Using Antarctic blue whale photo-ID data from the SOWER cruises: Capture-recapture estimates of abundance

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ABSTRACT

Photographs of Antarctic blue whales were collected as part of the IWC's SOWER cruises from 1987/88 to 2008/09. Photo-ID data from 15 cruises were used in a pilot study that conducted capture-recapture analysis to produce estimates of super-population abundance for the circumpolar Antarctic from 1992/93 to 2008/09 and for IWC Management Area III from 2004/05 to 2006/07. The circumpolar estimates are 3,178 (95% CI 534 to 24,239) Antarctic blue whales (left-side photographs) and 1,109 (95% CI 451 to 3,215) (right-side photographs) for the years 1991/92 to 2008/09. Estimates of super-population abundance for Area III are 1,318 (95% CI 515 to 3,716) (left-side photographs) and 939 (95% CI 421 to 2,323) (right-side photographs). The SOWER photo-ID database provides a starting point for improved estimates of population trends in the future as photographs of new individuals and additional recaptures of Antarctic blue whales are obtained.

KEYWORDS: ANTARCTIC; PHOTO-ID; MARK-RECAPTURE; ABUNDANCE

INTRODUCTION

The population of Antarctic blue whales (*Balaenoptera musculus intermedia*) fell during the 20th Century from an estimated pre-exploitation size of 256,000 (95% CI = 235,000–307,000) to less than 1% of its former abundance (Branch, 2008). In 1964, the International Whaling Commission (IWC) imposed a zero-catch limit, but the population has still not recovered, such that Antarctic blue whales are now listed as Critically Endangered by the IUCN (Reilly *et al*., 2008).

In 2006, the IWC Scientific Committee initiated an in-depth assessment of this population. Branch (2007) produced estimates of abundance from each of the three circumpolar (CP) surveys conducted under the IWC Southern Ocean Whale and Ecosystem Research (SOWER) programme. Each of these three surveys took multiple years to complete and are known as CPI (1978/79–1983/84), CPII (1985/86–1990/91) and CPIII (1991/92–2003/04). For detailed information about the cruises, see Branch (2007) and Ensor and Matsuoka (in review).

The most recent population abundance estimate accepted by the IWC, based on data from CPIII, was 2,280 (CV = 0.36) (Branch, 2007). In addition to a circumpolar population estimate, Branch (2007) also produced estimates for each of the six IWC management areas that together comprise the entire circumpolar region. Following completion of CPIII, the SOWER cruises with varying research objectives were conducted for a further six years from 2004/05 to 2009/10.

Identification photographs of individual Antarctic blue whales were collected during SOWER cruises from 1987/88 to 2008/09, providing data potentially suitable for capture-recapture analysis (Olson, 2010). Notable

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among the cruises conducted after CPIII are three surveys in Management Area III (0°–70°E, south of 60°S) during 2004/05, 2005/06 and 2006/07. There were a high number of blue whale sightings in Area III during these years, providing a substantial number of photographs for estimating the abundance of Antarctic blue whales within this Management Area (Ensor *et al*., 2005; 2006; 2007).

Here we explore how photo-ID data from 1991/92 to 2008/09 which are held in the SOWER database can be used in a pilot study for further capture-recapture analyses. We use different portions of the database (based on separate left or right-side photographs) to calculate: (a) two circumpolar estimates for the number of blue whales present from 1991/92 to 2008/09; and (b) two estimates for Management Area III from 2004/05 to 2006/07.

METHODS

Field methods

During the SOWER cruises, photo-ID effort was conducted as a secondary function to the primary cruise aim: obtaining minke whale abundance data. Effort therefore varied by year. Photo-ID was most often conducted from the bow of the research vessel in conjunction with biopsy sampling. Both left and right sides were photographed whenever possible, but not all whales could be photographed from both sides. 35mm SLR cameras using black and white film were used until 2004/05, overlapping with digital SLR cameras which began to be used in 2003/04. Digital SLR cameras were used exclusively from the 2005/06 season onwards. Cameras had zoom lenses with maximum focal lengths ranging from 200–400mm.

Photo-identification data

Usable photographs of Antarctic blue whales were available for 15 out of the 22-year period (1987/88–2008/09). Black and white photographs were digitised to improve access and facilitate comparison with other digital images.

Antarctic blue whale photographs were examined for unique natural markings and identified as individuals following methods outlined by Gendron and Ugalde de la Cruz (2012) and Sears *et al.* (1990). These methods required the presence of the dorsal fin in the photo. Identification photos were selected for each whale, an identification number assigned, and the photos compiled into a photo-ID catalogue. Photographs were compared within and between years. The Antarctic Blue Whale Photo-ID Catalogue is maintained at the Southwest Fisheries Science Centre (Olson, 2010).

