Abundance of Antarctic blue whales south of 60°S from three complete circumpolar sets of surveys

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ABSTRACT

Sightings from the IDCR/SOWER austral summer surveys are analysed to provide abundance estimates for Antarctic (true) blue whales (*Balaenoptera musculus intermedia*) south of 60°S. The IDCR/SOWER ship-borne surveys have completely circled the Antarctic three times: 1978/79-1983/84 (CPI); 1985/86-1990/91 (CPII); and 1991/92-2003/04 (CPIII), covering strata totalling 64.3%, 79.5% and 99.7% of the ocean surface between the pack ice and 60°S. During the surveys, blue whale sightings were rare but were recorded in all regions. Raw sighting rates (schools per 1,000 n.mile of primary search effort) were 0.44 (CPI), 0.67 (CPII) and 1.48 (CPIII). Respective circumpolar abundance estimates were 453 (CV=0.40), 559 (CV=0.47) and 2,280 (CV=0.36), with corresponding mid-years of 1981, 1988 and 1998. The CPIII estimates are the most complete and recent for this subspecies. When adjusted for unsurveyed regions in a simple way, the estimated circumpolar rate of increase is 8.2% (95% CI=1.6–14.8%) per year; nevertheless, Antarctic blue whales still number far less than the estimated 202,000-311,000 that existed before exploitation. These abundance estimates are negatively biased because some Antarctic blue whales may have been north of 60°S or in the pack ice at the time of the surveys and because a small number of blue whales on the trackline were probably missed. Furthermore, a small proportion of pygmy blue whales, probably less than 1%, may have been included in the sightings.

KEYWORDS: BLUE WHALE; SOWER; WHALING-HISTORICAL; ANTARCTIC; SOUTHERN HEMISPHERE; SURVEY-VESSEL; ABUNDANCE ESTIMATE

INTRODUCTION

Whaling reduced the once large numbers of blue whales (*Balaenoptera musculus*) to a small fraction of their original levels (e.g. Clapham *et al*., 1999). Of the three widely recognised subspecies, Antarctic blue whales (*B.m. intermedia*) greatly dominated pre-exploitation abundance and historical catches, while catches and pre-exploitation abundance of northern blue whales (*B.m. musculus*) and pygmy blue whales (*B.m. brevicauda*) were an order of magnitude lower (Branch *et al*., 2004; 2007a). Based on existing estimates of abundance, Antarctic blue whales originally numbered 239,000 (95% CI=202,000-311,000) but whaling from 1905-73 depleted them to a low of 360 (95% CI=150-840); despite statistically significant evidence for a subsequent increase, their numbers are still below 1% of their pre-exploitation level (Branch *et al*., 2004).

This estimated current status of Antarctic blue whales is based largely on abundance estimates from the IWC's International Decade for Cetacean Research (IDCR) and Southern Ocean Whale Ecosystem Research (SOWER) programmes. These ship-based surveys south of 60°S have been conducted annually since the 1978/79 austral summer season (i.e. December 1978 to February 1979). The surveys are conveniently grouped into three circumpolar sets of surveys (CPs), each of which completely encircled Antarctica – from 1978/79-1983/84 (CPI), 1985/86-1990/91 (CPII) and 1991/92-2003/04 (CPIII). The 1984/85 survey and those after 2003/04 were largely devoted to experiments and so are customarily excluded when obtaining abundance estimates (e.g. Branch, 2006a; 2007a; Branch and Butterworth, 2001a; 2001b). The most recent IDCR/SOWER estimates for CPI and CPII were 440 (CV=0.41) and 550 (CV=0.48) respectively (Branch and Butterworth, 2001a), but no estimates have been provided for the complete CPIII set. The CPIII estimate for the proportion of the area which had been covered up to 1997/98 (68%) was 1,100 (CV=0.45) (Branch and Butterworth, 2001a), and for that up to 2001/02 (91%) was 1,700 (CV=0.42) (Branch and Rademeyer, 2003). However, since these estimates were presented, CPIII has been completed, with the most important addition being the resurveying (2001/02-2003/04) of IWC Management Area V (130°E-170°W) from the pack ice northwards to 60°S. When Area V was previously surveyed earlier during the CPIII set in 1991/92, the survey did not include the northernmost area south of 60°S.

For the analyses that follow, blue whale sightings south of 60°S are assumed to be Antarctic blue whales, although some may be pygmy blue whales. The proportion that are pygmy blue whales has previously been assumed to be no more than 7% (IWC, 2003); however, evidence from length frequencies and from ovarian corpora data suggests that for females (and therefore probably also for males) the upper limit is closer to 1% (Branch, 2006b; Branch *et al*., 2007b).

This paper presents updated abundance estimates from the three completed circumpolar sets of surveys. Previous estimates were provided at the circumpolar level only, but here, estimates are also presented for individual surveys and for IWC Management Areas.

METHODS

The analysis methods are presented concisely below as they are only slightly modified from those in Branch and Butterworth (2001a). These minor modifications are listed in detail for humpback whales (Branch, 2007a) and so are only summarised here in Table 1. Data extraction and abundance estimation are mostly automated in the IWC's Database Estimation System Software (DESS 3.42 April 2006; described in Strindberg and Burt (2004)), but substantial post-DESS manipulation is required to divide estimates among the IWC Management Areas (Figs 1 and 2) and to account for multiple surveys of areas during the same CP set.

Table 1

Summary of changes to the analyses compared to those in Branch and Butterworth (2001a).

Topic	Branch and Butterworth (2001a)	This paper	Implications
Activity codes	BA, BB, BC, BL, BR, SE, BH, BI, BO, BP, BQ, BU, BV	BB renamed to BK	None
Duplicates and triplicates	'Definite' and 'possible' duplicates and triplicates treated as multiple records of a single sighting	Only 'definite' duplicates and triplicates treated as multiple records of a single sighting	Increases estimates by about 1%
Survey legs parallel to ice edge in 1988/89 and 1989/90	Included	Excluded	Decreases CPII estimate by 0.4%
Area of ES stratum in 1996/97	67,072 n.mile^2	Corrected to 52,534 n.mile^2	Decreases CPIII estimate by 0.5%
EN2 stratum in 1997/98	Treated as if divided into two separate strata each surveyed by one vessel	Treated as one stratum surveyed by two vessels	No effect
Estimated school size	Either regression method or mean within 1.5 n.miles	Regression method unless positive correlation or school size less than one, then mean within 0.5 n.mile	No effect since regression always positive for blue whales

