Abundance and distribution of Antarctic blue whales Balaenoptera musculus intermedia off the Queen Maud Land coast of Antarctica

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Abstract

The Antarctic blue whale *Balaenoptera musculus intermedia* was hunted to near extinction in the twentieth century. Current data on the abundance and distribution of the species are lacking owing to the difficulty and expense of surveys under adverse weather conditions in open-ocean habitats, and to the small population size. The most recently accepted global abundance estimate, based on the middle survey (1997/1998) of three circumpolar Antarctic surveys conducted between 1991/1992 and 2003/2004, was less than 1% of the original pre-whaling population size. The present study used a visual line-transect survey off the Queen Maud Land coast of Antarctica, in an area between 0° and 18° E and south of 67° S, in January 2014, to estimate the abundance of Antarctic blue whales in this area. Effort-accounted densities of sightings averaged 13.3 individuals per 1 000 nautical miles of survey effort (CV = 0.26) and reinforce recent findings that the area has significantly higher densities than averaged in circumpolar surveys (0.17–1.48 per 1 000 nautical miles). Distance sampling resulted in a population density estimate of 0.019 whales nautical-mile^{-2} (CV = 0.24) and an estimated abundance of 1 026 Antarctic blue whales (CV = 0.20, 95% CI 632–1 450) in the surveyed area. Obtaining such current estimates of abundance is crucial for assessment of the conservation status of the Antarctic blue whale population and for monitoring its recovery.

Keywords: baleen whale, distance sampling, endangered species, Southern Ocean, vessel survey, whale conservation

Introduction

The Antarctic blue whale *Balaenoptera musculus intermedia* is listed as Critically Endangered on the IUCN Red List of Threatened Species (Leatherwood and Reeves 1983; Reilly et al. 2008; Perrin et al. 2009; Cooke 2018). Hunted to near-extinction in the twentieth century, whaling depleted numbers from an estimated 239 000 (95% CI 202 000–311 000) to a low of 360 (95% CI 150–840) between 1905 and 1973 (Branch et al. 2004). Since the cessation of whaling, the population has been increasing annually (Branch 2007). Based on the middle survey (1997/1998) of three summer circumpolar survey series conducted south of 60° S by the International Whaling Commission (IWC) between 1991/1992 and 2003/2004, the abundance of Antarctic blue whales was estimated at 2 280 individuals (CV = 0.36) (Branch et al. 2007). This suggests that numbers have recovered to about 1% of pre-whaling levels (Branch et al. 2007). There are no recent updated estimates for total abundance. However, there is considerable information on distribution, migration and seasonal abundance of Antarctic blue whales available from whaling data (e.g. Mackintosh 1942), as well as evidence of three genetically differentiated populations likely occupying different breeding grounds (Attard et al. 2016). Currently, considerable acoustic monitoring of the species is being carried out (Branch et al. 2007; Samaran et al. 2013; Shabangu et al. 2017) to identify seasonal abundance in both the Southern Ocean high-latitude feeding grounds and in low-latitude areas. Findings show seasonal variability of call occurence (Shabangu et al. 2020) as well as correlations with environmental predictors (Shabangu et al. 2017). Such information is important because a revised comprehensive assessment of the Antarctic blue whale is expected to be concluded by the IWC Scientific Committee in 2023 (International Whaling Commission 2020).

During the austral summer, Antarctic blue whales feed in the Southern Ocean (Branch et al. 2007). Nutrient-rich upwelled waters provide for primary production (albeit limited by iron micronutrient availability) leading to secondary production that is dominated by Antarctic krill *Euphausia superba*, making the region a critical feeding ground for migratory baleen whales (Knox 2006; Perrin et al. 2009; Alder et al. 2016). Antarctic blue whales generally feed on Antarctic krill, with their summer distribution often mirroring high krill densities (Knox 2006; Branch et al. 2007). As large-sized, highly mobile predators with high metabolic rates, baleen whales play an essential role in structuring and maintaining marine ecosystems (Ainley et al. 2010; Kiszka and Heithaus 2015; Clapham 2016). However, the extent to which they can adapt to ocean change, including changes in temperature, sea levels, sea ice extent, wind speed, water acidity and salinity (Elliott and Simmonds 2007) or increasing human ocean resource-use (Clapham et al. 1999; Baker and Clapham 2004; Smetacek and Nicol 2005), remains unclear. Studies show potential threats include degradation of krill habitat (Hill et al. 2013) and a declining winter sea ice extent with associated changes in oceanographic circulation or krill recruitment (Clapham et al. 1999; Friedlaender et al. 2006; Leaper and Miller 2011).

