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 and SOWER austral summer surveys were 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 whales were only rarely sighted but were present around the Antarctic. Average sighting rates (schools per 1,000 km of primary search effort) were 0.24 (CPI), 0.36 (CPII) and 0.78 (CPIII). Respective circumpolar abundance estimates were 453 (CV=0.40), 559 (CV=0.47) and 2,280 (CV=0.36), with mid-years of 1980/81, 1987/88 and 1997/98. When adjusted simply for unsurveyed regions, the circumpolar rate of increase was 8.2% (95% CI 3.8–12.5%) per year, although they are still under 1% of their pre-exploitation abundance. These abundance estimates are negatively biased because they exclude some Antarctic blue whales that are north of 60°S, and because a low number of blue whales on the trackline may be missed. Additionally, estimates may include a small proportion of pygmy blue whales, probably less than 1%. Abundance estimates were also provided for each IWC Management Area and for each individual survey, but these have high associated uncertainty.

INTRODUCTION

Whaling reduced the once-vast numbers of blue whales to a small fraction of their original levels (Clapham *et al.*, 1999). Two blue whale subspecies occur in the Southern Hemisphere: Antarctic (or true) blue whales (*Balaenoptera musculus intermedia*), and pygmy blue whales (*B. m. brevicauda*). Antarctic blue whales are the main subject of this paper. Based on existing estimates of abundance, they originally numbered 239,000 (95% Bayesian interval 202,000–311,000) but extensive whaling from 1905–1973 depleted them to a low of 360 (95% Bayesian interval 150–840); despite statistically significant evidence for subsequent increases, their numbers are still below 1% of pre-exploitation levels (Branch *et al.*, 2004). The status of pygmy blue whales is poorly known, but compared to Antarctic blue whales their current sighting rates are higher, and their exploitation history shorter, thus they are probably less depleted (Branch *et al.*, in press).

The best available estimates of Antarctic blue whales come from the IWC's International Decade for Cetacean Research (IDCR) and Southern Ocean Whale Ecosystem Research (SOWER). These ship-borne surveys 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 circled the Antarctic—in 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 are excluded when obtaining abundance estimates (e.g. Branch and Butterworth, 2001a,b; Branch, 2006c).

The most recent estimates of blue whales from the IDCR/SOWER surveys were 440 (CV = 0.41) for CPI and 550 (CV = 0.48) for CPII (Branch and Butterworth, 2001a), but no estimates have been provided for the complete set of CPIII surveys (i.e. including all surveys to 2003/04). The CPIII estimate up to 1997/98 was 1,100 (CV=0.45) (Branch and Butterworth, 2001a), and up to 2001/02 was 1,700 (CV = 0.42) (Branch and Rademeyer, 2003). However, since these estimates were published, 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. This region was surveyed in 1991/92 but coverage was incomplete in the northern areas south of 60°S.

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); but evidence from length frequencies and from ovarian corpora data suggests that for females (and probably for males) the upper limit is actually 1% (Branch, 2006b; Branch *et al.*, accepted).

This paper presents final abundance estimates from the IDCR/SOWER surveys to date. Previous estimates were provided at the circumpolar level only, but here, estimates are also calculated for individual surveys and for IWC Management Areas.

METHODS

Only a cursory overview of the methods is provided as they have been detailed already for humpback whales (Branch, 2006a). Data extraction and abundance estimation are mostly automated in the IWC's Database Estimation System Software (DESS; Strindberg and Burt, 2004), but substantial post-DESS manipulation is required to divide estimates among the IWC

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Management Areas and to account for non-standard data collection. DESS version 3.42 (April 2006) is used here. Methods differ slightly from the most recent published paper on Antarctic blue whales, as outlined in Table 1.

Survey design

Overviews of the surveys have been published (Branch and Butterworth, 2001b; Matsuoka *et al.*, 2003). Survey design differed among the three CPs, thus it is difficult to compare abundance estimates between CPs (Figs 1–2). In CPI, one vessel generally followed the pack ice while the other surveyed in the turret-shaped pattern, leaving unsurveyed regions both between the northern and southern strata, and between the northern survey boundary and 60°S. In CPII, the surveys normally 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 took 13 years compared to the 6 years for CPI and CPII, and completely surveyed the region south of 60°S to the ice edge. Additionally, in CPIII, some longitudinal regions were surveyed multiple times. Survey modes also differed among the CPs: in CPI the surveys were conducted only in closing mode, while in the other two CPs the surveys alternated between closing mode and independent observer (IO) mode, where the vessel did not leave the trackline to confirm the species identity and school size of the sighting.