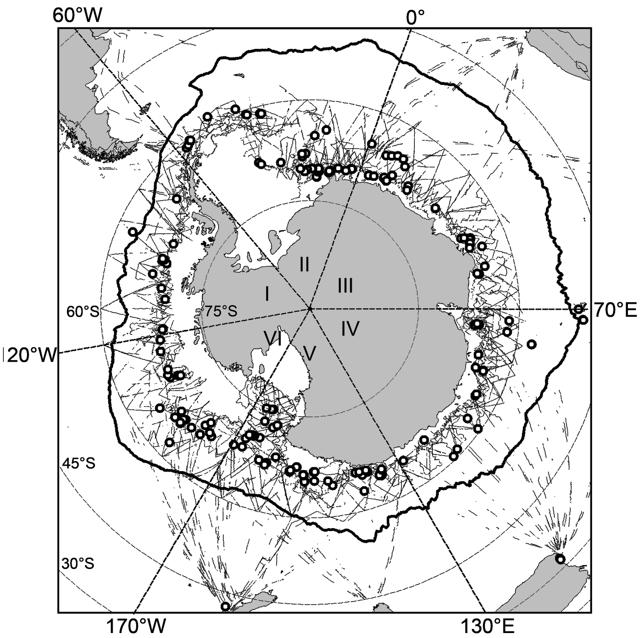

Fig. 1. Primary effort (thin grey lines) and all sightings of blue whales (black circles) from the IDCR/SOWER surveys, 1978/79-2004/05. Plotted survey effort includes transits to and from the survey regions and survey years (1984/85, 2004/05) devoted primarily to experiments that are not included in the abundance estimates. Sightings include those made off effort and during refuelling, but exclude duplicate and triplicate sightings of the same school. The Antarctic Polar Front is represented by a thicker line and is based on data from Moore *et al*. (1999). Dashed lines extending from the South Pole and associated Roman numerals I–VI demarcate the IWC Management Areas.

Survey design

Details of the surveys can be obtained from annual reports (e.g. Ensor *et al*., 2007), while most of the survey methods are summarised in multi-year reviews (Branch and Butterworth, 2001b; Joyce *et al*., 1988; Matsuoka *et al*., 2003). Survey design differed among the three CPs, complicating efforts to compare abundance estimates between CPs (Figs 1-2). In CPI, one vessel generally followed the pack ice while the other surveyed in a rectangular pattern, leaving unsurveyed regions both between the northern and southern strata, and between the northern survey boundary and 60°S. In CPII, the surveys generally followed a zig-zag design with no gap between northern and southern strata, but left unsurveyed regions between the northernmost boundary and 60°S. Finally, the CPIII surveys completely surveyed the region south of 60°S to the ice edge, but had to reduce annual longitudinal coverage to achieve the additional latitudinal coverage, and hence needed 13 years to complete compared to the six years for each of CPI and CPII. Additionally, in CPIII but not in CPI or CPII, some longitudinal regions were surveyed more than once. Survey modes differed among the CPs; in CPI the surveys were conducted in closing mode only, while in the other two CPs the surveys alternated between closing mode and independent observer (IO) mode. IO mode is a form of passing mode where the vessel did not leave the trackline to confirm the species identity and school size of the sighting, and there was an observer in the independent observer barrel on the mast in addition to the observers in the topman platform.

Data selected for analysis

Closing mode and IO mode data are combined for analysis in this paper, due to the low number of blue whale sightings. The raw sighting rates (per 1,000 n.mile) for CPII and CPIII were 0.93 for closing mode and 1.08 for IO mode, based on a small number (82) of sightings. Although the closing mode sighting rate is somewhat smaller, the estimated search half width is expected to be narrower in closing mode (because there is one fewer observer), which would offset this difference. Previous Antarctic analyses have also combined these data and sensitivities to this kind of pooling showed that estimates for other species obtained separately for each mode were similar (Branch and Butterworth, 2001a). Many different effort codes have been recorded over the years as listed in Branch and Butterworth (2001a; 2001b). Primary effort is when the vessels were searching for whales, and excludes, for example, effort spent confirming species identity or school size, refuelling, experiments and drifting during bad weather. In this paper, all primary search effort is included, except for research effort specifically directed towards areas of high expected blue whale density (BB activity code). Sightings were included when calculating the estimates if recorded as code 01 (Antarctic blue whale), code 98 (blue whale, probably Antarctic), or code 99 (blue whale, undetermined subspecies), but were excluded if recorded as code 56 (pygmy blue whale) or code 96 (blue whale, probably pygmy). Where duplicate and triplicate sightings were recorded from multiple platforms during IO mode, those classified as 'definite' duplicates and triplicates were assumed to refer to a single school, while 'possible' and 'remote' duplicates and triplicates were assumed to be sightings of multiple schools. Only 0.3% of sightings of all

