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ABSTRACT
Photo-identification data of Antarctic blue whales from 1990/91 to 2014/15 were used in a capture-recapture analysis to produce estimates of super-population abundance for the circumpolar Antarctic. An estimate for IWC Management Area III 1992/93 to 2013/14 was also produced. Photographs were collected during IWC, IWC-SORP, ICR, and SAABWS cruises and also made available by opportunistic contributors. The circumpolar estimates are 4,629 (95% CI 2,563 to 8,558) Antarctic blue whales (left side photographs) and 4,485 (95% CI 2,514 to 8,192) (right side photographs) for the years 1990/91 to 2014/15. These estimates show improved precision with the addition of 30% more photo-ID data than was available for a previous capture-recapture study based on data from 1992/93 to 2008/09. Estimates of abundance for Area III are 1,944 (95% CI 903 to 4,390) (left side photographs) and 2,575 (95% CI 1,089 to 6,380) (right side photographs). As more data become available in the future, the reliability of capture-recapture estimates should improve.

KEYWORDS: ANTARCTIC, PHOTO-ID, MARK-RECAPTURE, ABUNDANCE ESTIMATE

INTRODUCTION

During the first half of the 20th Century, the population of Antarctic blue whales (*Balaenoptera musculus intermedia)* was reduced by whaling from an estimated pre-exploitation size of 239,000 (95% CI=202,000-311,000) to less than 1% of its former abundance (Branch, 2007). To date the population has not recovered to its pre-exploitation size, although Branch *et al.* (2004) provides evidence that the population is increasing. Antarctic blue whales are listed as Critically Endangered by the International Union for the Conservation of Nature (Reilly *et al*., 2008). In 2006 the IWC Scientific Committee initiated an in-depth assessment of this population and Branch (2007) produced estimates of abundance from each of the three circumpolar sets of surveys[1] conducted under the IWC IDCR/SOWER[2] program. Branch's (2007) work provides the most recent population abundance estimate accepted by the IWC, 2,280 (CV=0.36), and is based on data from the last IDCR/SOWER circumpolar series, CPIII. The estimate was based on the CPIII midpoint year 1997/98 (and is now 20 years old).

The population status of Antarctic blue whales is also a focus of the IWC-SORP[3] Antarctic Blue Whale Project, which is aimed on improving the understanding of population structure and working toward an updated circumpolar abundance estimate (Bell, 2017). The use of photo-identification data in a capture-recapture analysis for the production of a contemporary (new) estimate of abundance of Antarctic blue whales is a component of the Antarctic Blue Whale Project (Bell, 2012). The amount of photo-identification data in the Antarctic Blue Whale Catalogue has been increasing annually, and has almost doubled since a pilot study using photo-ID data from IDCR/SOWER in a capture/recapture was conducted in 2014 (Olson and Kinzey, in press). That study confirmed proof of concept but the resulting estimates were imprecise. Given the interest of the Scientific Committee in the possibility of a new population assessment of Antarctic blue whales (IWC, 2017), we conducted a capture-recapture estimate of abundance using the most recent photo-ID data from the circumpolar Antarctic. This study builds on the work of the

[1] CPI (1978/79-1983/84), CPII (1985/86-1990/91), CPIII (1991/92-2003/04)
[2] International Decade of Cetacean Research/Southern Ocean Whale Ecosystem Research
[3] Southern Ocean Research Partnership

previous study. We use different portions of the database to calculate two circumpolar estimates (left-side and right-side photos) for the number of blue whales present from 1990/91 to 2014/15, and two estimates for Area III from 1992/93 to 2013/14.

