary of sighting rates for Antarctic blue whales during IWC-SOWER voyages between 130 and 180ºE, for the years 2001/02, 2002/03 and 2003/04, in the regions 0-200km and 200-500km from the local ice edge.

Region		***0-200km from ice edge***					***200-500km from ice edge***				
	Year of survey	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**	**Distance covered (km)**	**No. of blue whale sightings**	**Total animals**	**Sighting rate (per 1000 km)**	**Total animals sighting rates (per 1000 km)**
130-180ºE	2001/02 (130-150ºE)	6916.7	14	35	2.02	5.06	3120.4	0	0	0.00	0.00
	2002/03 (150-170ºW)	6846.5	6	18	0.88	2.63	2861.7	0	0	0.00	0.00
	2003/04 (170ºE-170ºW)	3498.3	5	7	1.43	2.00	1397.9	0	0	0.00	0.00
Mean (st. dev.; CV)					1.45 (0.64; 0.44)	3.48 (1.64; 0.47)				0.00 (-)	0.00 (-)
95% CI					-0.148, 1.45	-0.61, 7.56				-	-

APPENDIX C – SUPPLEMENTARY DATA FROM IWC CATCH RECORDS

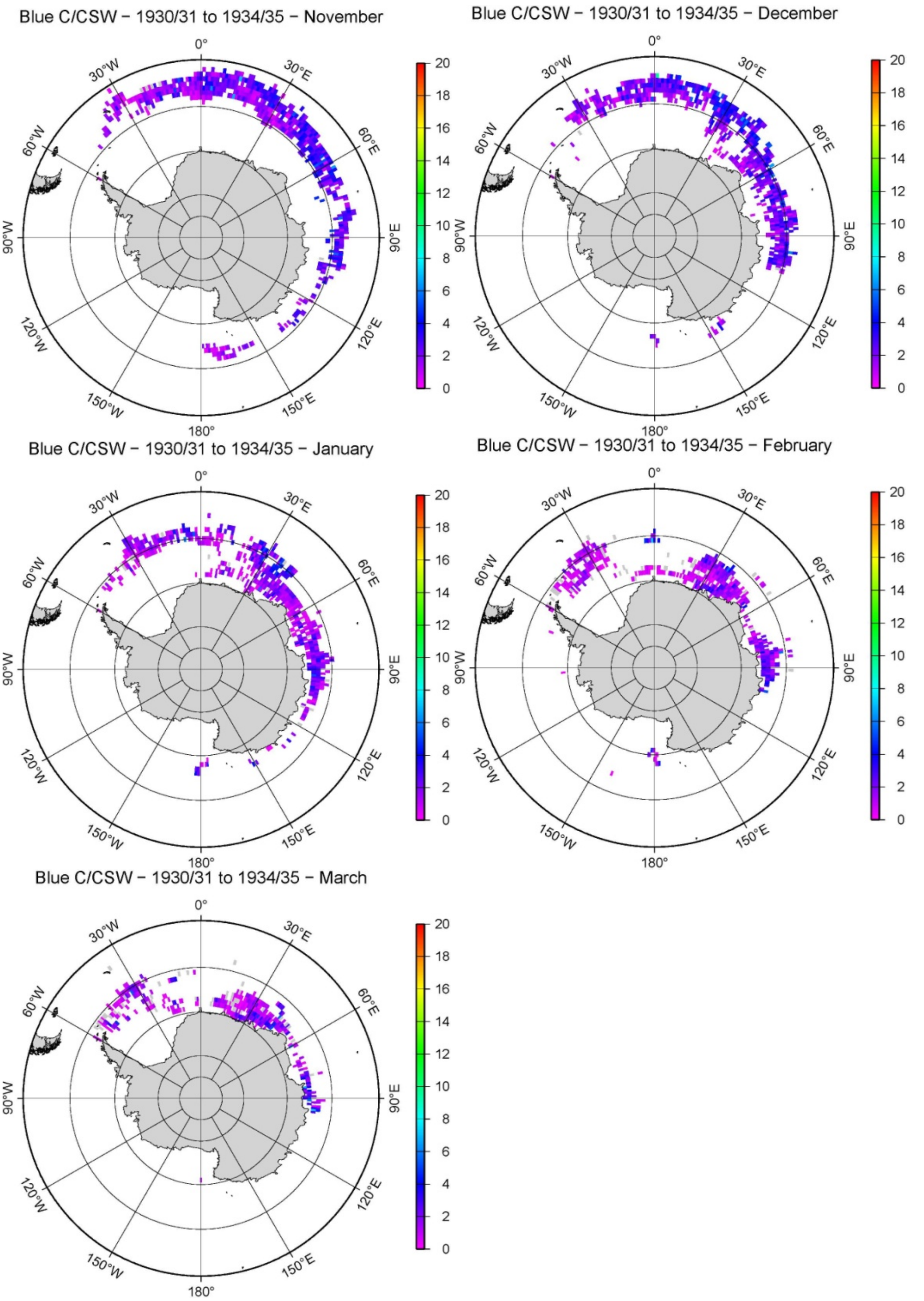

Figure 14 Apparent density of blue whales from whaling operations in the period 1930/31 through to 1934/35, for each month November-March, based on catch per catcher searching day worked (C/CSW). Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey.