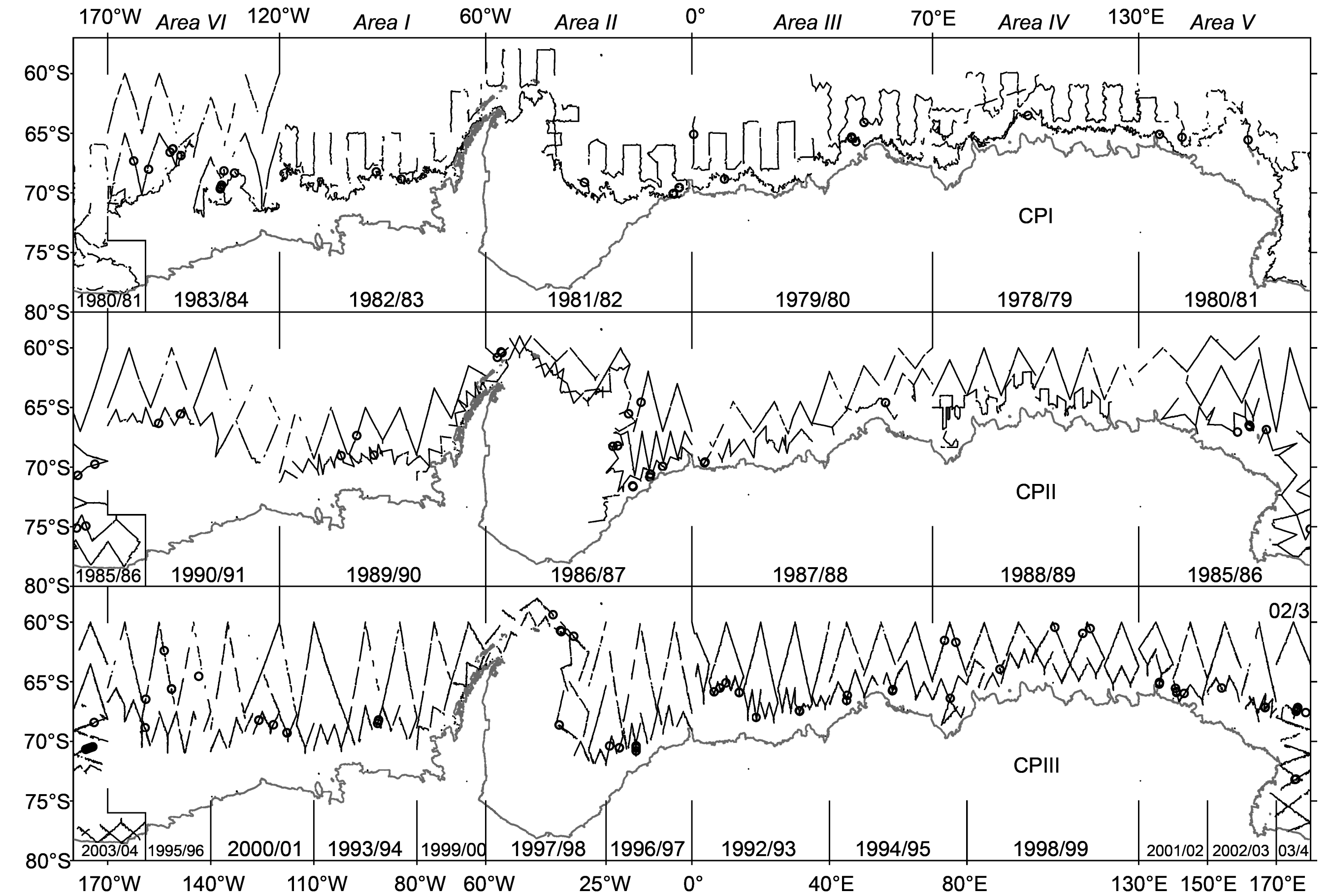

Fig. 2. Primary search effort (solid lines) during each of the surveys included in the first, second and third circumpolar sets of surveys (CPI, CPII and CPIII), and associated sightings of blue whales (circles). Only the effort and sightings used in estimating circumpolar abundances are shown. Vertical lines at the top of each panel indicate the six IWC Management Areas, while vertical lines at the bottom of each panel show the divisions between the surveys.

species were recorded as 'possible' duplicates (Branch and Butterworth, 2001a), thus this decision about duplicates should have negligible impact on the results.

Abundance estimation

Abundance estimates were obtained using the standard line transect formula:

$$N = \frac{A \cdot E[s] \cdot n}{2 \cdot w_s \cdot L} \quad (1)$$

where:

N = abundance estimate;
A = area of stratum (n.mile²);
$E[s]$ = mean school size;
n = number of schools sighted during primary search effort;
w_s = effective search half-width for schools (n.mile);
L = primary search effort (n.miles).

The CV for N was calculated from:

$$CV(N) = \sqrt{\left[CV\left(\frac{n}{L}\right)\right]^2 + \left[CV\left(E[s]\right)\right]^2 + \left[CV\left(w_s\right)\right]^2} \quad (2)$$

Sightings were smeared using Method II of Buckland and Anganuzzi (1988) and then grouped into 0.1 n.mile bins to the truncation distance of 3.0 n.miles, as recommended during analyses by Branch and Butterworth (2001a). In analyses for minke whales and humpback whales, smearing parameters were estimated from the data (Branch, 2006a; 2007a). However, because of the paucity of data for blue whales, smearing parameters could not be estimated reliably from the data and were instead set to 4.0° (angle) and 0.3 n.mile (distance), based on average values for other species and the recommended values used by Branch and Butterworth (2001a). The hazard rate detection function was fitted to the smeared perpendicular distances of the selected sightings:

$$\begin{aligned} f(y) &= f(0)g(y) \\ &= f(0)\left[1-\exp\left(-\left[\frac{y}{a}\right]^{-b}\right)\right] \end{aligned} \quad (3)$$

where $g(y)$ is the probability that a school at a perpendicular distance y from the trackline will be sighted, and a and b are estimated parameters subject to the constraints that $a \geq 0.0001$ n.mile and $b \geq 1$. For the abundance estimates it was assumed that $g(0)=1$, i.e. that all schools on the trackline were sighted, which seems a reasonable approximation given the highly visible cues produced by blue whales.

School size estimates were obtained from sightings with confirmed school sizes in closing mode only. Large schools are visible at greater distances than small schools and therefore estimates of school size were corrected for bias using the regression method proposed by Buckland *et al.* (1993), which accounts for changes in the detectability of different school sizes with distance from the vessel. Sample sizes were small, requiring sightings to be pooled over all surveys in a CP set to estimate search half-width and mean school size.

Combining estimates

Abundance estimates were obtained for individual surveys, for each IWC Management Area, and for each CP set. For CPI and CPII, the survey design rendered estimates easy to obtain for Management Areas and for circumpolar sets, but during CPIII some surveys repeated longitudinal coverage and others were spread over two Management Areas. Therefore, CPIII Management Area and circumpolar estimates required the splitting of strata and the division of survey effort and sightings between the new substrata as outlined in detail in Branch (2005). Note that circumpolar estimates from CPIII exclude the 1991/92 survey in Area V since this region was more completely covered during 2001/02-2003/04.

The differing nature of the three CPs poses several issues when comparing estimates, including: the different survey design and survey modes; the unsurveyed central regions in CPI; the lack of survey effort northwards to 60°S in most of the CPI and CPII surveys; and the unknown proportion of blue whales north of 60°S during the survey period. The most important of these issues is the unsurveyed northern areas in CPI and CPII, which are taken into account using the simple assumption employed by Branch and Butterworth (2001a; 2001b) and Branch (2006a; 2007b) that the density in the unsurveyed northern areas is the same as in the adjacent northern strata. This assumption will tend to over-estimate the 'comparable-areas' estimates in CPI and CPII because the density in the unsurveyed northern areas is likely lower than in the corresponding northern strata, given that their density declines with increasing distance from the pack ice (Branch *et al*., 2007a; Kasamatsu *et al*., 2000). Following this reasoning, the best estimates for the whole area south of 60°S based on CPI and CPII are likely between the base survey estimates (which assume zero whales in the unsurveyed northern areas) and the 'comparable-areas' estimates, which are 31% (CPI) and 23% (CPII) higher (see Results).

Circumpolar sighting rates

For comparison with other blue whale surveys in the Southern Hemisphere and northern Indian Ocean listed in Branch *et al*. (2007a), the number of schools sighted per 1,000 n.mile of primary effort was calculated for all strata surveyed during 1978/79-1983/84 (CPI), 1985/86-1990/91 (CPII) and 1992/93-2003/04 (CPIII). For these calculations, sighting numbers were neither smeared nor truncated at 3.0 n.mile.

Annual rate of change

The annual rate of increase for the circumpolar comparable-area abundance estimates was estimated by fitting an exponential growth model to the log of the estimates:

$$\ln \hat{N}_t = \ln N_0 + rt$$

where

N_0 is the abundance in the starting year (1981);
$\hat{N}_t$ is the model-estimated abundance t years after the starting year;
r is the annual rate of increase.

For many reasons, the distribution of whales within and also between Management Areas changes from year to year, and this inter-Area variability would not be taken into account if the variance of an abundance estimate obtained by summing over Areas (i.e. the CP abundance estimates) accounted only for the sampling variance estimate from each survey. This missing component of the overall variance is termed 'additional variance'. The variance (in the form of a CV^2) for fitting a growth model to interannual estimates therefore comprises both the variance for each survey, CV_t^2, and the additional variance, CV_{add}^2, which is assumed to be the same for all CP estimates. The resulting negative log likelihood expression for obtaining maximum likelihood estimates of N_0, r, and CV_{add}^2 (ignoring constant terms) is:

$$-\ln L = \sum_t \left[\ln \sqrt{CV_t^2 + CV_{\text{add}}^2} + \frac{\left(\ln N_t - \ln \hat{N}_t\right)^2}{2\left(CV_t^2 + CV_{\text{add}}^2\right)} \right]$$

The 95% confidence intervals for r were obtained by likelihood profiling, i.e. by finding the two values of r for which the negative log likelihood is 1.92 units higher than for the maximum likelihood estimate (MLE) (e.g. Hilborn and Mangel, 1997).