The South African Blue Whale Project (SABWP), initiated by the Mammal Research Institute (MRI) and funded by the South African National Antarctic Programme (SANAP) in 2013, was established with the long-term aim of investigating the abundance and distribution of Antarctic blue whales. During the 2013/2014 South African National Antarctic Expedition (SANAE) cruise, a line-transect survey was conducted across an area delimited by 0°–18° E and between 67° S and the ice edge (Findlay et al. 2014), since the greatest density of Antarctic blue whales is expected close to the ice edge (Branch et al. 2007). This study investigates the abundance, population density and distribution of Antarctic blue whales encountered on this cruise.

Materials and methods

Study area

Considering concentrations and discontinuities in the distribution of historical catches, the IWC divided the Southern Ocean into six designated management areas for baleen whales, termed Areas I–VI (Donovan 1991; Bjørge et al. 2010). The area of the present study, off the coast of Queen Maud Land, eastern Antarctica, falls within Area III (0°–70° E). Sightings of 400 Antarctic blue whales made during summer cruises conducted by the IWC's International Decade of Cetacean Research (IDCR) and the Southern Ocean Whale Ecosystem Research (SOWER) programmes (1978–2010) showed a high concentration of the species in this area (Ensor et al. 2005, 2006, 2007).

Survey methodology

Between 13 and 22 January 2014, a ship-based line-transect survey was conducted from the SA *Agulhas II* between 0° and 18° E and between 67° S and the ice edge (defined as ice conditions that caused the ship to decrease speed or change course for any length of time; see Findlay et al. 2014). During the survey, the ship followed a series of pre-determined dedicated zigzag transect lines to maximise survey coverage without compromising the random survey design in relation to expected whale distribution (Figure 1) (Cassey and McArdle 1999; Buckland et al. 2001, 2004).

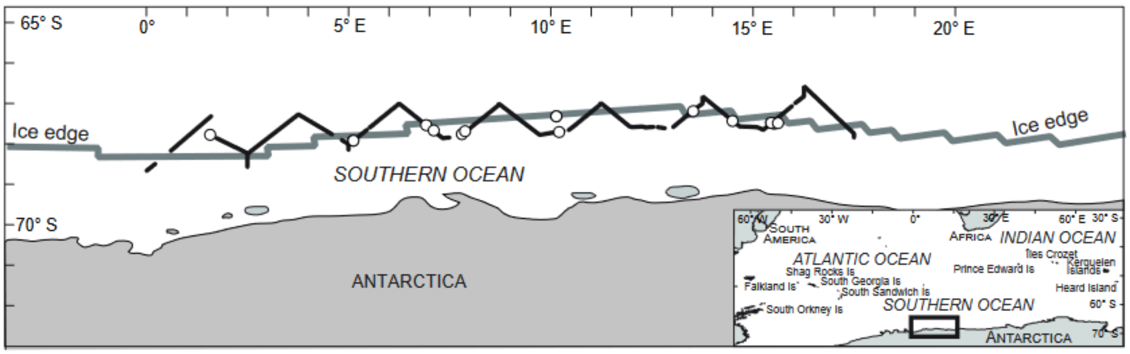

Figure 1: Distribution of Antarctic blue whale sightings (circles) from the SA *Agulhas II* in relation to the survey trackline followed between 13 and 22 January 2014. The ice edge was captured from satellite imagery. The survey area was defined by the encountered ice edge at the southern limit of the survey trackline

When a proposed southern waypoint of a transect was reached before the ice edge, the vessel steamed due south until the ice was reached and then returned northwards until reaching the proposed waypoint. Thereafter the new northerly transect was steamed. Where the ice edge was encountered before the waypoint, the vessel transited off effort along the ice edge until a clear transect was encountered. This survey methodology was similar to that used on IDCR/SOWER cruises (Branch 2007). The cruise track design was further modified on an ad hoc basis as ice conditions or poor weather conditions demanded (Findlay et al. 2014), to maintain survey effort at a similar latitudinal range from the ice edge across the longitudinal extent of the survey area.