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. Previous analyses have also combined these data; and sensitivities to this kind of pooling has shown that estimates obtained separately from each mode are similar (Branch and Butterworth, 2001a). Many different types of activity codes have been recorded over the years; 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 in 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 96 (blue whale, probably pygmy) or code 56 (pygmy blue whale). 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.

Abundance estimation

Abundance estimates were obtained using the standard distance sampling formula:

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

where:
N = abundance estimate
A = area of stratum (n.miles^2)
$\bar{s}$ = mean school size
n = number of schools sighted during primary search effort
w_s = effective search half-width for schools (n.miles)
L = primary search effort (n.miles)

The CV for N was calculated from:

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

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. In analyses for minke whales and humpback whales, smearing parameters were estimated from the data (Branch, 2006a,c). 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.mi (distance), the values used by Branch and Butterworth (2001a) for blue whales. The detection function $f(y)$ was fitted to these data based on the perpendicular distances of the sightings.

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

where $g(y)$ is the probability that a school at a perpendicular distance *y* from the trackline will be sighted, and $a \geq 0.0001$ n.miles and $b \geq 1$ are parameters to be estimated. In the estimates, it was assumed that $g(0) = 1$, i.e. that all schools on the trackline were sighted.

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 by CP set to estimate search half-width and mean school size.

Combining estimates
Surveys in 1984/85, 2004/05 and 2005/06 were omitted because these were devoted primarily to experiments. For CPI and CPII, circumpolar estimates were easy to obtain, but during CPIII some surveys overlapped in longitudinal coverage and sometimes covered two Management Areas, requiring the strata to be split and the area, survey effort and sightings divided between new substrata as outlined in Branch (2006a).

The differing nature of the three CPs poses several issues when comparing estimates. Major issues include the different survey design, survey modes, and 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. Only the unsurveyed northern areas are taken into account to obtain estimates from 'comparable areas'. The simple assumption employed by Branch and Butterworth (2001a,b) is used here: that the density in the unsurveyed northern areas is the same as in the adjacent northern strata.

Circumpolar sighting rates
For comparison with other surveys in the Southern Hemisphere listed in Branch *et al*. (in press), the number of schools sighted per 1,000 km of primary effort was calculated for all strata surveyed during 1978/79–1983/84 (CPI), 1985/86–1990/91 (CPII) and 1991/92–2003/04 (CPIII). For these calculations, sighting numbers were neither smeared nor truncated at 3.0 n.miles.

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

$$\ln \hat{N}_{1981} = \ln N_0$$
$$\ln \hat{N}_{t+1} = \ln \hat{N}_t + r$$

where $\hat{N}_t$ is the model-estimated abundance in year *t*, N_0 is the abundance in the starting year, and *r* is the annual rate of increase.

The CV of the abundance estimates is approximately equal to the standard deviation in log-space, therefore maximum likelihood estimates (MLEs) for N_0 and *r* were obtained by minimizing the following negative log likelihood expression (ignoring constant terms):

$$-\ln L = \sum_t \frac{(N_t - \hat{N}_t)^2}{2CV_t^2}$$

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 from the MLE (Hilborn and Mangel, 1997).

RESULTS

Survey coverage and primary effort distribution
Blue whales were sighted around the Antarctic, usually close to the pack ice, and were also sighting occasionally during transits through regions of pygmy blue whale habitat (Figure 1). Survey coverage of the ice-free area south of 60°S was most extensive in CPIII, when 99.7% of the area was covered, compared to 64.3% (CPI) and 79.5% (CPII) in the earlier surveys. Primary survey effort and associated sightings are plotted in Figure 2a-c.