METHODS

Field methods

During IDCR/SOWER and ICR[4] cruises, photo-identification effort was conducted ancillary to the primary cruise objectives, thus the amount of effort varied by year (Matsuoka *et al.*, 2003; Matsoka and Pastene, 2009; Olson, 2010). Photo-ID was most often conducted from the bow of the research vessel in conjunction with biopsy sampling. Blue whale research was the primary objective of the IWC-SORP and SAABWS[5] voyages where photo-ID was also conducted in conjunction with biopsy sampling (Double *et al.*, 2013; Double *et al.*, 2015; Findlay, *et al*. 2014). The 2013 IWC-voyage operated an inflatable boat for approaches as well as the larger ship.

Both left and right sides of the whales were photographed whenever possible, but not all whales were approachable on both sides. 35mm SLR cameras using black and white film were used through 2004/05, overlapping in use with digital SLR cameras beginning in 2003/04. Digital SLR cameras were used exclusively starting with the 2005/06 season. Cameras had zoom lenses with maximum focal lengths ranging from 200-400mm.

Photo-ID data

Identification photographs of Antarctic blue whales were available from 16 IWC cruises, 13 ICR cruises, 2 IWC-SORP voyages, and 1 SAABWS voyage over the 25-year period, 1990/91 through 2014/15. Black and white photographs were digitized for archiving and to facilitate comparison with digital images. Photographs that were collected opportunistically by scientists working on other projects in the Antarctic and from citizen scientists aboard tourist vessels were also made available to the Antarctic Blue Whale Catalogue. These photographs come from four years: 2005/05, 2009/10, 2010/2011, and 2014/15.

Photographs from all sources were obtained during the Austral summer.

Antarctic blue whale photographs were examined for unique natural markings and identified as individuals following methods outlined in Gendron and Ugalde de la Cruz (2012) and Sears *et al.* (1990). The 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. (Identifications from the SAABWS photo collection were cross-referenced.) Identification photographs were compared within and between years. The Antarctic Blue Whale Photo-identification Catalogue is maintained at the Southwest Fisheries Science Center in the USA (Olson, 2010).

Identification photos (the best left side and best 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. Photos with the top three codes were used in capture-recapture analysis (and weighted equally).

Capture-recapture analysis

Capture-recapture estimates were made for two areas during different time periods: 1) the circumpolar Antarctic from 1990/91 to 2014/15, and 2) Area III from 1992/93 to 2013/14. Population estimates were made separately based on the left and right side photos from each area. Thus four overlapping data series, using either left or right side photos and either circumpolar or Area III photo-identified whales, were modeled. Within-year re-sightings were ignored. Each research year was considered a sampling occasion so that the circumpolar estimates were based on 23 occasions over the 25-year period 1990/91 to 2014/15. (There was no sampling effort in 1997/1998 and 2011/2012.) Area III estimates were based on eight occasions over a 22-year period (1992/93 to 2013/14).

The two ways of aggregating the circumpolar or Area III data made different assumptions about Antarctic blue whale spatial population boundaries and mixing. In the first, all Antarctic blue whales were treated as a single

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population assumed to mix freely throughout Antarctica. Individual Antarctic blue whales have been documented to move at least 6,550km within the Southern Ocean between inter-annual re-sightings (Olson *et al*., 2013). In the second, the 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 are available these two ways 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 program MARK version 8.0 (Cooch and White, 2011). The POPAN capture-recapture model is an open-population model implementation of the Jolly-Seber model, allowing births, deaths, immigration and emigration during the time period of the study.

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 annually. The parameter *p* represents the capture probability given 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 not survived or have emigrated. It is always a single, time-invariant number.

Assuming rates of permanent immigration and emigration of blue whales between the Southern Ocean and areas to the north were negligible during the 25-year period of the study, *pent* and *phi* would represent recruitment and annual survival, respectively, for the circumpolar estimates. For the Area III estimates these parameters could include the effects of movement out of and into Area III from other Management Areas.

All combinations of annually-varying vs. time-invariant values for each of the *p*, *pent*, and *phi* parameters were modeled, and the best configuration was selected using AIC. The estimates of *phi* from the best models identified by AIC_c were then examined for biological plausibility. If the estimate(s) of *phi* from the best model were less than 0.5, *phi* was pre-specified as 0.96 (Branch *et al*., 2004) and the other parameters were re-estimated.