Identification photos (the best left-side and right-side for each individual whale) were coded for quality using a four-tier system representing photo quality ranging from excellent (Code 1) to poor (Code 4). Photo quality was based on three features: angle to the subject, exposure and focus. Only photos with the top three codes were used in capture-recapture analysis where they were given equal weighting.

Capture-recapture analysis

Capture-recapture estimates were made for two management areas in different time periods: (a) the circumpolar Antarctic from 1991/92 to 2008/09; (b) Management Area III from 2004/05 to 2006/07. Population estimates were made separately based on the left and right-side photos from each area. Four overlapping data series were modelled: either left or right-side photos; whales identified in either Area III or the circumpolar region. Within-year re-sightings were ignored. Each research year was considered a sampling occasion so that circumpolar estimates were based on 15 occasions over the 18-year period from 1991/92 to 2008/09. Area III estimates were based on three occasions (2004/05 to 2006/07).

These two methods of aggregating the circumpolar or Area III data entailed different assumptions about Antarctic blue whale spatial population boundaries and mixing. In the first, all Antarctic blue whales were treated as a single population assumed to mix freely throughout Antarctica. Individual Antarctic blue whales have been documented to move at least 6,550km between re-sightings (Olson *et al*., 2013). In the second, blue whales in Area III were treated as a distinct population with a higher probability of being re-sighted in Area III than in other Antarctic management areas. The true population structure(s) represented in the capture-recapture database is probably somewhere between these extremes. Until more data on individual movements become available,

these two methods of aggregating the capture-recaptures allow optimum use of the existing data to compare population estimates at different scales.

The R package RMark version 2.1.12 (Laake and Rexstad, 2011) was used as an interface to the programme MARK version 8.0 (Cooch and White, 2011). The POPAN capture-recapture model is an open-population implementation of the Jolly-Seber model which allows births, deaths, immigration and emigration during the relevant time period.

Three years in the circumpolar time series – 1993/94, 1997/98, and 1999/00 – lacked photographs which means capture probabilities in these years were not estimated and assigned zeros instead. This allowed the POPAN model to continue to include these years in the estimates of survival and entry for the circumpolar population using information from years that were sampled.

Four parameters were estimated using POPAN, of which three – *p*, *pent* and *Phi* – could each be either a single (time-invariant) value or allowed to vary between years. The parameter *p* represents the capture probability given that the animal is in the population available to be captured. The parameter *pent* represents the probability of new individuals entering the population between sampling occasions either through birth or immigration. *Phi* represents apparent survival as a combination of survival and not permanently emigrating. The fourth parameter – the super-population abundance *N* – represents the number of all whales present in the population at any time during the study, including those that have either emigrated or not survived.

Assuming rates of permanent immigration and emigration of blue whales between the Southern Ocean and areas to the north were negligible during the 18-year study period, *pent* and *Phi* would represent recruitment and annual survival respectively for the circumpolar estimates. For the purpose of Area III estimates, these parameters could include the effects of movement into and out of Area III from other management areas.

Different combinations of annually-varying vs. time-invariant parameters were modelled (Table 1). Eight candidate configurations of parameter values were modelled for each of the four data series. The maximum number of annually-varying parameters was one less than the number of years for which they were estimated (17 for *Phi* and *pent* for the circumpolar estimates); fewer in the case of *p* (15 estimates for the circumpolar models) where values for the three years without photos were pre-specified as zero.

The total number of parameters estimated for each series varied from four (all parameters time-invariant, configuration α) to a maximum of 50 for one configuration of the circumpolar model, with 17 *Phi*, 15 *p* and 17 *pent* annually-varying parameters (configuration γ) (Table 1A). The Area III model configurations varied from

Table 1a

Numbers of parameters estimated in the eight model configurations (columns α to γ) for each of the four parameters for the two circumpolar databases. Configurations based on the same dataset (left or right photos) with the numbers of parameters listed in each column were compared using AICc.

Configuration	α	β	χ	δ	ε	ϕ	φ	γ
N	1	1	1	1	1	1	1	1
Phi	1	1	17	1	1	17	17	17
Pent	1	1	1	17	17	1	17	17
p	1	15	1	1	15	15	1	15

Table 1b

Numbers of parameters estimated in the eight model configurations (columns η to π) for each of the four parameters for the two Area III databases. Configurations based on the same dataset (left or right photos) with the numbers of parameters listed in each column were compared using AICc.