Abundance estimates

Components of the abundance estimates are presented in Table 2, and estimates of search half width and estimated school size in Table 3. Search half width and estimated school size were highest in CPI, but were not markedly different from the CPII and CPIII estimates. The detection function fits to the sighting distributions in each CP are given in Figures 3a-c. Fits were poor in CPI and CPII due to the small number of sightings in those years.

Circumpolar abundance estimates increased by a small amount from CPI to CPII but were markedly higher for CPIII, even when the estimates were simply adjusted for unsurveyed areas (Table 4). Abundance estimates were 453 (CV = 0.40) for CPI, 559 (CV = 0.47) for CPII and 2,280 (CV = 0.36) for CPIII.

Simple abundance estimates were highest in CPIII for all IWC Management Areas, but when the estimates were adjusted to comparable areas, this pattern did not remain for all Areas (Table 5). Area V was estimated to contain the highest abundance of blue whales.

Blue whales were recorded at during all surveys except 1988/89 and 1999/00; the highest estimated abundance for a single survey was 557 in 2003/04 (Table 6).

Estimated rate of increase

Overall sighting rates (number of schools per 1,000 km of primary effort) increased over time from 0.24 (CPI) to 0.36 (CPII) to 0.78 (CPIII). The estimated rate of increase based on circumpolar abundance estimates was 8.2% per annum (95% CI: 3.8–12.5%).

DISCUSSION

The IDCR/SOWER surveys provide the most complete estimates that are available 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 were north of 60°S during the survey months, although some of these catches were pygmy blue whales (Horwood, 1986). Unlike Antarctic minke whales (*Balaenoptera bonaerensis*), Antarctic blue whales seldom, if ever, venture into the unsurveyed southern pack ice. 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. Given the great visibility of blue whale cues and the frequency of cue production, $g(0)$ is probably between 0.9 and 1 (Best *et al.*, 2003; Calambokidis and Barlow, 2004), thus the bias from this assumption is relatively small.

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.*, accepted) demonstrates that this proportion is even smaller, no more than 1%, for females in the historical catches. As there is no evidence in the corpora data that this proportion 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.*, accepted), it is likely that the current proportion of pygmy blue whales south of 60°S is less than 1%.

Estimated sighting rates (schools per 1,000 km of primary effort) increased from 0.24 (CPI) to 0.36 (CPII) to 0.78 (CPIII). These sighting rates are similar to those from other studies in the Antarctic: 0.17 from the earlier JSV data (1965/66–1988/89) and 0.34 from JARPA surveys (1989/90–2004/05), but are substantially lower than sighting rates (2.0–52.4) recorded for other populations of blue whales in the remainder of the Indian Ocean, around southern Australia, and in Chilean waters (Branch *et al.*, in press).

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, first, the previous estimates relied on lower survey coverage of 68% (Branch and Butterworth, 2001a) and 91.1% (Branch and Rademeyer, 2003) of the region south of 60°S; second, 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 around the Antarctic, thus it is not surprising that the abundance estimates are spread among all of the IWC Management Areas. Highest historical catches were taken from Areas I–III, which have lower current abundances of Antarctic blue whales than Areas IV–VI. However, estimates are highly variable from year-to-year because of the low numbers of sightings, a feature also apparent in JARPA estimates for Areas IV and V (Matsuoka *et al.*, 2006), depicted in Figure 4.

Comparable abundance estimates are difficult to obtain from the circumpolar sets of surveys, because of changes in survey design, percent coverage, and type of survey mode (Branch and Butterworth, 2001b; Matsuoka *et al.*, 2003). A simple method was used to obtain comparable estimates: it was assumed that unsurveyed northern strata contained the same density of blue whales as in the corresponding northern strata. This method has been used in previous IDCR/SOWER assessments (Branch and Butterworth, 2001a; Branch and Rademeyer, 2003). There is a need to develop more sophisticated methods for comparability, but this is beyond the scope of this paper.