RESULTS

Photo-ID

The identification photos of 279 individual whales (272 left sides and 279 right sides) met the criteria for the top three quality codes from the years 1990/91-2014/15. This is 12% of the most recent total population size (2,280) estimated by Branch (2007). Whales were photo-identified in all six IWC Management Areas (Figure 1). 50% 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 2004/05-2006/07 and the SAABWS voyage in 2014.

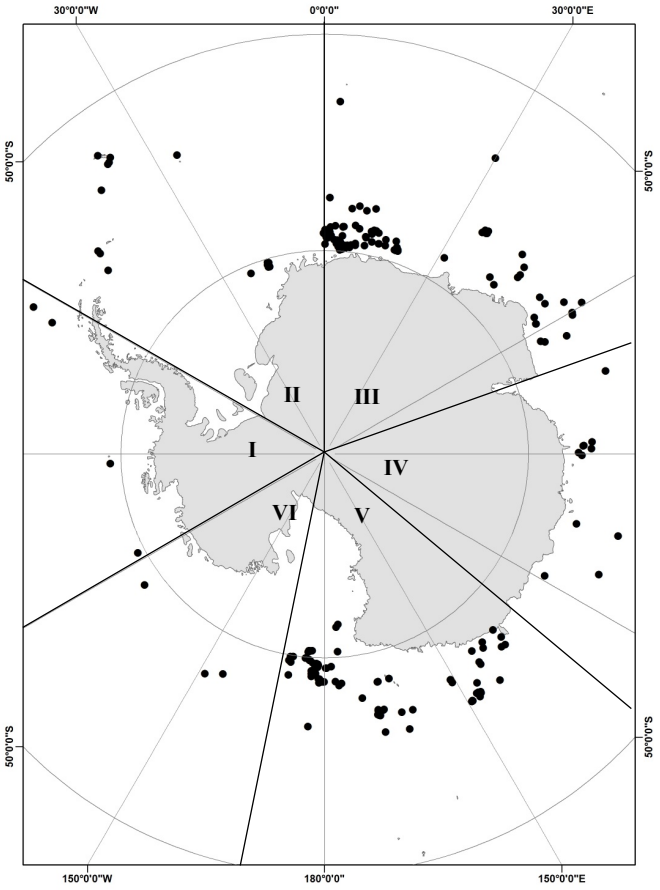

Figure 1. The distribution of 279 photo-identified Antarctic blue whales 1990/91–2014/15 in the six IWC Management Areas (demarcated by heavy black meridian lines and Roman numerals).

For the circumpolar capture-recapture analysis 272 individual whales were photographed on the left side and 279 were photographed on the right side (Table 1). For each side there were 10 single recaptures. On the right side one individual was recaptured twice. The Area III subset included 133 left side individuals (with 5 single recaptures) and 137 right side individuals (two single recaptures and one whale recaptured twice) (Table 3). Whales were recaptured within 1-7 years of the initial sighting, except for one 12-year interval between sightings (Table 2). For the Area III analysis, only whales that had been both captured and recaptured in Area III were used.

Table 1. Numbers by year of left and right side Antarctic blue whale identification photographs, quality codes 1-3, used in the capture-recapture analyses. (Photographs of recaptured whales appear more than once.) Seasons in Area III are indicated with an asterisk (*). Opportunistic = photos contributed from collegial and citizen scientists.