Survey effort was carried out daily, between 05:00 and 21:00, for 10 consecutive days, when wind speeds were less than 25 knots and visibility was acceptable. Visibility was assessed as an estimate of the maximum distance the blow of a humpback whale *Megaptera novaeangliae* could be seen and ranged from 0 to 4 nautical miles.

All survey effort was conducted by two alternating teams of four observers using both the naked eye and Nikon 10 × 50 Aculon binoculars with a 6.5° angle of view. Teams kept a continuous watch from a platform located on the starboard wing of the vessel at a position 30.55 m above sea level (classified as primary search effort). The platform was a last-minute addition to the vessel just prior to departure from Cape Town, and the starboard location of this platform meant that viewing at the port side of the vessel was slightly compromised (effective search widths have been estimated as the means of both the port and starboard sightings). During adverse weather conditions (such as extreme cold) that were deemed to compromise observer efficiency, secondary search effort was conducted from an enclosed observation platform, located directly above the bridge (also at 30.55 m above sea level). At the end of each day's survey the vessel drifted, and the survey track was commenced at the start of the following day's research. Each allocated research day was allocated a transect code (I_1 –I_{10}).

Four types of data were recorded: (i) effort, (ii) environmental, (iii) sightings, and (iv) interceptions (Findlay et al. 2014). Effort data logged the observation effort of the observer teams, such as primary or secondary survey effort, as well as the attainment of waypoints or any breaks in observation effort. Environmental conditions were recorded by the observers every hour on the hour from 05:00 to 21:00. The record included the position of the vessel and a code for the general description of weather conditions. The wind was recorded as the direction to the nearest 5 degrees and speed to the nearest knot. At each sighting, direct animal-observer distance (r) in nautical miles was immediately recorded together with the sighting angle (θ) from the transect line, using an angle board, for distance analyses (Thomas et al. 2010); this method of distance sampling is particularly suited to populations of animals that are readily detectable (at least at close quarters) and sparsely distributed over a large area (Buckland et al. 2001; Perrin et al. 2009).

An automated system recorded the vessel position, speed, heading and water depth as well as environmental data (wind speed and direction, sea surface temperature and salinity) every minute for the duration of the cruise. Interception data, collected during deployed small-boat approaches to Antarctic blue whale groups and possible only when weather conditions allowed, included photographs and biopsy samples (Findlay et al. 2014).

Analyses

Abundance and population density analyses were conducted using the program DISTANCE 7.3 (Thomas et al. 2010). Generally, the detection function decreases with increased distance. For the purpose of this study, detectability was assumed as g(0) = 1 (i.e. probability 1) (Cassey and McArdle 1999; Buckland et al. 2001, 2004). For DISTANCE to produce reliable output, the sample size should be between 60 and 80 sightings, but as few as 40 observations can be used in some cases (Buckland et al. 2001). For small sample sizes (e.g. less than 30 sightings) the precision of the estimate declines significantly (Barlow et al. 2001).