RESULTS

Survey coverage and primary effort distribution

Survey coverage of the ice-free area south of 60°S was most complete in CPIII, when 99.7% of the area was covered, compared to 64.3% (CPI) and 79.5% (CPII) in the earlier surveys (Fig. 2). Blue whales were sighted in all regions of the Antarctic, typically close to the pack ice, and were also sighted occasionally north of the survey region during transits in the southern Indian Ocean and close to New Zealand (Fig. 1). Based on historical catch length frequencies and their current distribution, the northerly sightings were most likely to have been pygmy blue whales (Branch *et al*., 2007a; 2007b).

Abundance estimates

Stratum-specific components of the abundance estimates are presented in Table 2. CP-specific estimates of search half width and mean school size were highest in CPI, but were not significantly different from the CPII and CPIII estimates (Table 3). The detection function fits to the sighting distributions (Fig. 3) appear poor in CPI and CPII, but care must be taken in interpreting the apparent systematic deviations between 'data' and model estimates in these plots, as the 'data' here are smeared, which in conjunction with the small associated sample sizes (Table 3) leads to substantial correlation across neighbouring perpendicular distance bins in the histograms shown. The only 'mis-fit' of potential concern is the large peak for the first 0.1 n.mile bin for CPI, which probably reflects insufficient smearing to account for the relatively large number of angle observations rounded to 0 in the CPI cruises. To test whether this lack of fit to the apparent peak introduced any bias, the data were grouped into 0.5 n.mile bins (instead of 0.1 n.mile bins) and the hazard rate model re-fitted. The estimate of search half width changed from 1.97 to 1.99, indicating that this introduces little bias to the estimates.

Estimated circumpolar abundance increased by a small amount from CPI to CPII but was markedly higher for CPIII, even when each is adjusted simply for unsurveyed areas (Table 4). Abundance estimates were 453 (CV=0.40)

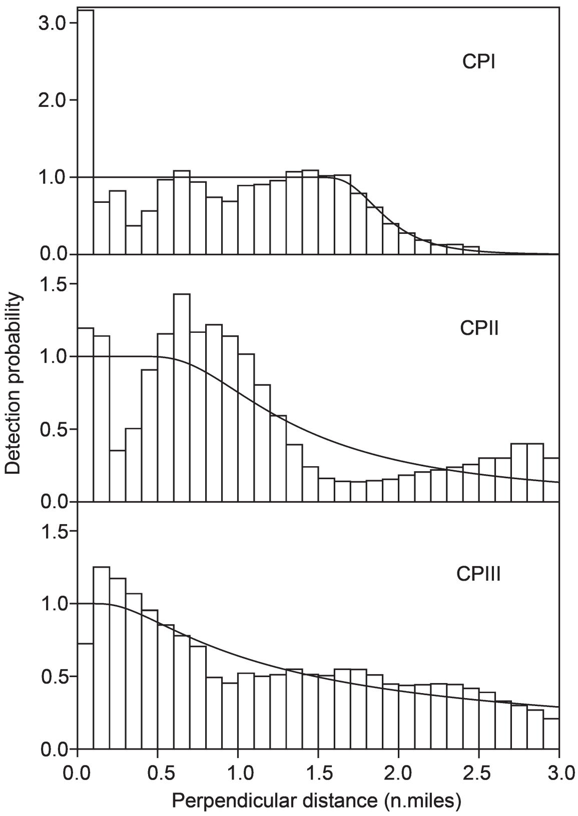

Fig. 3. Detection function fits to the smeared and truncated sightings for the circumpolar abundance estimates based on data from CPI (top panel), CPII (middle panel) and CPIII (bottom panel). Note that a different vertical scale is used for CPI.

for CPI, 559 (CV=0.47) for CPII and 2,280 (CV=0.36) for CPIII. Note that the CPIII circumpolar estimate declined when adjusted for comparable areas because some primary survey effort north of 60°S in Area II was excluded.

Abundance estimates were highest in CPIII for all IWC Management Areas, but when the estimates were adjusted for unsurveyed areas, this pattern did not hold in Areas I and III (Table 5), although the CVs at this fine spatial scale are too large to allow detection of differences of any statistical significance. Area V was consistently estimated to contain the most blue whales.

At least one blue whale was recorded during primary search effort in all surveys except 1988/89 and 1999/00, for which the abundance estimates were zero, while the highest estimated abundance for a single survey was 557 in 2003/04 (Table 6).

Estimated rate of increase

The estimated rate of increase based on 'comparable-area' circumpolar abundance estimates was 8.2% per annum (95% CI=1.6-14.8%). Had additional variance been ignored, the 95% CI would have been underestimated as 3.8-12.5%. Overall sighting rates (number of schools per 1,000 n.mile of primary effort) increased over time from 0.44 (CPI) to 0.67 (CPII) to 1.48 (CPIII).

DISCUSSION

The IDCR/SOWER surveys provide the most comprehensive circumpolar abundance estimates to date for Antarctic blue whales. During CPIII, survey coverage was 99.7% of the ice-free area south of 60°S during the austral summer when most Antarctic blue whales are found in the survey region. Estimates are negatively biased to some extent because some Antarctic blue whales do not enter the survey region; 20.2% of the historical catches (some of which were pygmy blue whales) were north of 60°S during the survey months (Horwood, 1986). Furthermore, some Antarctic blue whales do venture into the unsurveyed southern pack ice (Tomilin, 1967; Best, 2007; P. Ensor, pers. comm.), although acoustic evidence suggests they generally avoid areas covered by sea ice (Širovíc *et al*., 2004). Negative bias to the estimates also occurs because it is assumed that all whales on the trackline were sighted, i.e. that $g(0)=1$. The bias resulting from this assumption is probably small because of the great visibility of blue whale cues and their frequency of cue production: $g(0)$ for the surveys is probably between 0.9 and 1 (Best *et al*., 2003; Calambokidis and Barlow, 2004; Kasamatsu, 2000). There is great uncertainty about the magnitude of these factors, but if the estimates above are applicable, the CPIII abundance estimates would be negatively biased by 20-30%.

It has previously been assumed that a small proportion of these estimates (no more than 7%) could be pygmy blue whales (IWC, 2003). However, recent mixture models of ovarian corpora data (Branch, 2006b) and the length frequencies of mature females (Branch *et al*., 2007b) demonstrate that this proportion is no more than 1% for females in the historical catches. There is no obvious reason to suppose that these results might not apply to the present-day population of both sexes: there is no evidence in the corpora data that the proportion of pygmy blue whales south of 60°S increased over time despite substantial depletion of Antarctic blue whales (Branch, 2006b) and the sex ratio in catches was close to the birth sex ratio (Branch *et al*., 2007b).