Season	No. left side photos	No. right side photos	Source
1990/91	1	2	IWC
1991/92	1	1	IWC
1992/93*	5	2	IWC, ICR
1993/94	0	1	ICR
1994/95*	4	1	IWC
1995/96	1	0	IWC
1996/97	8	2	IWC
1998/99*	6	5	IWC
1999/00	0	1	ICR
2000/01	0	4	IWC
2000/02	5	8	IWC, ICR
2002/03*	3	2	IWC, ICR
2003/04	8	16	IWC, ICR
2004/05*	17	12	IWC, ICR, opportunistic
2005/06*	39	42	IWC, ICR
2006/07*	70	75	IWC, ICR
2007/08*	2	2	IWC, ICR
2008/09	12	12	IWC, ICR
2009/10*	6	8	ICR, opportunistic
2010/11	1	0	opportunistic
2012/13	40	46	IWC-SORP, ICR
2013/14*	7	9	SAABWS
2014/15	46	39	IWC-SORP, opportunistic

Table 2. Recaptured Antarctic blue whales in the circumpolar data series.

Whale ID	Side	Number of recaptures	Years between capture/recapture
0607	left	1	2
0622	left	1	1
0623	left	1	1
0738	left	1	3
0758	left	1	6
0761	left	1	2
0772	left	1	12
0802	left	1	5
1313	left	1	7
1322	left	1	7
0104	right	1	3
0622	right	1	1
0623	right	2	1, 1
0758	right	1	6
0761	right	1	2
0802	right	1	5
1005	right	1	3
1313	right	1	7
1322	right	1	7
1343	right	1	2

Table 3. Recaptured Antarctic blue whales in Area III; a subset of the circumpolar Antarctic blue whales identified in Table 3.

Whale ID	Side	Number of recaptures	Years between capture/recapture
0607	left	1	2
0622	left	1	1
0623	left	1	1
0761	left	1	2
0772	left	1	12
0622	right	1	1
0623	right	2	1, 1
0761	right	1	2

Capture-recapture

The final configurations of the left-side and right-side estimates for the circumpolar population used a pre-specified, time-invariant value of 0.96 (from Branch *et al*., 2004) for *phi*. The other parameter estimates from these models with fixed values of *phi* appeared biologically plausible (Table 4, Fig. 2). During initial model runs, the configurations of time-varying and time-invariant parameters that fit the data the best for the left and right side circumpolar and Area III databases were selected using AICc. In the case of the circumpolar left side model the configuration with annually-varying *phi* had the best AICc score, but the *phi* values ranged between 0.999 for some years and essentially zero for others, resulting in annual abundance estimates that increased and decreased four times from about 500 to 2000 whales during the 25 year time span. In the case of the circumpolar right side, the configuration selected by AICc produced errors for some of the variance estimates.

Table 4. Maximum likelihood estimates and 95% CI for the super-population (*N*) of all blue whales present during the study, survival/emigration (*phi*), and probability of recruitment/immigration (*pent*). Probabilities of identifying individual whales given they were present (*p*) varied annually (values not shown).

	N	*phi*	*pent*	*p*
Circumpolar left	4629 (2563, 8558)	0.96 (fixed)	0.038 (0.012, 0.111)	annually-varying
Circumpolar right	4485 (2514, 8192)	0.96 (fixed)	0.040 (0.009, 0.157)	annually-varying
Area III left	1944 (903, 4390)	0.97 (0.012, 1.0)	0.040 (0.004,0.301)	annually-varying
Area III right	2575 (1089, 6380)	0.96 (fixed)	0.046 (0.043, 0.049)	annually-varying