Only 12 sightings of Antarctic blue whales during this survey were made on effort or had reliable distance measurements (see Results) and the low number necessitated analyses using proxy distance data from all 'large baleen whale' encounters, a group that included Antarctic blue whales, fin whales Balaenoptera physalus, sei whales Balaenoptera borealis, and large unidentified baleen whales, as well as large unidentified whales. Cues of this group of cetaceans are assumed to be similar to those of Antarctic blue whales and were analysed as proxy detection distances for Antarctic blue whales in the determination of the effective search width (ESW_{Baleen}). The effective search width (ESW) was estimated as follows:

$$\text{ESW} = \text{maximum search width } (W) \times \text{probability of observing an object } (p)$$

Several statistical models for the estimation of ESW were tested, with the lowest Akaike information criterion (AIC) value determining the most appropriate model. Comparing the discrepancy between distributions, Cramér–von Mises and Kolmogorov–Smirnov tests were used to assess the goodness of fit of the models used. A similar analysis using only Antarctic blue whale sightings was conducted to determine the expected group size ($E[S]_{Blue\ whale}$).

The estimated density of Antarctic blue whales in the surveyed area (the length of the survey trackline and twice the ESW) was determined as follows:

$$D_{Blue\ whale} = \frac{n(E[S]_{Blue\ whale})}{2(ESW_{Baleen})L}$$

where n = number of Antarctic blue whales observed; $E(S)_{Blue\ whale}$ = group size of Antarctic blue whales; L = total length of transect (nautical miles); and ESW_{Baleen} = effective search width (nautical miles) determined for large baleen whales.

Variance ($V[N/N^2]$) of the abundance estimate was calculated using the Delta method (Oehlert 1992):

$$V(N/N^2) = V(f[0])/(f[0]^2) + V(E[S])/E(S)^2$$

where V(f[0]) = variance of the density function f(0), and
N = abundance.

To estimate the abundance of Antarctic blue whales in the total survey area, the area bounded by the waypoints of the transect line was determined using QGIS (2009) and using WGS 84/NSIDC EASE Grid South EPSG: 3974 as the projected coordinate system. The estimated abundance was then determined (after Buckland et al. 2001) as follows:

$$N_{Blue\ whale} = D_{Blue\ whale} \times A$$

where $N_{Blue\ whale}$ = abundance of Antarctic blue whales, and A = total survey area (nautical miles 2).

Results
In total, the SA *Agulhas II* travelled 1 312.2 nautical miles within the 10 days allocated for Antarctic blue whale research. Primary search effort (493.47 nautical miles) and secondary search effort (411.45 nautical miles) accounted for a total of 904.92 nautical miles of survey trackline under these survey modes (Table 1), with the remainder used in transit and for observer training purposes. Of the 160 hours allocated, 132.5 hours were spent in search during acceptable weather conditions.

Table 1: Survey effort for each survey day on the SA *Agulhas II* during a line-transect survey of Antarctic blue whales off Queen Maud Land, Antarctica

Date	Transect line (l)	Primary search effort (nautical miles)	Secondary search effort (nautical miles)	Total distance (nautical miles)
13 Jan 2014	l_1	6.40	78.99	85.39
14 Jan 2014	l_2	71.28	81.92	153.20
15 Jan 2014	l_3	11.10	79.78	90.89
16 Jan 2014	l_4	43.31	59.70	103.01
17 Jan 2014	l_5	131.59	0	131.59
18 Jan 2014	l_6	84.33	4.74	89.07
19 Jan 2014	l_7	86.61	0.67	87.28
20 Jan 2014	l_8	43.01	73.63	116.64
21 Jan 2014	l_9	15.84	13.99	29.83
22 Jan 2014	l_{10}	0	18.03	18.03
Total		493.47	411.45	904.92

During the survey, 17 groups of Antarctic blue whales with a total of 26 individuals were sighted. Of these, 12 sightings occurred during primary or secondary survey effort. Most sightings were of either individuals or pairs. Considering body shape, all blue whales sighted were assumed to be Antarctic blue whales, and not pygmy blue whales *Balaenoptera musculus brevicauda* (Branch et al. 2007). This is considered a safe assumption given the latitudinal range covered by the cruise (e.g. Ichihara 1966; Kato et al. 1995; Branch et al. 2009).

The position of each Antarctic blue whale sighting was plotted in relation to the trackline (Figure 1). Antarctic blue whales were fairly evenly distributed with sightings between 67.19° and 67.92° S and between 1.57° and 15.62° E, and with a slightly higher concentration between 67.19° and 67.5° S.