Configuration	η	ι	κ	λ	μ	ν	o	π
N	1	1	1	1	1	1	1	1
Phi	1	1	2	1	1	2	2	2
Pent	1	1	1	2	2	1	2	2
p	1	2	1	1	2	2	1	2

four parameters (configuration η) to seven (configuration π) (Table 1B). The final best model of the eight parameter configurations for each of the four data series was chosen using AICc (Burnham and Anderson, 1998).

RESULTS

Photo-ID

A total of 219 whale identifications (left, right or both sides) were made from photographs taken during 15 SOWER surveys in the 18-year period from 1991/92 to 2008/09. This is approximately 10% of the most recent total population size (2,280) estimated by Branch (2007). Whales were photo-identified in all six management areas (Figure 1). 70% of the identified whales were seen in Area III. This was due primarily to the high number of blue whales found there during the SOWER cruises from 2004/05 to 2006/07.

The identification photos of 196 individual whales met the criteria for the top three quality codes between 1991/92 and 2008/09. Of these, 158 left-side photos and 156 right-side photos were used in the capture-recapture analysis (Table 2). Five whales were recaptured: four whales once; one whale twice. Four of the

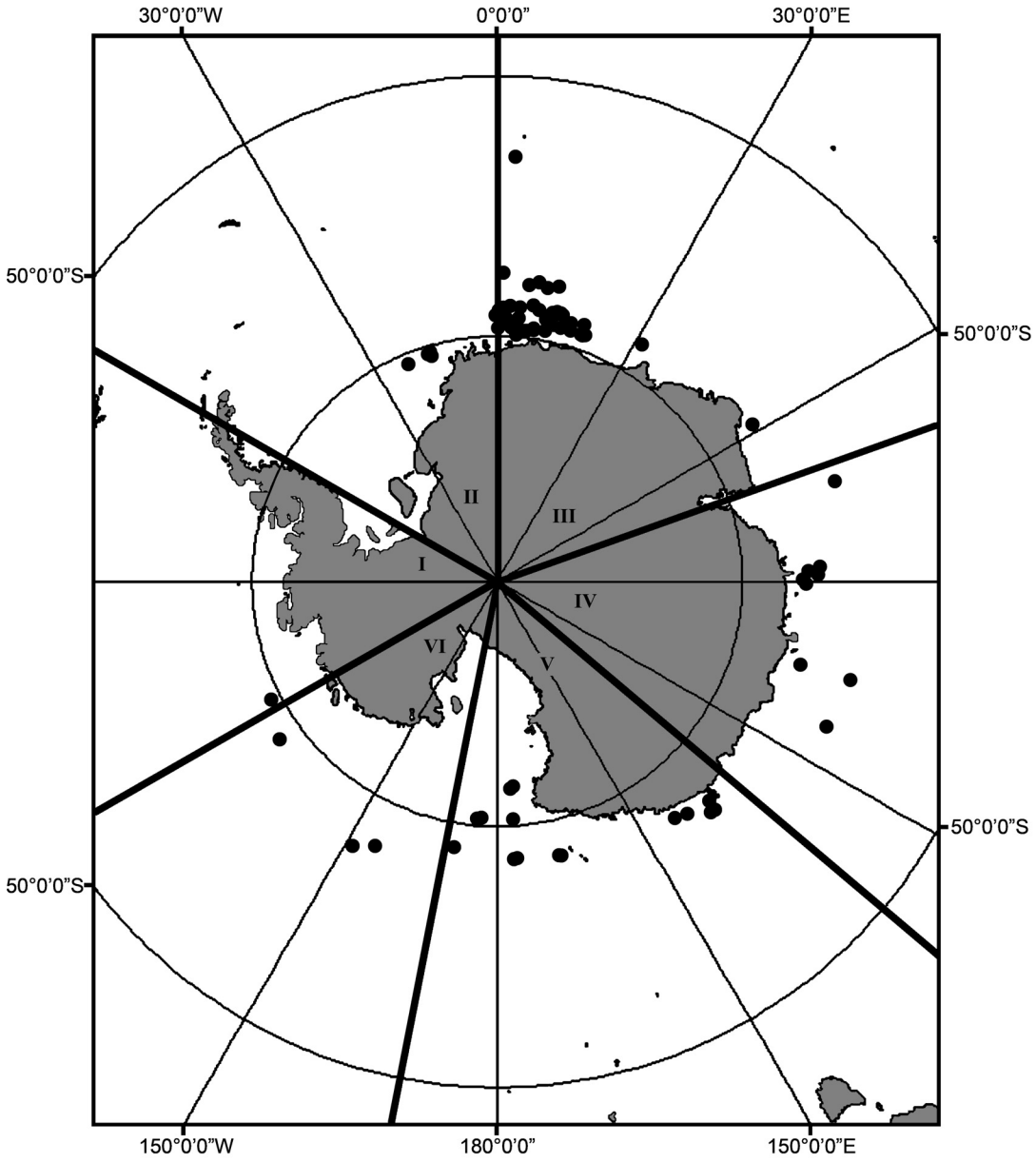

Fig. 1. The distribution of 219 photo-identified Antarctic blue whales from 1990/91 to 2008/09 in the six IWC Management Areas (demarcated by heavy black meridian lines and Roman numerals).