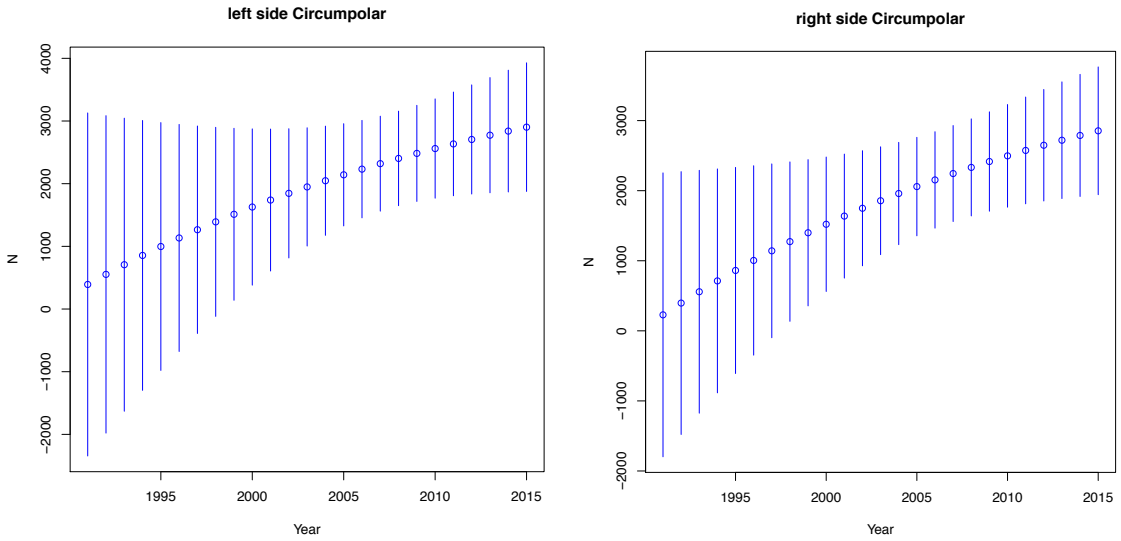

Figure 2. Annual estimates with 95% confidence intervals of circumpolar population abundance for blue whales using fixed *phi* value of 0.96 for the left- and right-side photos.

The best configurations of the Area III left-and right-side configurations were similarly selected using AICc. For the left-side configuration, the estimated value of *phi* in the best configuration was 0.97 and time-invariant. The other parameter estimates appeared biologically plausible, so this model was retained.

The right-side model for Area III produced a time-invariant estimate of 0.1 for *phi* and some of the variance estimates were negative. Fixing *phi* at 0.96 in this model eliminated the negative variances but the population estimate for 1993 was near zero because the time-varying estimate of *p* was 0.66 for this year (the other annual *p* estimates were 0.01 or less). Fixing the value of *p* in 1993 in the right-side model to 0.013, the value estimated for this year in the left-side model, produced plausible estimates for the remaining parameters (Table 4). The narrow confidence intervals for right-side abundance at the start of the time series (Fig. 3) are probably an artifact of fixing instead of estimating *p* in 1993.