Collectively termed 'large baleen whales,' the sightings of Antarctic blue whales (n = 12), fin whales (n = 8) and sei whales (n = 1)[1] , as well as unidentified large baleen whales (n = 9) and unidentified large whales (n = 1) were mapped in relation to the trackline to identify the distribution of proxy sightings used in the estimation of the ESW. Such sightings of large baleen whales were fairly evenly distributed throughout the survey region, but with greater concentrations found between 8.78° and 11.0° E.

The distance from the trackline ($x = r \sin(\theta)$) was determined for each large baleen whale sighting (Table 2). The minimum and maximum perpendicular distances for observing Antarctic blue whales were 0.054 and 1.590 nautical miles, respectively, while the median value was 0.325 nautical miles. The effective search width (ESW) was determined using perpendicular distances to the collective group 'large baleen whales' (n = 31) as proxy for Antarctic blue whales. The minimum and maximum perpendicular distances to the trackline were 0.026 and 2.868 nautical miles, respectively, while the median value was 0.442 nautical miles. The probability of observing a large baleen whale was determined applying the hazard rate model (AIC = 31.34). A goodness of fit test with pooling was conducted (χ^2 = 2.33, df = 3, p = 0.507). This model showed p = 0.162 (SE = 0.068, CV = 0.42, 95% CI 0.071–0.371) (Figure 2). ESW was estimated at 0.466 nautical miles (SE = 0.195, CV = 0.42, 95% CI 0.205–1.062).

Table 2: Sighting coordinates, species code, group size, observed distance, observed angle and calculated distance to the trackline for completed records of primary and secondary effort sightings of large baleen whales from the SA *Agulhas II* in January 2014. Species codes: 1 = Antarctic blue whale; 2 = fin whale; 3 = sei whale; 64 = unidentified large baleen whale; 73 = unidentified large whale

Date	Sighting coordinates	Species code	Group size	Distance observed (nautical miles) (r)	Angle observed (degrees) (θ)	Distance to trackline (nautical miles) ($x = r \sin(\theta)$)
13 Jan	68.095° S, 3.646° E	64	1	0.432	7	0.053
13 Jan	67.905° S, 0.090° E	2	3	0.800	36	0.470
14 Jan	67.773° S, 1.571° E	1	2	1.500	26	0.658
14 Jan	68.405° S, 1.571° E	64	1	0.243	20	0.083
14 Jan	67.173° S, 3.432° E	2	4	1.500	1	0.026
15 Jan	67.332° S, 3.861° E	64	2	1.600	7	0.195
15 Jan	67.485° S, 4.122° E	2	3	3.500	4	0.244
15 Jan	67.445° S, 4.333° E	64	1	3.500	28	1.643
15 Jan	67.919° S, 5.102° E	1	2	1.200	72	1.141
15 Jan	67.674° S, 5.413° E	2	1	2.200	28	1.033
16 Jan	67.349° S, 5.815° E	64	2	0.400	18	0.124
16 Jan	67.032° S, 6.292° E	64	1	1.500	19	0.488
16 Jan	67.345° S, 6.682° E	2	1	0.900	7	0.110
16 Jan	67.534° S, 6.915° E	1	1	1.500	27	0.681
16 Jan	67.666° S, 7.101° E	1	1	0.270	20	0.092
16 Jan	67.739° S, 7.170° E	2	1	0.800	5	0.070
16 Jan	67.684° S, 7.878° E	1	2	0.500	22	0.187
17 Jan	67.160° S, 8.549° E	2	1	2.000	36	1.176
17 Jan	67.025° S, 8.778° E	64	1	3.000	18	0.927
17 Jan	67.704° S, 10.203° E	1	2	1.000	57	0.839
17 Jan	67.368° S, 10.295° E	64	1	1.000	43	0.682
17 Jan	67.520° S, 10.602° E	2	1	1.400	34	0.783
17 Jan	67.052° S, 11.000° E	64	1	4.000	20	1.368
18 Jan	67.584° S, 12.414° E	3	3	2.800	2	0.098
18 Jan	67.190° S, 13.518° E	1	1	3.000	32	1.590
19 Jan	67.431° S, 14.492° E	1	1	0.540	55	0.442
19 Jan	67.497° S, 15.527° E	1	1	0.800	15	0.207
20 Jan	67.287° S, 15.268° E	1	1	0.054	90	0.054
20 Jan	67.287° S, 15.268° E	1	1	0.108	90	0.108
20 Jan	67.485° S, 15.617° E	1	3	0.200	80	0.197
20 Jan	67.093° S, 15.943° E	73	2	5.000	35	2.868