recaptured whales were observed in more than one of the data series (i.e., left or right-side circumpolar or Area III data series; see Tables 3 and 4). Most whales were recaptured within one to three years of the initial sighting, though there was one 12-year interval between sightings (Table 3).

Table 2

Numbers by year of left and right side Antarctic blue whale identification photographs, quality codes 1–3, used in the capture-recapture analyses.

	1991/92	1992/93	1994/95	1995/96	1996/97	1998/99	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	
	Area V	III	III	VI	II	IV	I and VI	V	V	V	III	II	III	IV	IV	**Total**
No. of left-side photos	1	4	3	1	8	2	0	4	3	7	15	35	66	2	7	158
No. of right-side photos	0	2	0	0	2	1	4	7	0	15	12	36	68	1	8	156

Table 3

Recaptured Antarctic blue whales in the circumpolar data series.

Whale ID	Side	Number of recaptures	Years between capture/recapture
622	Left	1	1
623	Left	1	1
761	Left	1	2
772	Left	1	12
104	Right	1	3
622	Right	1	1
623	Right	2	1, 1
761	Right	1	2

Table 4

Recaptured Antarctic blue whales in Area III: a subject of the circumpolar Antarctic blue whales identified in Table 3.

Whale ID	Side	Number of recaptures	Years between capture/recapture
622	Left	1	1
623	Left	1	1
761	Left	1	2
622	Right	1	1
623	Right	2	1, 1
761	Right	1	2

Capture-recapture

The AICc comparisons produced two best models (left and right data series) for the circumpolar population and two best models for the Area III population (Table 5). The two estimates for the same areas cannot be compared directly using a method such as AICc because they use different data. The 95% CIs can be compared between the left and right-side models to evaluate consistency between the two sets of model estimates.

The delta AICc between the best model ε for the circumpolar left dataset and the second-best (configuration γ, Table 1, values not shown) was 7.2. For the circumpolar right dataset, the delta AICc between the best configuration ψ and the second-best (configuration γ) was 0.01. For Area III best left, the difference between the best configuration η and the two second-best configurations (AICc values for configurations π and were μ identical) was 3.1. For Area III best right, the difference between the best two configurations η and κ (identical AICc values to four decimal places, parameter estimates identical to two decimal places) and second-best configuration was 1.7.

The best model using the circumpolar left-side data series, configuration ε, had 34 estimated parameters (Table 1A). The mean estimate for the super-population between 1991/92–2008/09 from this model was 3,178 (95% CI = 534 to 24,239). The best model using the circumpolar right-side data series, configuration ψ, had 36

Table 5

Time-invariant parameter estimates and 95% confidence intervals from the best model configurations for the four data series. 'Best' column indicates the configuration (Table 1) selected using AICc. Annually-varying models had the numbers of values estimated (either 17 or 15) for the configuration parameter type from Table 1 (numerical values of annually-varying parameters not reported).

	Best	*N*	*Phi*	*pent*	*p*
Circumpolar left	ε	3,178 (534, 24,239)	0.97 (0.01, 1.0)	Annually-varying	Annually-varying
Circumpolar right	φ	1,109 (451, 3,215)	Annually-varying	Annually-varying	0.11 (0.03, 0.35)
Area III, left	η	1,318 (515, 3,716)	1.0 (0.0, 1.0)	0.38 (0.32, 0.45)	0.05 (0.02, 0.14)
Area III, right	η	939 (421, 2,323)	1.0 (0.0, 1.0)	0.41 (0.36, 0.47)	0.07 (0.03, 0.17)

parameters (Table 1A) with an estimated super-population of 1,109 (95% CI = 451 to 3,215) for the same time period (Table 5).

The best model based on the left-side Area III data series (2004/05 to 2006/07), configuration η, had four parameters (Table 1B) and estimated super-population of 1,318 (95% CI = 515 to 3,716). The best right-side model for Area III also had the four parameter values in configuration η and estimated 939 (95% CI = 421 to 2,323) (Table 5).