Estimated sighting rates (schools per 1,000 n.mile of primary effort) increased from 0.44 (CPI) to 0.67 (CPII) to 1.48 (CPIII). These sighting rates are in line with simple estimates from other Antarctic studies listed in Branch *et al.* (2007a), 0.31 from the earlier Japanese Scouting Vessel (JSV) data (1965/66-1988/89) and 0.63 from Japanese Whaling Research Program under Scientific Permit in the Antarctic (JARPA) surveys (1989/90-2004/05), but are substantially lower than sighting rates (3.7-97.0) recorded for other populations of blue whales in the remainder of the Indian Ocean, around southern Australia and in Chilean waters.

Circumpolar estimates for CPI and CPII differ little from previous estimates (Branch and Butterworth, 2001a; Branch and Rademeyer, 2003), but the CPIII estimate of 2,280 (CV=0.36) is substantially larger than the 1,069 (CV=0.45) in Branch and Butterworth (2001a) and the 1,671 (CV=0.42) in Branch and Rademeyer (2003). There are two reasons for the increase: (1) the previous estimates were for areas that covered only 68% (Branch and Butterworth, 2001a) and 91% (Branch and Rademeyer, 2003) of the region south of 60°S; and (2) Area V was resurveyed in 2001/02 to 2003/04 and the new estimate of 765 replaced the previous estimate of 260 from 1991/92.

Antarctic blue whales were sighted throughout the Antarctic, so it is not surprising that the abundance estimates are spread among all of the IWC Management Areas. The highest historical catches were taken from Areas I-III, which have lower current abundances of Antarctic blue whales than Areas IV-VI. This may suggest that the extent of depletion was greater in Areas I-III, but the evidence for this is weak given the great uncertainty around the abundance estimates. JARPA estimates for Areas IV and V are also highly uncertain (Matsuoka *et al*., 2006), (Fig. 4).

Table 2

Components of abundance estimates for each survey. Indicated for each stratum are the stratum name, vessel, area (A), number of transects (N_L), number of schools sighted during primary search effort (n), number of schools sighted after smearing and truncation (n_s), search effort (L), sighting rate (n_s/L), and estimates of abundance in each stratum (N). Strata that were surveyed by more than one vessel have the same number in the 'Ave' column.

Stratum	IWC Area	Year	Vessel	Stratum	A (n.mile^2)	N_L	n	n_s	L (n.mile)	$n_s/L*10^3$	CV	N	CV	Ave
1	IV	1978/79	T16	EN	156,766	18	0	0.0	2,155.5	0.00	0.00	0	0.00	
2	IV	1978/79	T16	W1N	39,256	2	0	0.0	222.2	0.00	0.00	0	0.00	1
3	IV	1978/79	T16	W1S	20,389	5	0	0.0	200.6	0.00	0.00	0	0.00	
4	IV	1978/79	T16	W2N	153,914	3	0	0.0	384.7	0.00	0.00	0	0.00	2
5	IV	1978/79	T16	W2S	29,600	12	1	1.0	1,073.3	0.93	1.03	13	1.04	3
6	IV	1978/79	T18	ES	27,571	16	0	0.0	1,436.6	0.00	0.00	0	0.00	
7	IV	1978/79	T18	W1N	39,256	6	0	0.0	685.3	0.00	0.00	0	0.00	1
8	IV	1978/79	T18	W2N	153,914	11	0	0.0	1,212.5	0.00	0.00	0	0.00	2
9	IV	1978/79	T18	W2S	29,600	4	0	0.0	393.4	0.00	0.00	0	0.00	3
10	III	1979/80	K27	ES	41,772	20	3	3.0	1,346.5	2.23	0.68	43	0.70	
11	III	1979/80	K27	WN	200,724	16	1	1.0	2,014.9	0.50	1.03	46	1.04	
12	III	1979/80	T11	EN	217,865	20	1	1.0	2,636.7	0.38	0.99	38	1.00	
13	III	1979/80	T11	WS	33,619	19	1	1.0	968.2	1.03	0.82	16	0.84	
14	V	1980/81	K27	EN	208,159	14	0	0.0	877.3	0.00	0.00	0	0.00	
15	V	1980/81	K27	ES	98,766	5	0	0.0	439.6	0.00	0.00	0	0.00	4
16	V	1980/81	K27	WS	34,164	17	0	0.0	698.1	0.00	0.00	0	0.00	
17	V	1980/81	T11	ES	98,766	21	1	1.0	2,133.3	0.47	0.81	21	0.83	4
18	V	1980/81	T11	WN	139,191	15	1	1.0	1,151.6	0.87	0.80	56	0.83	
19	II	1981/82	SM1	ES	29,633	18	1	1.0	1,162.9	0.86	0.99	12	1.01	
20	II	1981/82	SM1	W1N	135,504	10	0	0.0	1,064.9	0.00	0.00	0	0.00	
21	II	1981/82	SM1	W2S	52,096	10	0	0.0	920.6	0.00	0.00	0	0.00	5
22	II	1981/82	SM2	EN	145,063	17	0	0.0	1,748.8	0.00	0.00	0	0.00	
23	II	1981/82	SM2	W1S	35,725	9	0	0.0	872.2	0.00	0.00	0	0.00	
24	II	1981/82	SM2	W2S	52,096	12	1	1.0	812.4	1.23	1.17	30	1.18	5
25	I	1982/83	SM1	ES	33,050	15	1	1.0	928.0	1.08	0.95	16	0.97	
26	I	1982/83	SM1	WN	163,926	15	0	0.0	1,426.1	0.00	0.00	0	0.00	
27	I	1982/83	SM2	EN	149,433	17	0	0.0	1,054.4	0.00	0.00	0	0.00	
28	I	1982/83	SM2	WS	25,596	19	1	1.0	1,414.8	0.71	1.27	8	1.29	
29	VI	1983/84	K27	EMS	158,893	5	1	1.0	1,094.4	0.91	1.67	67	1.68	
30	VI	1983/84	K27	WN	207,721	5	0	0.0	875.6	0.00	0.00	0	0.00	
31	VI	1983/84	SM1	EN	202,108	5	0	0.0	911.6	0.00	0.00	0	0.00	
32	VI	1983/84	SM2	WMS	156,457	5	2	2.0	1,309.0	1.53	0.72	110	0.75	
1	V	1985/86	K27	EN	279,611	16	0	0.0	1,757.7	0.00	0.00	0	0.00	
2	V	1985/86	K27	WS	104,814	28	4	3.9	1,596.8	2.45	1.06	113	1.11	
3	V	1985/86	SM1	EM	165,912	20	2	2.0	1,866.4	1.07	0.83	78	0.90	
4	V	1985/86	SM1	WM	166,349	8	0	0.0	850.0	0.00	0.00	0	0.00	
5	V	1985/86	SM2	ES	107,717	22	3	1.0	1,737.8	0.56	0.74	27	0.81	
6	V	1985/86	SM2	WN	139,065	10	0	0.0	1,121.5	0.00	0.00	0	0.00	
7	II	1986/87	K27	ES1	23,142	8	0	0.0	527.6	0.00	0.00	0	0.00	
8	II	1986/87	K27	WS1	10,270	4	1	1.0	185.5	5.39	1.08	24	0.35	
9	II	1986/87	K27	WS2	21,143	4	0	0.0	239.7	0.00	0.00	0	0.00	6
10	II	1986/87	K27	WS3	79,605	15	0	0.0	1,014.8	0.00	0.00	0	0.00	7
11	II	1986/87	K27	EN	124,057	7	1	1.0	965.9	1.01	0.98	55	1.04	
12	II	1986/87	SM1	EBAY	15,242	7	0	0.0	232.2	0.00	0.00	0	0.00	
13	II	1986/87	SM1	ES2	44,975	29	3	3.0	1,287.8	2.33	0.69	46	0.77	
14	II	1986/87	SM1	WBAY	11,505	3	0	0.0	166.4	0.00	0.00	0	0.00	
15	II	1986/87	SM1	WN	95,361	6	0	0.0	516.6	0.00	0.00	0	0.00	
16	II	1986/87	SM2	EM	69,908	9	0	0.0	1,445.6	0.00	0.00	0	0.00	
17	II	1986/87	SM2	WS2	21,143	3	0	0.0	234.6	0.00	0.00	0	0.00	6
18	II	1986/87	SM2	WS3	79,605	19	0	0.0	1,119.8	0.00	0.00	0	0.00	7
19	III	1987/88	SM1	ES	87,677	15	1	1.0	1,196.0	0.84	0.78	32	0.85	
20	III	1987/88	SM1	WN	148,821	13	0	0.0	857.3	0.00	0.00	0	0.00	
21	III	1987/88	SM2	EN	168,881	14	0	0.0	1,086.7	0.00	0.00	0	0.00	
22	III	1987/88	SM2	WS	74,351	21	3	3.0	1,247.3	2.41	0.88	79	0.94	
23	IV	1988/89	SM1	BS	6,520	4	0	0.0	231.9	0.00	0.00	0	0.00	
24	IV	1988/89	SM1	EN	181,166	12	0	0.0	1,116.3	0.00	0.00	0	0.00	
25	IV	1988/89	SM1	WS	58,693	10	0	0.0	483.5	0.00	0.00	0	0.00	
26	IV	1988/89	SM2	BN	17,486	15	0	0.0	627.7	0.00	0.00	0	0.00	
27	IV	1988/89	SM2	ES	52,441	9	0	0.0	554.3	0.00	0.00	0	0.00	
28	IV	1988/89	SM2	WN	156,617	12	0	0.0	1,431.9	0.00	0.00	0	0.00	
29	I	1989/90	SM1	ESBAY	62,594	24	0	0.0	1,386.7	0.00	0.00	0	0.00	
30	I	1989/90	SM1	WN	168,761	13	1	1.0	1,167.1	0.86	1.03	64	1.09	
31	I	1989/90	SM2	EN	153,029	14	0	0.0	1,429.8	0.00	0.00	0	0.00	
32	I	1989/90	SM2	WS	45,128	30	2	1.5	1,433.1	1.03	0.61	21	0.70	