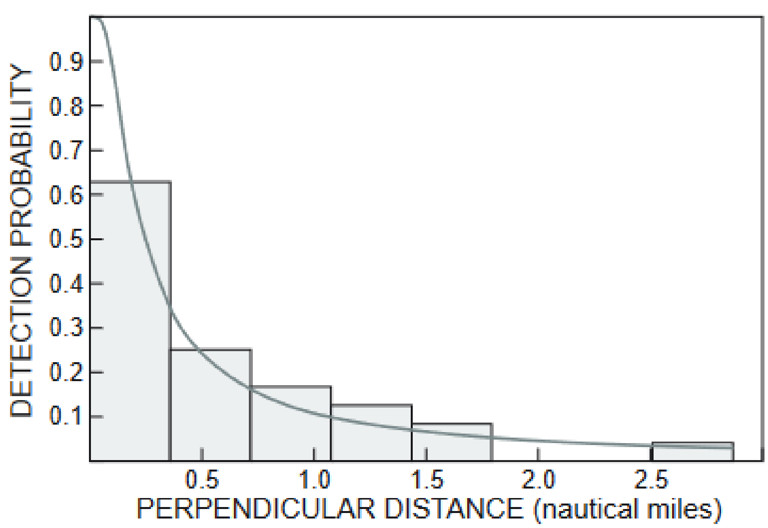

Figure 2: Detection probability for sighting large baleen whales, using the hazard rate function, during a line-transect survey of Antarctic blue whales off the Queen Maud Land coast of Antarctica

A Cramér–von Mises test (uniform weighting) confirmed that the distribution of perpendicular distances of large baleen whales conformed to a normal distribution (T = 0.057, with 0.800 < p ≤ 0.900, while the cosine weighting test yielded a test statistic of T = 0.037, with 0.800 < p ≤ 0.900). The Kolmogorov–Smirnov test yielded D_n = 0.099 with a p-value of 0.921. The low D n and corresponding high p-value indicated a normal distribution.

Expected group size ($E[S]_{\text{Blue whale}}$) (n = 12) was 1 As sightings of sei whales at this latitude are unusual, the ship approached and observed the sighting for more than 30 minutes, with photographs taken from a short distance. The sighting was identified as a sei whale by an experienced IWC/SOWER researcher determined using the hazard rate model (AIC = 9.66). A goodness-of-fit test with pooling was conducted (χ^2 = 2.88, df = 2, p = 0.237). The expected group size ($E[S]_{\text{Blue whale}}$) was 1.358 (SE = 0.197, CV = 0.15; 95% CI 1.00–1.87). The number of sightings per 1 000 nautical miles of survey effort (n/L) was 13.3 Antarctic blue whales per 1 000 nautical miles (CV = 0.26, 95% CI 7.5–23.5).

A Cramér–von Mises test (uniform weighting) confirmed that the distribution of perpendicular distances of Antarctic blue whales conformed to a normal distribution (T = 0.037, with 0.900 D_n< p ≤ 1.000, while the cosine weighting test statistic was T = 0.027 and 0.900 < p ≤ 1.000). A Kolmogorov–Smirnov test yielded = 0.158 with a p-value of 0.925. The low D_n -value and corresponding high p-value indicated a normal distribution.