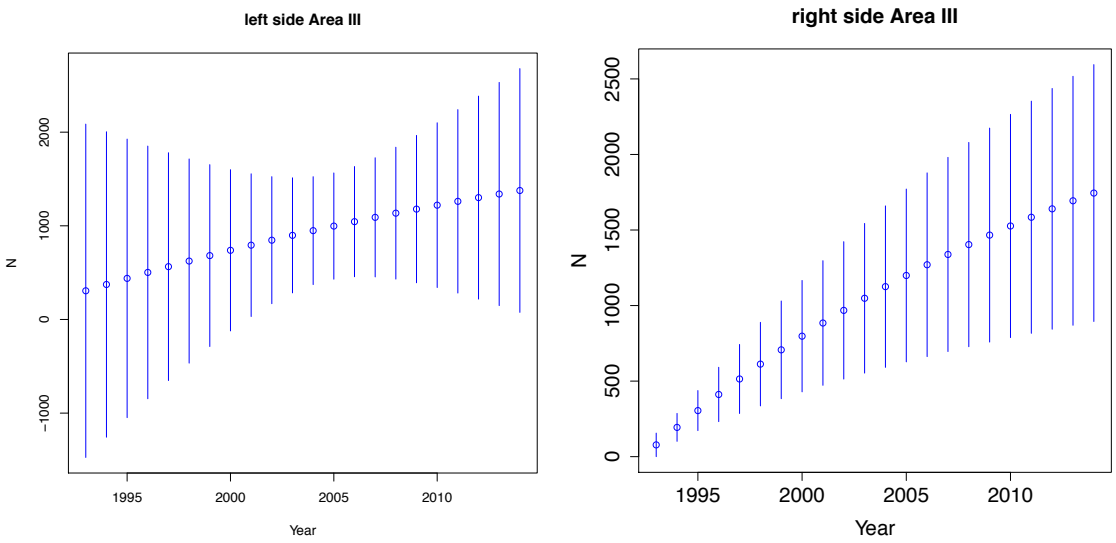

Figure 3. Annual estimates with 95% confidence intervals of Area III population abundance for blue whales using all estimated parameter values for the left-side configuration and fixed *phi* and *p*(1993) values of 0.96 and 0.13, respectively, for the right-side photos.

DISCUSSION

The estimates for super-population sizes and annual abundances for the circumpolar and Area III blue whales should be considered as hypotheses based on the available data, to be compared to future estimates as more mark-recapture data are obtained. Ideally, with additional sampling at some point the data will be sufficient to estimate all parameters instead of pre-specifying the *phi* values in three of the models, and the first-year *p* for the Area III right-side photos, as we have done here.

The estimates for the super-population and annual trends from the left- and right-side circumpolar and Area III models appear plausible. The spread of the 95% CIs for the super-populations (Table 4) shows an improvement over the CIs from our first study using data from 1992/93 to 2008/09 (Olson and Kinzey, in press). The dataset for the present study was 30% larger than the previous dataset, and the number of circumpolar recaptures more than doubled. However, there are still a relatively small number of recaptures in the Antarctic blue whale database (10 recaptures each on left and right sides) and that makes these POPAN estimates very sensitive to small differences in the timing and location of each recapture. As more recapture data are collected, parameter uncertainty should be reduced. Additional covariates representing such issues 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 modeling.

The results from Area III were less precise. The new data added only two left side recaptures and no right side recaptures to Area III, although the dataset for this Area has increased in size in recent years (11% left side, 16% right side). There are two whales in the circumpolar recaptures that were initially photographed in Area III but were recaptured in another Area. These were excluded from the Area III analysis and highlight the spatial heterogeneity in the Antarctic population.

The super-population estimates of abundance of Antarctic blue whales (presented here) can be viewed in context with the line-transect estimates of Branch (2007), although 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 over which it is estimated.

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 the photo-ID data used in this study. He estimated 2,280 Antarctic blue whales for the CPIII midpoint year 1997/98, which is 18 years prior to the final year, 2014/15, of this study. The left side and right side mean super-population estimates of this study, 4,629 and 4,485 respectively (Table 5), were greater than that of Branch (2007).

In addition to estimating the super-population above, the mark-recapture models can be used to estimate annual abundance. The left-side and right-side model mean estimates for 1998 are 1,399 and 1,252, respectively, smaller than the 2,280 estimated by Branch (2007), although the Branch value is inside the 95% CI of the mark-recapture estimates.

Mean rates of increase for the circumpolar population over the 25-year interval from the left-side and right-side photos 1990/91 to 2014/15 were 0.08 and 0.11 per annum, respectively. This is higher than would be expected although Branch (2007) reported 0.082 based on IDCR/SOWER data (1978/79 to 2003/04) and Branch *et al*. (2004) estimated a growth rate of 0.73 based on three sighting survey databases (1968 to 2001). For Area III the population growth rate estimates were 0.07 and 0.15 for the left and right sides, respectively.

Conclusion

The abundance estimates reported in this paper using Antarctic blue whale photo-ID data show improvement over the results reported in Olson and Kinzey (in press) with the addition of five more years of capture-recapture data. We are encouraged that as more data continue to become available the uncertainty associated with the estimates in this study (Table 4) will continue to decline, and ultimately more reliable population estimates will be achieved.

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