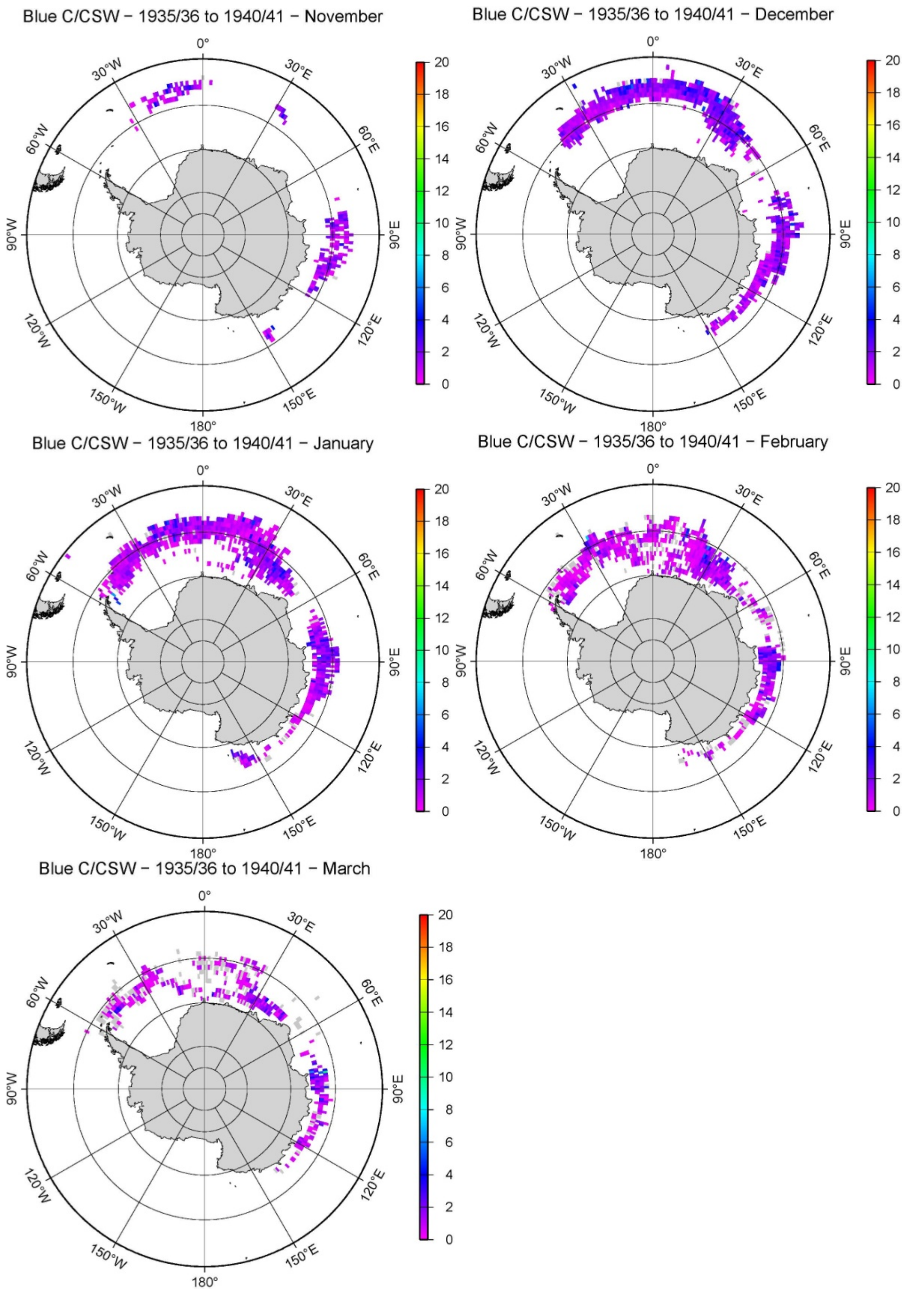

Figure 15 Apparent density of blue whales from whaling operations in the period 1935/36 through to 1940/41, for each month November-March, based on catch per catcher searching day worked (C/CSW). Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey.