The rate of increase from the circumpolar estimates is 8.2% per year, which is significantly greater than zero (95% CI: 3.8–12.5%). The validity of the estimated rate of increase is subject to the comparability of the CP sets. However, it should be noted that in-depth assessments of the comparability of the CPs for Antarctic minke whales have focused on reasons why the CPIII estimates should be negatively biased compared to the CPII estimates (Branch, 2006d); thus the identified biases would tend to inflate the rate of increase for blue whales if taken into account (Branch *et al.*, 2004). The estimated rate of increase is similar to the 8.2% (95% credibility interval 1.9–14.8%) obtained from a Bayesian assessment of Antarctic blue whales based on the IDCR/SOWER, JARPA and JSV data, when the prior was U(-0.3, 0.3) (Branch *et al.*, 2004). The estimated rate of increase from the JARPA surveys is also similar: 7.4% per annum (CV = 1.19). These rates of increase are close to the maximum biologically possible (10.1–12.6%) for blue whales and humpback whales (Brandão *et al.*, 2000; Clapham *et al.*, 2001; Branch *et al.*, 2004; Clapham *et al.*, 2006).

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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% according to Branch and Butterworth (2001a)
Survey legs parallel to ice edge in 1988/89 and 1989/90	Included	Excluded	Decreases estimate by 2 whales (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 11 whales (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.miles	No effect since regression always positive for blue whales

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 school 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	
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
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), estimated school size ($E[s]$) and their associated CVs for each circumpolar set. 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

Table 4. Estimates of abundance obtained from each circumpolar set of surveys, and 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 equal 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; 1270)
CPII	1987/88	559	0.47	(230; 1350)	686	0.47	(280; 1660)
CPIII	1997/98	2,280	0.36	(1160; 4500)	2,249	0.36	(1140; 4440)

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 but 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/s	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