Combining ESW_{Baleen} = 0.466 with the expected group size $E(S)_{\text{Blue whale}}$ = 1.358 and variance using the Delta method determined the estimated density of Antarctic blue whales, $D_{\text{Blue whale}}$ = 0.019 whales-nautical mile $^{-2}$ (SE = 0.0046, CV = 0.24). The survey area (A = 54 000 nautical miles^2) was determined using waypoints from the survey trackline, mapped in QGIS. A total of 1 026 Antarctic blue whales (SE = 209.5, CV = 0.20, 95% CI 632–1 450) were estimated to be present in the survey area (Table 3).

Table 3: Test statistics for sightings of Antarctic blue whales and large baleen whales off Queen Maud Land, Antarctica. CV = coefficient of variation; SE = standard error

Group	Group size (n)	Density function (f[0]) (SE)	Effective search width (ESW) (SE)	Expected group size (E[S]) (SE)	Density (D) (SE)	Abundance (N) (CV)
Large baleen whales	31	0.162 (0.068)	0.466 (0.195)			
Antarctic blue whales	12			1.358 (0.197)	0.019 (0.0046)	1 026 (0.20)

Discussion

Sightings of Antarctic blue whales are rare in the Southern Ocean (Branch 2007). This study suggests a sighting rate of 13.3 per 1 000 nautical miles in the Queen Maud Land region of the Antarctic. These results are very similar to a dedicated 2019/20 Japanese Abundance and Stock-structure Survey in the Antarctic [JASS-A] of IWC Management Area III, which reported a rate of 13.8 Antarctic blue whales per 1 000 nautical miles (Isoda et al. 2020). Such a density is substantially higher than previous reported sighting rates, estimated at 1.48 per 1 000 nautical miles based on the middle survey (1997/1998) of three IDCR/SOWER circumpolar surveys between 1991/1992 and 2003/2004, with Antarctic blue whales sighted in all IWC Management Areas south of 60° S (Branch 2007). The findings therefore reinforce the perception that the 0–18° S region off the Queen Maud Land coast is a 'hotspot' for Antarctic blue whales (e.g. Ensor et al. 2005, 2006, 2007; Findlay et al. 2014). It is important to note that sighting rates can differ substantially between regions as the type and amount of survey effort differs (Branch 2007; Branch et al. 2007).

The estimated abundance of Antarctic blue whales in the survey area (1 026 individuals) should be interpreted with care as the low number of sightings (Barlow et al. 2001) resulted in the ESW of 0.466 being determined using the group 'large baleen whales' as a proxy detection function of the population. Circumpolar survey ESW for Antarctic blue whales ranged from 1.62 to 1.97 nautical miles (Branch 2007). Although the ESW used in this study is smaller than in previous surveys, the use of a proxy population resulted in a larger ESW than had it been determined using sightings of Antarctic blue whales alone. The comparatively smaller ESW used in this study may result in an overestimation of the population; however, the expected group size of Antarctic blue whales was slightly smaller in this study (1.36) compared with previous surveys where estimated group sizes range from 1.6 to 2 (Branch 2007).

Obtaining stronger statistical evidence for the current population size of Antarctic blue whales remains difficult because of their scarcity and diffuse distribution in offshore waters. Nonetheless, the monitoring and estimating of population abundance and trends is a critical component of any population status assessment (Buckland et al. 2001). Additional data are needed to fully understand the movement of Antarctic blue whales between and within seasons, especially considering the major climate changes taking place in the Antarctic (Baker and Clapham 2004 Smetacek and Nicol 2005; Bell 2013, 2015; Peel et al. 2015; Olson et al. 2016). Updating the global abundance estimate for Antarctic blue whales is currently a priority of the IWC (International Whaling Commission 2020). As low-latitude distributions are not well understood, sightings of the species are rare while research within the known ranges is costly (Attard et al. 2016). It is therefore believed that the findings from this study will be valuable in the development of the IWC Antarctic blue whale comprehensive assessment, expected to conclude in 2023 (International Whaling Commission 2020).

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Notes

[1] As sightings of sei whales at this latitude are unusual, the ship approached and observed the sighting for more than 30 minutes, with photographs taken from a short distance. The sighting was identified as a sei whale by an experienced IWC/SOWER researcher

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