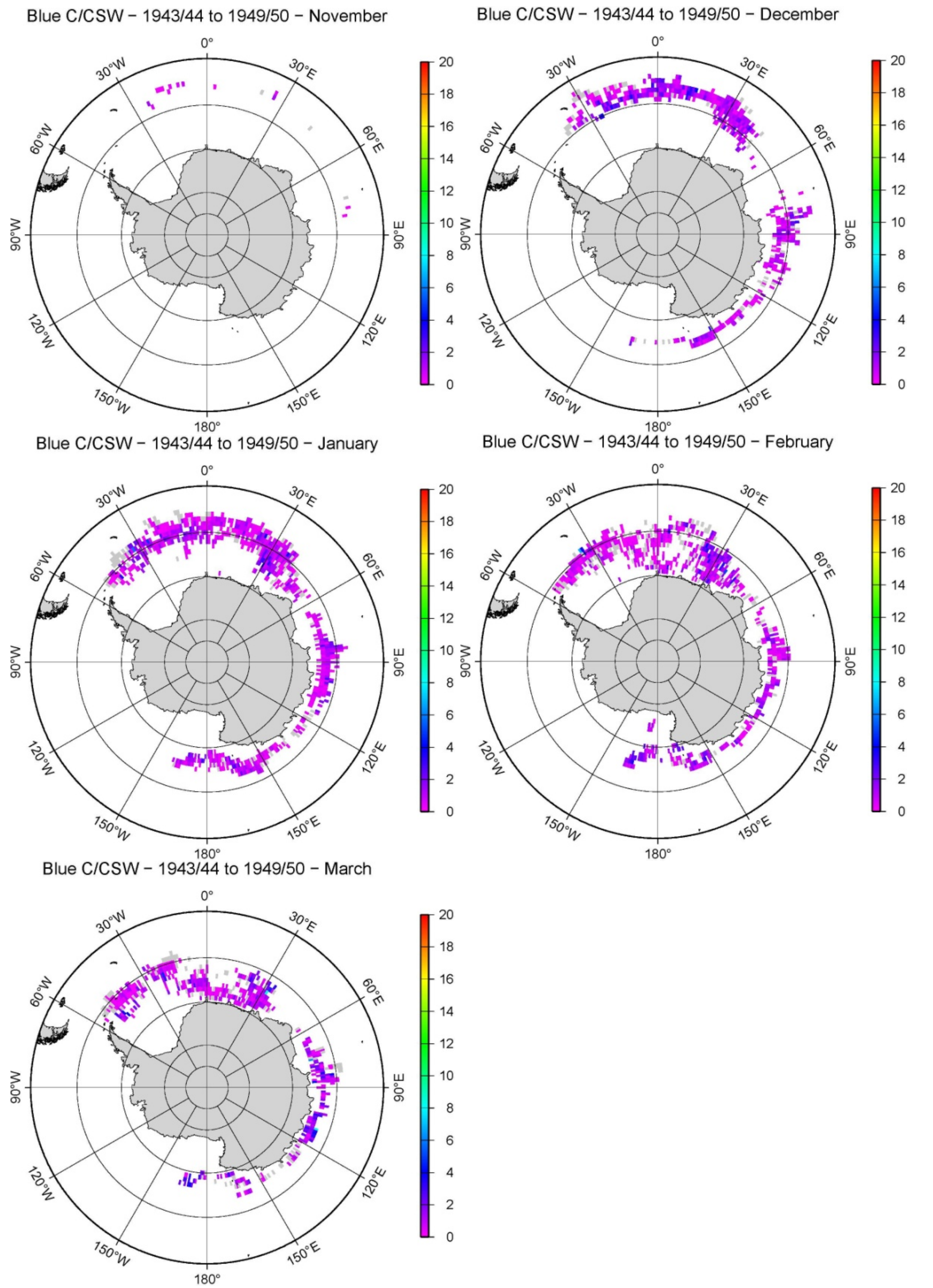

Figure 16 Apparent density of blue whales from whaling operations in the period 1943/44 through to 1949/50, for each month November-March, based on catch per catcher searching day worked (C/CSW). Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey.