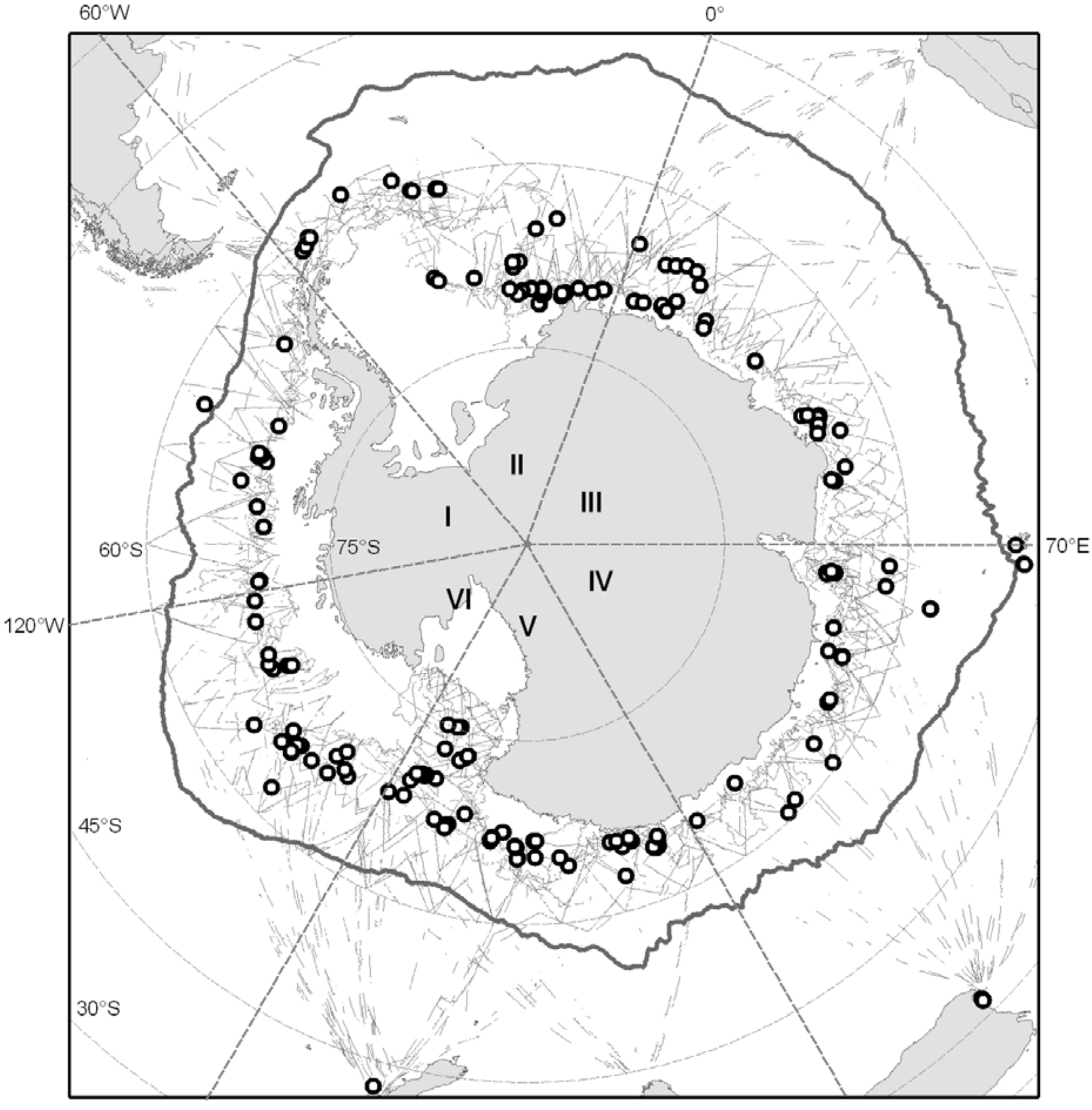

Figure 1. Primary effort (thin grey lines) and all sightings of blue whales (black circles) from the IDCR/SOWER surveys, 1978/79–2004/05. Plotted survey effort includes transits to and from the survey regions and survey years (1984/85, 2004/05) devoted primarily to experiments that are not included in the abundance estimates. Sightings include those made off effort and during refueling, 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 letters I–VI represent the IWC Management Areas.

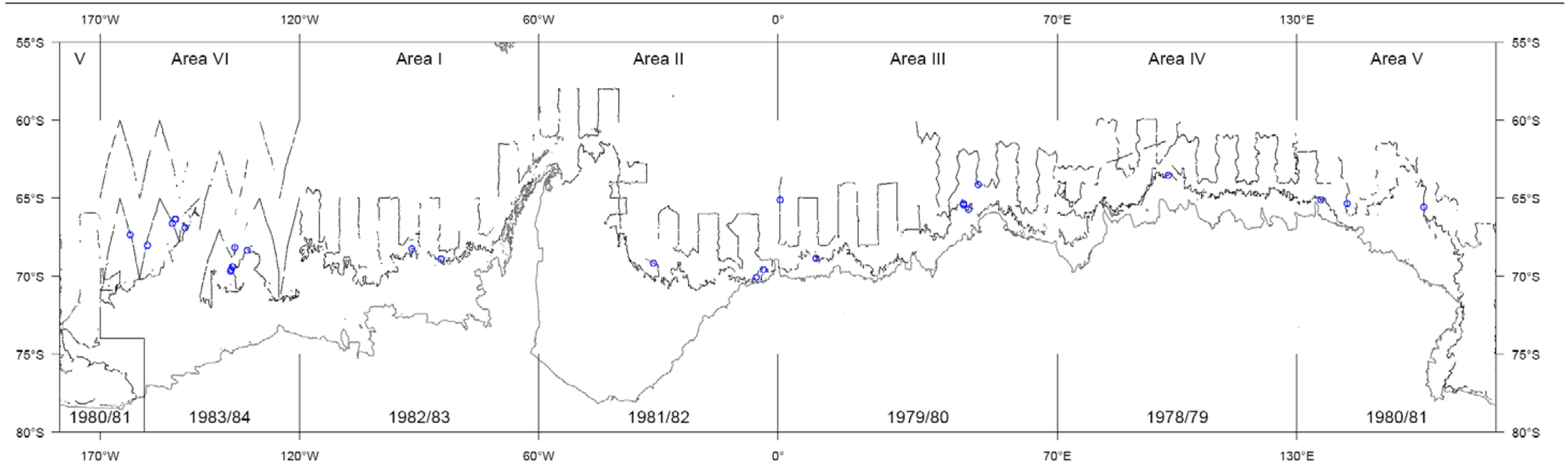

Figure 2a. Primary search effort during each of the surveys included in the first circumpolar set of surveys, CPI, and associated sightings of blue whales. Only the longitudinal regions included in the CPI estimate are depicted. Dashed lines on the bottom of the figure indicate longitudinal regions covered by each survey, while dashed lines at the top of the figure separate the IWC Management Areas.