Cont.

Stratum	IWC Area	Year	Vessel	Stratum	A (n.mile^2)	N_L	n	n_s	L (n.mile)	$n_s/L*10^3$	CV	N	CV	Ave
33	VI	1990/91	SM1	EN	191,954	7	0	0.0	666.6	0.00	0.00	0	0.00	
34	VI	1990/91	SM1	WS	45,414	14	2	1.0	950.1	1.05	0.75	21	0.83	
35	VI	1990/91	SM2	ES	108,268	9	0	0.0	952.9	0.00	0.00	0	0.00	
36	VI	1990/91	SM2	WN	211,788	9	0	0.0	1,043.4	0.00	0.00	0	0.00	
1	V	1991/92	SM1	EN	165,429	17	2	1.7	1,008.8	1.67	0.77	127	0.82	
2	V	1991/92	SM1	WS	58,643	15	1	1.0	748.2	1.34	0.63	36	0.69	
3	V	1991/92	SM2	ES	82,039	22	0	0.0	1,416.4	0.00	0.00	0	0.00	
4	V	1991/92	SM2	WN	137,734	9	1	1.0	655.3	1.53	0.64	97	0.70	
5	III	1992/93	SM1	ES	23,207	23	1	0.0	893.4	0.00	0.00	0	0.00	
6	III	1992/93	SM1	WN	210,035	15	0	0.0	1,404.5	0.00	0.00	0	0.00	8
7	III	1992/93	SM1	WS	61,527	3	0	0.0	143.0	0.00	0.00	0	0.00	9
8	III	1992/93	SM2	EN	150,547	9	0	0.0	1,101.2	0.00	0.00	0	0.00	
9	III	1992/93	SM2	WS	61,527	31	5	5.0	1,774.6	2.82	0.53	80	0.60	9
10	III	1992/93	SM2	WN	210,035	1	0	0.0	134.2	0.00	0.00	0	0.00	8
11	I	1993/94	SM1	WS	50,596	23	3	3.0	1,068.3	2.81	1.02	66	1.06	
12	I	1993/94	SM1	EN	293,196	22	0	0.0	1,581.8	0.00	0.00	0	0.00	
13	I	1993/94	SM2	WN	251,735	16	0	0.0	1,134.0	0.00	0.00	0	0.00	
14	I	1993/94	SM2	ES	72,249	20	0	0.0	1,076.4	0.00	0.00	0	0.00	
15	III	1994/95	SM1	WS	51,938	23	4	3.7	919.6	3.97	0.74	95	0.79	
16	III	1994/95	SM1	EN	146,681	15	2	2.0	1,154.5	1.73	0.69	117	0.75	
17	III	1994/95	SM2	WN	148,803	14	0	0.0	921.6	0.00	0.00	0	0.00	
18	III	1994/95	SM2	ES	60,046	17	1	1.0	899.2	1.11	0.92	31	0.96	
19	III	1994/95	SM2	PRYD	21,096	8	0	0.0	414.2	0.00	0.00	0	0.00	
20	VI	1995/96	SM1	WS	34,051	19	0	0.0	738.9	0.00	0.00	0	0.00	
21	VI	1995/96	SM1	EN	242,073	21	4	4.0	1,045.3	3.83	0.66	427	0.72	
22	VI	1995/96	SM2	WN	97,945	9	0	0.0	528.5	0.00	0.00	0	0.00	
23	VI	1995/96	SM2	ES	72,349	19	1	1.0	1,068.5	0.94	0.88	31	0.92	
24	II	1996/97	SM1	ES	52,534	38	3	2.0	1,229.2	1.63	0.86	39	0.90	
25	II	1996/97	SM1	WN	113,687	10	0	0.0	463.9	0.00	0.00	0	0.00	
26	II	1996/97	SM2	EN	241,928	32	0	0.0	1,260.4	0.00	0.00	0	0.00	
27	II	1996/97	SM2	WS	23,028	15	2	2.0	384.5	5.20	0.37	55	0.46	
28	II	1997/98	SM1	WS	32,620	17	0	0.0	490.3	0.00	0.00	0	0.00	
29	II	1997/98	SM1	EN1	84,726	12	1	1.0	581.1	1.72	0.83	67	0.88	
30	II	1997/98	SM1	ES2	10,451	9	0	0.0	226.3	0.00	0.00	0	0.00	
31	II	1997/98	SM1	EN2	80,013	4	0	0.0	202.1	0.00	0.00	0	0.00	10
32	II	1997/98	SM2	WN	52,135	8	1	1.0	493.3	2.03	0.86	49	0.91	
33	II	1997/98	SM2	ES1	47,036	16	4	4.0	741.5	5.40	0.93	117	0.97	
34	II	1997/98	SM2	EN2	80,013	4	0	0.0	330.8	0.00	0.00	0	0.00	10
35	IV	1998/99	SM1	WS	42,605	26	0	0.0	850.0	0.00	0.00	0	0.00	
36	IV	1998/99	SM1	EN	169,387	25	3	3.0	1,136.1	2.63	0.55	205	0.62	
37	IV	1998/99	SM2	WN	105,396	18	1	1.0	637.2	1.57	0.98	76	1.02	
38	IV	1998/99	SM2	ES	70,193	50	0	0.0	1,241.6	0.00	0.00	0	0.00	
39	IV	1998/99	SM1	ES	70,193	2	0	0.0	52.5	0.00	0.00	0	0.00	
40	I	1999/00	SM1	WS	20,506	13	0	0.0	446.9	0.00	0.00	0	0.00	
41	I	1999/00	SM1	EN	57,309	11	0	0.0	417.7	0.00	0.00	0	0.00	
42	I	1999/00	SM2	WN	110,906	11	0	0.0	664.4	0.00	0.00	0	0.00	
43	I	1999/00	SM2	ES	23,632	11	0	0.0	298.0	0.00	0.00	0	0.00	
44	VI	2000/01	SM1	WN	252,078	12	0	0.0	514.0	0.00	0.00	0	0.00	11
45	VI	2000/01	SM1	WS	43,916	16	0	0.0	446.5	0.00	0.00	0	0.00	12
46	VI	2000/01	SM2	WN	252,078	21	0	0.0	710.3	0.00	0.00	0	0.00	11
47	VI	2000/01	SM2	WS	43,916	16	2	2.0	311.5	6.42	0.38	130	0.47	12
48	I	2000/01	SM1	EN	127,789	19	0	0.0	700.8	0.00	0.00	0	0.00	13
49	I	2000/01	SM2	EN	127,789	2	0	0.0	37.3	0.00	0.00	0	0.28	13
50	I	2000/01	SM2	ES	29,080	20	1	1.0	542.7	1.84	0.66	25	0.72	
51	V	2001/02	SM1	WS	34,886	21	2	2.0	550.4	3.63	0.50	59	0.57	
52	V	2001/02	SM1	ES	26,099	11	5	3.5	292.9	12.08	0.54	146	0.60	14
53	V	2001/02	SM2	WN	46,333	7	0	0.0	438.5	0.00	0.00	0	0.00	
54	V	2001/02	SM2	EN	83,082	8	0	0.0	486.4	0.00	0.00	0	0.00	
55	V	2001/02	SM2	ES	26,099	3	0	0.0	131.2	0.00	0.00	0	0.00	14
56	V	2002/03	SM1	ES	126,870	24	1	1.0	1,018.0	0.98	1.03	58	1.07	
57	V	2002/03	SM1	EN	135,038	6	0	0.0	183.9	0.00	0.00	0	0.00	15
58	V	2002/03	SM1	W2N	101,237	11	0	0.0	459.1	0.00	0.00	0	0.00	16
59	V	2002/03	SM1	W1S	22,128	12	1	1.0	352.0	2.84	1.67	29	1.69	
60	V	2002/03	SM2	EN	135,038	23	0	0.0	861.6	0.00	0.00	0	0.00	15
61	V	2002/03	SM2	W2S	21,327	27	2	2.0	526.0	3.80	0.85	37	0.89	
62	V	2002/03	SM2	W1N	75,395	13	0	0.0	466.0	0.00	0.00	0	0.00	
63	V	2002/03	SM2	W2N	101,237	4	0	0.0	43.8	0.00	0.00	0	0.00	16