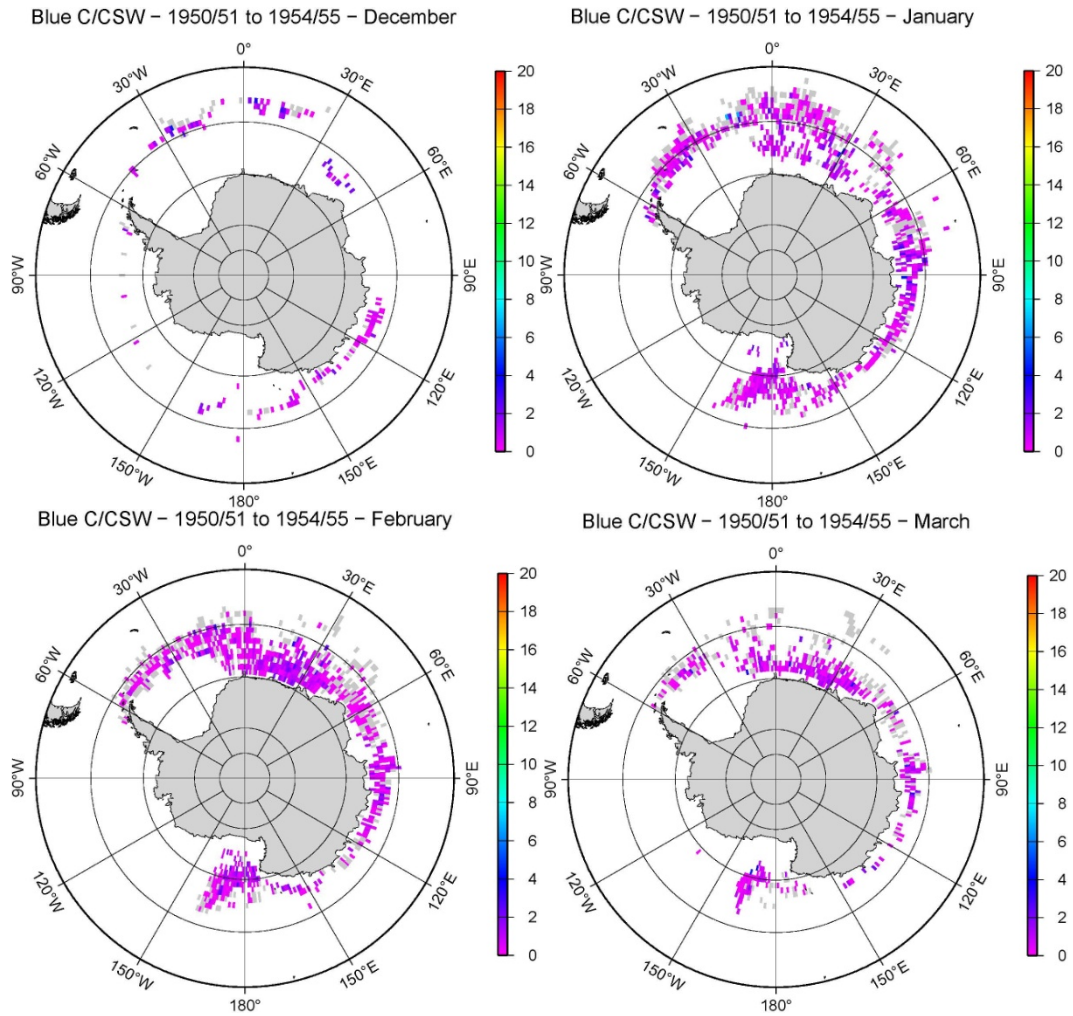

Figure 17 Apparent density of blue whales from whaling operations in the period 1950/51 through to 1954/55, for each month December-March, based on catch per catcher searching day worked (C/CSW). Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey.

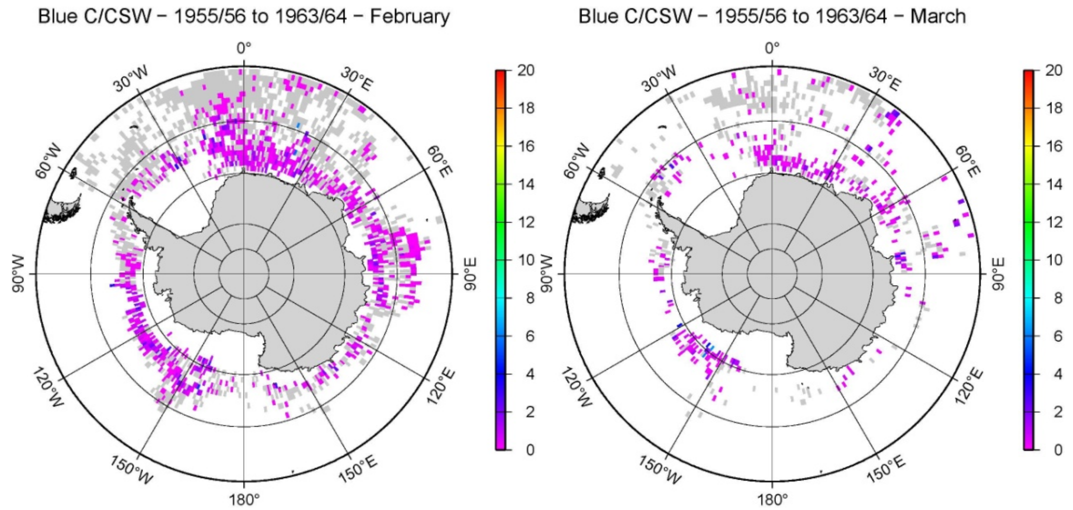

Figure 18 Apparent density of blue whales from whaling operations in the period 1955/56 through to 1963/64, for each month February-March, based on catch per catcher searching day worked (C/CSW). Locations where no whales were taken of any species are left blank. Locations where whales other than blue whales were taken are shown as grey.