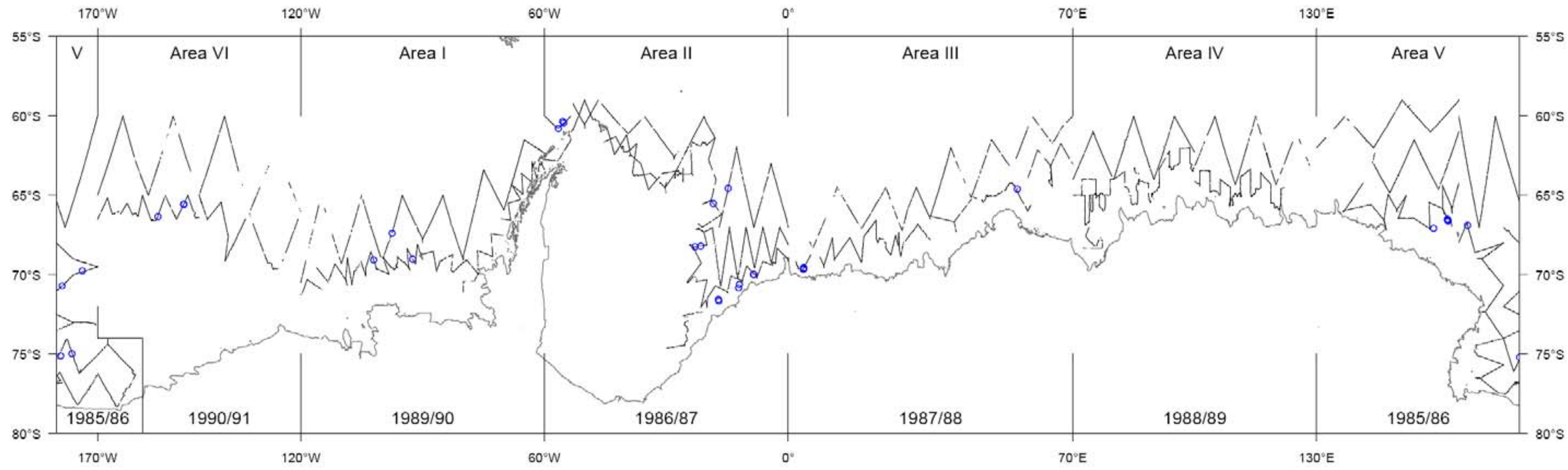

Figure 2b. Primary search effort during each of the surveys included in the second circumpolar set of surveys, CPII, and associated sightings of blue whales. Only the longitudinal regions included in the CPII estimate are depicted. Dashed lines on the bottom of the figure indicate longitudinal regions covered by each survey, while dashed lines at the top of the figure separate the IWC Management Areas.