Cont.

Stratum	IWC Area	Year	Vessel	Stratum	A (n.mile^2)	N_L	n	n_s	L (n.mile)	$n_s/L*10^3$	CV	N	CV	Ave
64	V	2003/04	SM2	N1	123,227	13	0	0.0	489.1	0.00	0.00	0	0.00	
65	V	2003/04	SM1	N2	95,445	18	0	0.0	587.2	0.00	0.00	0	0.00	
66	V	2003/04	SM1	N3	14,598	4	4	4.0	153.0	26.14	1.13	176	0.28	
67	V	2003/04	SM1	ROSS	56,444	23	0	0.0	544.6	0.00	0.00	0	0.00	17
68	V	2003/04	SM2	ROSS	56,444	15	0	0.0	556.7	0.00	0.00	0	0.00	17
69	V	2003/04	SM1	MID	131,782	18	7	6.9	707.3	9.82	0.73	597	0.78	18
70	V	2003/04	SM2	MID	131,782	23	3	3.0	881.5	3.40	0.51	207	0.58	18

Table 3

Estimates of search half-width (w_s), mean school size ($E[s]$) and their associated CVs for each circumpolar set of surveys. Estimates differ slightly for each category of the CPIII estimates due to slight changes in how the strata were divided and which strata were included to obtain the estimates.

Surveys	w_s	CV	$E[s]$	CV
CPI all	1.966	0.110	1.81	0.149
CPII all	1.624	0.277	1.43	0.208
CPIII circumpolar	1.700	0.286	1.59	0.105
CPIII IWC areas	1.736	0.280	1.57	0.101
CPIII individual surveys	1.854	0.262	1.71	0.102

Comparable abundance estimates are difficult to obtain from the circumpolar sets of surveys, primarily because of differences in percent coverage, but also because of changes in survey design (Branch and Butterworth, 2001b; Matsuoka *et al.*, 2003). A simple method was used to account for the unsurveyed areas south of 60°S; it was assumed that unsurveyed northern strata contained the same density of blue whales as in the corresponding northern strata. This method increases the CPI estimate by 31% and the CPII estimate by 23% and has been used in previous IDCR/SOWER assessments for blue and minke whales (Branch and Butterworth, 2001a;2001b; Branch and Rademeyer, 2003). More sophisticated methods of comparing the circumpolar estimates are beyond the scope of this paper, but could include estimating abundance south of a northern boundary common to all CP sets, or fitting a model to the downward trend in density with increasing distance from the ice edge. It is expected that these more sophisticated methods would result in a higher ratio between CPIII abundance estimates and those from CPI or CPII.