The 95% CIs for parameter estimates of the best models were wide (Table 5). In models where *Phi*, *pent* and *p* were annually-varying, the mean values (values not shown), especially for annual survival *Phi*, also varied widely between years. *Phi* could not be estimated with reliable precision using POPAN with these capture-recapture data.

Branch (2008) assigned a mean prior adult survival rate for blue whales of 0.96 based on a literature review. This is close to the mean value of 0.97 obtained using the left-side photos in this study. When left and right-side photos were modelled using an assigned apparent survival value of 0.96 (model results not shown), rather than estimating this parameter, the super-population circumpolar estimates were 3,650 (95%CI = 1,520 to 9,101) and 2,347 (95%CI = 1,078 to 5,353) blue whales from the left and right sides respectively. The Area III estimates with *Phi* pre-specified as 0.96 were 1,293 (95%CI = 506 to 3,648) and 920 (95%CI = 413 to 2,278) blue whales from the left and right sides respectively.

DISCUSSION

The photo-ID catalogue for Antarctic blue whales initiated during the SOWER cruises will be a resource for future studies of blue whale abundance, survival and movement in this region. The abundance estimates reported in this paper using these data are imprecise. They represent a starting point rather than an end point for photo-ID studies of Antarctic blue whales. As more data become available in the future, the high variability of estimates in this study should reduce (Table 5).

The small number of recaptures in the Antarctic blue whale database obtained from 1991/92 to 2008/09 (six recaptures of five whales) makes these POPAN estimates very sensitive to small differences in the timing and location of each recapture, as evidenced in the difference between models using the left and right data series. As more data are collected, parameter uncertainty should reduce. Additional covariates representing issues such as heterogeneity in effort (smaller proportions of the total whales sighted were photographed in earlier years than later) and possible directed movements among areas could be considered as candidates for modelling. New capture-recapture methods that combine different sources of ID data, such as left and right-side photos and potentially genetic sampling (Madon *et al.*, 2011; McClintock *et al.*, 2013) could also be used with a dataset that includes more recaptures.

It is useful to view these super-population estimates of abundance of Antarctic blue whales in context with the line-transect estimates of Branch (2007). They are not directly comparable. The line-transect estimates are for the population during a stationary point in time while the super-population is an estimate of total abundance over a number of years. When a line-transect estimate of abundance is made for a population inside a longer time interval for which super-population abundance is also estimated, the latter should be greater than the line-transect estimate because the super-population estimate does not include mortality during the longer time period.

Branch (2007) estimated the circumpolar abundance of Antarctic blue whales based on the line-transect data from CPIII (1991/92–2003/04; the same surveys that provided photo-ID data used in this study). He estimated 2,280 Antarctic blue whales for the CPIII midpoint year 1997/98, which is 11 years prior to the final year of this study (2008/09).

The left-side mean super-population estimate of 3,178 was greater than Branch (2007) (Table 5). The right-side mean super-population estimate of 1,109 was less than the line-transect estimate for 1997/98. The capture-recapture super-population estimates of 3,650 and 2,347 for the left and right side, respectively, when survival was pre-specified to 0.96, were closer to expectations than when survival was estimated inside POPAN. This is a further indication that there was insufficient information in the circumpolar capture-recapture database to reliably estimate all parameters.

For Area III, Branch (2007) estimated 166 whales in 1994/95. Our estimate for Area III from 2004/05–2006/07 comes 15 years after the previous estimate for this Area based on the line-transect data from CPIII (Branch, 2007). Simple mean rates of increase over the 15-year interval from 166 whales to 1,318 whales (left-side photos) and 939 whales (right-side photos) are 15% and 12% per annum respectively. These rates of increase may be high because they are calculated between line-transect and super-population estimates and do not account for mortality during the three-year period of the Area III super-population estimate.

This was a pilot study, illustrating the utility of photo-ID data collected during the SOWER programme. Following the cessation of these cruises, the Southern Ocean Research Partnership (SORP) was formed within the IWC as a collaborative means to continue research on Antarctic whale populations (Bell, 2012). The Antarctic Blue Whale Project (ABWP) was initiated as a flagship project under SORP. Using photo-ID data for capture-recapture analysis to generate new estimates of abundance is a cornerstone of the Antarctic Blue Whale Project (Bell, 2015; Peel *et al*., 2015). Recent ABWP-SORP voyages in 2013, 2015 and 2019 added 119 photo-identified whales to the Antarctic Blue Whale Catalogue, which currently totals 552 individuals (Olson *et al*., 2021). The SOWER photo-ID data, combined with photo-ID data from ABWP-SORP research cruises, will provide further estimates of abundance based on larger datasets.

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