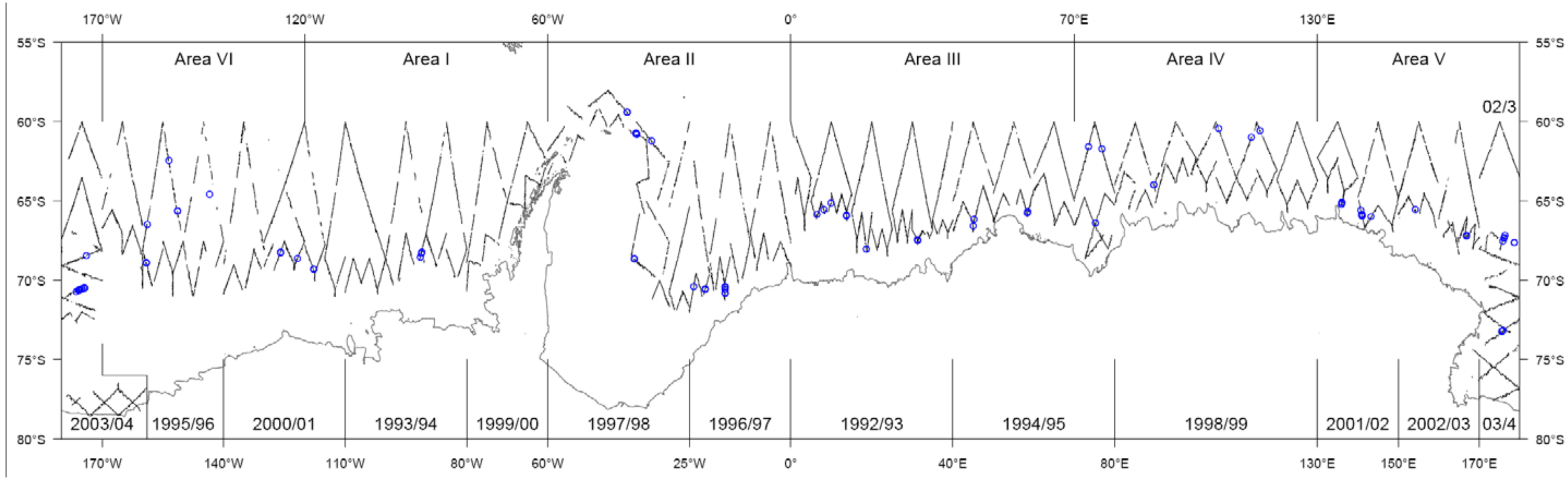

Figure 2c. Primary search effort (lines) during each of the surveys included in the third circumpolar set of surveys, CPIII, and associated sightings of blue whales (circles). Only the longitudinal regions included in the CPIII estimate are depicted. Dashed lines on the bottom of the figure indicate longitudinal regions covered by each survey, while dashed lines at the top of the figure separate the IWC Management Areas.

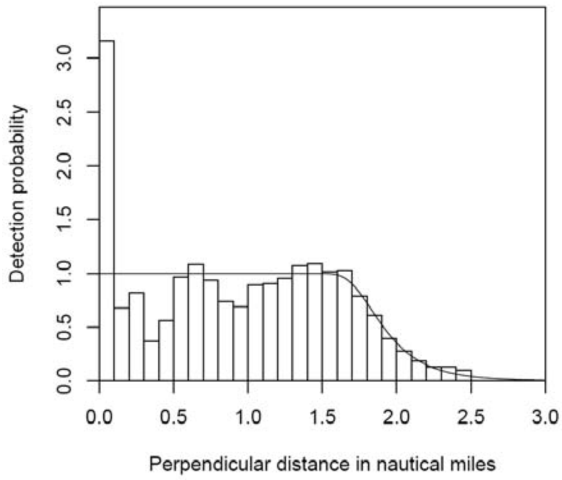

Figure 3a. Fit of the detection function to the smeared and truncated sightings during CPI.

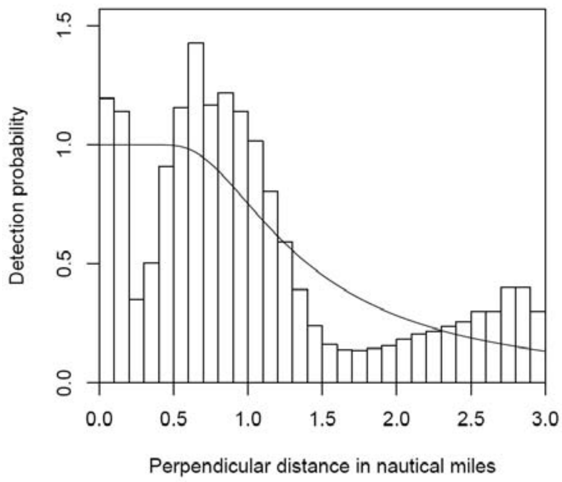

Figure 3b. Fit of the detection function to the smeared and truncated sightings during CPII.