The rate of increase from the comparable-areas circumpolar estimates is 8.2% per year, which is significantly greater than zero (95% CI=1.6-14.8%). The validity of this rate of increase is subject to the reasonableness of the comparable-area CP estimates. However, it should be noted that the IWC's in-depth assessments of Antarctic minke whales have highlighted several reasons why the CPIII minke estimates are probably negatively biased compared to the CPII estimates (Branch, 2007b); if they are also applicable to blue whales, they would tend to increase the estimated rate of increase for blue whales if taken into account (Branch *et al.*, 2004). The estimated rate of increase is nearly identical to the 8.2% (95% CI=1.9-14.8%) obtained from a Bayesian assessment of Antarctic blue whales based on the IDCR/SOWER, JARPA and JSV data, when the rate of increase was weakly constrained by a Bayesian prior ~ U(-0.3, 0.3). The estimated rate of increase from the JARPA surveys is also similar: 7.4% per annum (CV=1.19) (Matsuoka *et al.*, 2006). These rates of increase are close to the maximum biologically possible (10.1-12.6%) for blue whales and humpback whales (Branch *et al.*, 2004; Brandao *et al.*, 2000; Clapham *et al.*, 2001; Clapham *et al.*, 2006).

In summary, the updated circumpolar estimate of abundance for Antarctic blue whales, following completion of CPIII, is 2,280 (95% CI=1,160-4,500). This estimate is negatively biased (perhaps by 20-30%) because some Antarctic blue whales remain north of 60°S during the survey time period and because some whales on the trackline are missed. The available evidence continues to support increases in this population, although the population still remains far below the pre-exploitation levels of 202,000-311,000 estimated in Branch *et al.* (2004).

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Table 4

Estimates of abundance obtained from each circumpolar set of surveys, with the associated CVs and 95% confidence intervals obtained using the method of Buckland (1992). CPIII estimates exclude the 1991/92 survey.

		Circumpolar estimates			Adjusted simply for comparable areas		
Circumpolar set	Mid-year	N	CV	95% CI	N	CV	95% CI
CPI	1980/81	453	0.40	(210; 970)	592	0.40	(280; 1,270)
CPII	1987/88	559	0.47	(230; 1,350)	686	0.47	(280; 1,660)
CPIII	1997/98	2,280	0.36	(1,160; 4,500)	2,249	0.36	(1,140; 4,440)

Table 5

Estimates of abundance for each IWC Management Area. Estimates from Area V in CPIII were obtained from complete coverage south of 60°S in 2001/02-2003/04, and were also repeated for the survey with incomplete coverage in 1991/92 (denoted by CPIII*).

					Estimates		Comparable areas	
IWC Area	CP set	Seasons	Long. range	Mid-year	*N*	CV	*N*	CV
Area I	CPI	1982/83	60	1982/83	25	0.80	25	0.80
(120°W-60°W)	CPII	1989/90	60	1989/90	84	0.91	178	1.03
	CPIII	1993/94	30					
		1999/00	20					
		2000/01	10	1997/98	88	0.85	88	0.85
Area II	CPI	1981/82	60	1981/82	26	0.81	26	0.81
(60°W-0°)	CPII	1986/87	60	1986/87	126	0.64	158	0.71
	CPIII	1996/97	25					
		1997/98	35	1997/98	298	0.55	268	0.58
Area III	CPI	1979/80	70	1979/80	143	0.52	219	0.61
(0°-70°E)	CPII	1987/88	70	1987/88	111	0.79	111	0.79
	CPIII	1992/93	40					
		1994/95	30	1993/94	166	0.60	166	0.60
Area IV	CPI	1978/79	60	1978/79	9	1.06	9	1.06
(70°E-130°E)	CPII	1988/89	60	1988/89	0	0.00	0	0.00
	CPIII	1994/95	10					
		1998/99	50	1997/98	419	0.51	419	0.51
Area V	CPI	1980/81	60	1980/81	73	0.68	110	0.73
(130°E-170°W)	CPII	1985/86	60	1985/86	218	0.75	218	0.75
	CPIII*	1991/92	60	1991/92	260	0.56	534	0.61
	CPIII	2001/02	20					
		2002/03	20					
		2003/04	20	2002/03	765	0.43	765	0.43
Area VI	CPI	1983/84	50	1983/84	177	0.81	177	0.81
(170°W-120°W)	CPII	1990/91	50	1990/91	21	0.90	21	0.90
	CPIII	1996/96	30					
		2000/01	20	1998/99	500	0.68	500	0.68

Table 6

Estimates of abundance for each IWC survey.

Year	Area	Longitudes	*N*	CV
1978/79	IV	70°E-130°E	9	1.06
1979/80	III	0-70°E	143	0.52
1980/81	V	130°E-170°W	73	0.68
1981/82	II	60°W-0	26	0.81
1982/83	I	120°W-60°W	25	0.80
1983/84	VI	170°W-120°W	177	0.81
1985/86	V	130°E-170°W	218	0.75
1986/87	II	60°W-0	126	0.64
1987/88	III	0-70°E	111	0.79
1988/89	IV	70°E-130°E	0	0.00
1989/90	I	120°W-60°W	84	0.91
1990/91	VI	170°W-120°W	21	0.90
1991/92	V	130°E-170°W	260	0.56
1992/93	III	0°E-40°E	74	0.66
1993/94	I	110°W-60°W	66	1.09
1994/95	III+IV	40°E-80°E	243	0.56
1995/96	VI	170°W-140°W	459	0.73
1996/97	II	30°W-0	95	0.54
1997/98	II	60°W-25°W	233	0.65
1998/99	IV	80°E-130°E	282	0.60
1999/00	I	80°W-60°W	0	0.00
2000/01	VI+I	140°W-110°W	78	0.49
2001/02	V	130°E-150°E	159	0.52
2002/03	V	150°E-170°W	124	0.74
2003/04	V	170°E-170°W	557	0.49

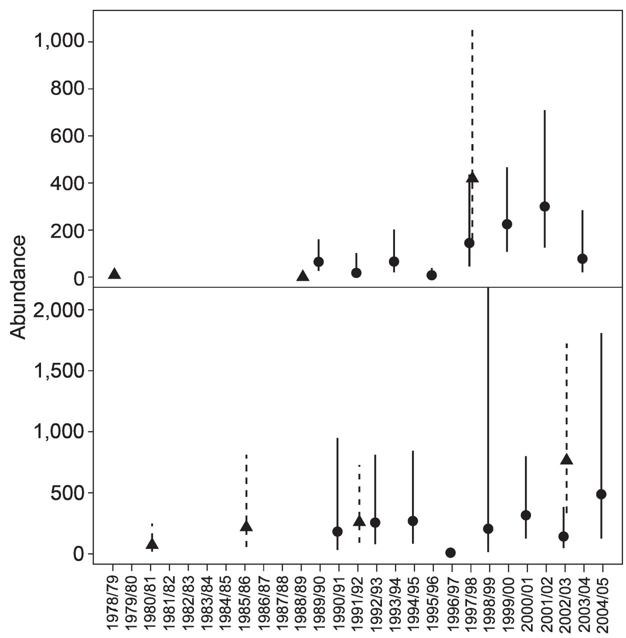

Fig. 4. Comparison of comparable-areas abundance estimates for blue whales from the IDCR/SOWER surveys and those from the JARPA surveys for Area IV (top figure) and Area V (bottom figure). The 95% CIs are shown for both sets of estimates. JARPA estimates are taken from Matsuoka *et al*. (2006).

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