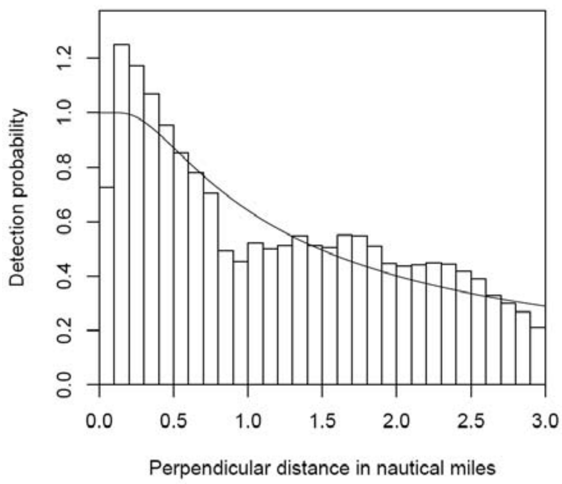

Figure 3c. Fit of the detection function to the smeared and truncated sightings during CPIII, for the survey-once circumpolar estimates.

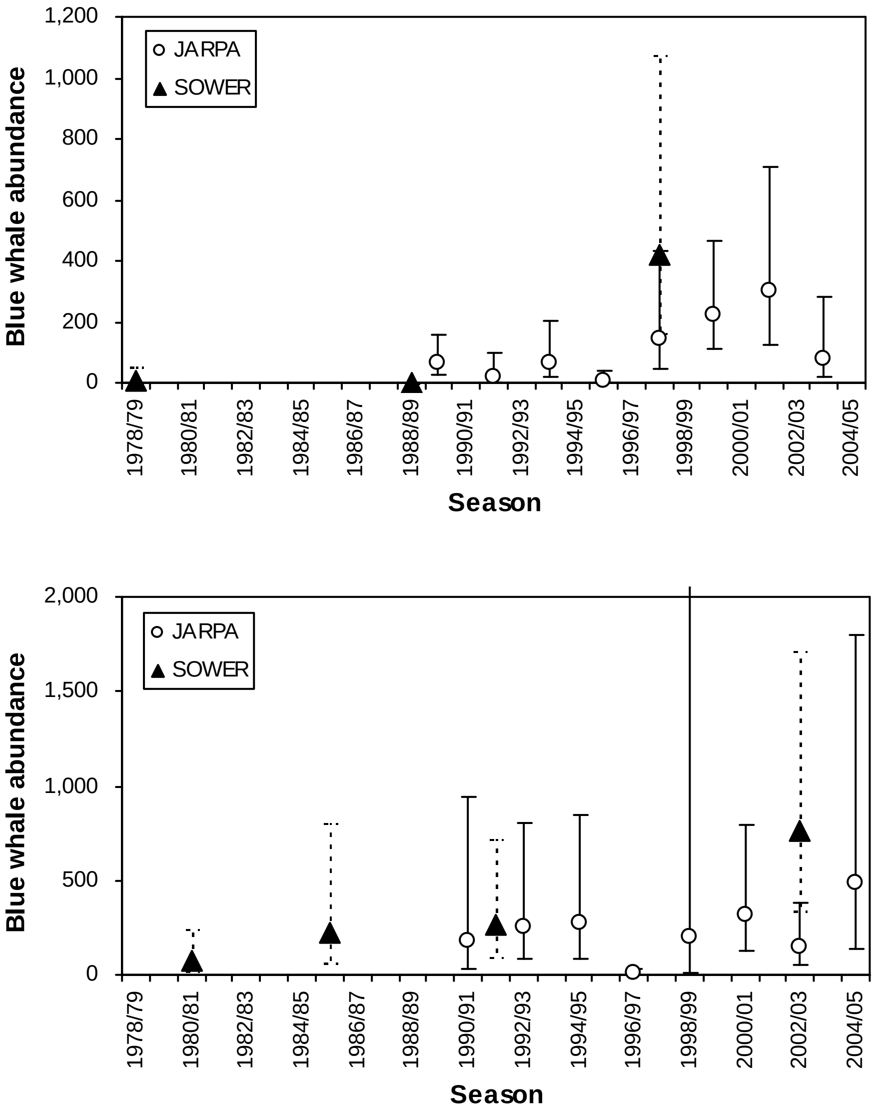

Figure 4. Comparison of abundance estimates for blue whales from the IDCR/SOWER surveys and those from the JARPA surveys for Area IV (top panel) and Area V (bottom panel). The 95% confidence intervals are shown for both sets of estimates.