Estimates of abundance south of 60°S for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys

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ABSTRACT

Estimates of abundance are calculated for six cetacean species in the Southern Ocean south of 60° in the austral summer, using the IWC database estimation package (DESS). The sightings data in DESS were collected during the 1978/79 to 1997/98 IWC/IDCR and SOWER circumpolar surveys. Abundance estimates are developed for the first (1978/79–1983/84), second (1985/86–1990/91) and currently incomplete third (1991/92–1997/98) circumpolar sets of surveys. The strata surveyed in these three sets cover about 65%, 81% and 68% respectively of the open ocean area south of 60°S. The surveys were designed for Antarctic minke whales and may not be optimal for all these species. Furthermore, the estimates presented below (CVs in brackets) should not necessarily be considered as estimates for the whole Southern Hemisphere.

Species	First circumpolar		Second circumpolar		Third circumpolar	
Blue whale	440	(0.41)	550	(0.48)	1,100	(0.45)
Fin whale	2,100	(0.36)	2,100	(0.45)	5,500	(0.53)
Sperm whale	5,400	(0.38)	10,000	(0.15)	8,300	(0.16)
Humpback whale	7,100	(0.36)	9,200	(0.29)	9,300	(0.22)
Killer whale	91,000	(0.34)	27,000	(0.26)	25,000	(0.23)
Southern bottlenose whale	-	-	72,000	(0.13)	54,000	(0.12)

Some results are also presented for hourglass dolphins and sei whales, but estimates of abundance are not considered reliable for those two species. Effective search half-width and mean school size were estimated by pooling across strata and years. Pooling is effected separately for each circumpolar set of surveys. Additional pooling across closing and passing modes did not introduce substantial bias. The most frequently sighted species were minke, southern bottlenose, sperm, humpback and killer whales; the effective search half-widths for all five increase over time. The sensitivity of the abundance estimates to a number of factors is investigated, none of which appears to impact the results substantially, except that the incorporation of 'like species' would increase the estimate for blue whales from the third circumpolar set of surveys by 25% and for fin whales by 61%. In general, the assumption that 100% of schools on the trackline are sighted introduces variable negative bias to estimates for all species. Only two significant trends in abundance over time (for comparable areas) were detected, but both may be artefacts of changes in survey design.

KEYWORDS: BLUE WHALE; FIN WHALE; SEI WHALE; SPERM WHALE; HUMPBACK WHALE; KILLER WHALE; HOURGLASS DOLPHIN; SOUTHERN BOTTLENOSE WHALE; SOUTHERN HEMISPHERE; SOUTHERN OCEAN; ANTARCTIC; ABUNDANCE ESTIMATE; SURVEY-VESSEL

INTRODUCTION

The International Whaling Commission (IWC) has conducted annual cetacean sighting surveys south of 60°S since 1978/79 as part of first the IDCR (International Decade of Cetacean Research) and then the SOWER (Southern Ocean Whale and Ecosystem Research) circumpolar programmes. In total, 23 shipborne surveys have been completed, which fall into three circumpolar sets: 1978/79-1983/84, 1985/86-1990/91 and 1991/92-2000/01 (still incomplete). The 1984/85 survey was devoted mostly to experiments and is normally excluded when estimating abundance (e.g. Brown and Butterworth, 1999). Although the primary aim of the surveys has been to estimate minke whale abundance, all cetacean sightings are recorded, which makes it possible to estimate abundance for species other than minke whales. This paper provides estimates for those cetacean species in the research area at the time of the surveys for which this seems appropriate, given the quantity of data available and information on their overall distribution in the Southern Ocean during the survey period. It is intended to be a companion paper to Branch and Butterworth (2001), which estimated minke whale abundance from these surveys. The sightings data have been encoded and validated up to 1997/98 and are contained in a database package DESS 3.0 (IWC Database-Estimation Software System v 3.0, Strindberg and Burt, 2000), which automates the process of abundance estimation. Results are purposefully restricted to outputs from the standard options available in DESS to ensure that they can be easily replicated and extended by other researchers. As a result, analysis options outside the scope of DESS have not been considered here (e.g. exploring a more flexible form for the detection function).

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Survey strategy and area covered

Up to four vessels were used in the early surveys, but two vessels (the *Shonan Maru* and *Shonan Maru 2*) have provided the majority of the data since 1981/82. From 1978/79-1982/83 the southern vessel generally followed the ice-edge, while the northern vessel followed a grid pattern, alternating legs of fixed longitude and latitude, thus leaving an unsurveyed stratum between the two vessels (Figs 1a-b). From 1983/84 onwards, a zigzag (or sawtooth) grid was used by the survey vessels, and this unsurveyed area was eliminated (Figs 1c-f).

As depicted in Figs 2a-c, the surveyed strata covered approximately 65% of the open ocean area south of 60°S in the first circumpolar set and 81% in the second circumpolar set of surveys (Butterworth *et al.*, 1994). Thus far about 68% of this area has been covered by the incomplete third circumpolar set, but this third set does range completely from the ice-edge to 60°S (except in Area V[1]).

Note that all Tables in this paper refer to sightings and effort within the area for which surveys were conducted to estimate abundance (this is referenced subsequently as ‘during the surveys’). Data are excluded from, for example, transits to and from the Antarctic, and refuelling of vessels in mid-cruise during the earlier surveys.

Survey mode

In the first circumpolar set, all surveys were conducted in closing mode, i.e. when a school was sighted, the vessel turned off the trackline to confirm the sighting. In later surveys, the vessels alternated between closing mode and passing mode. In passing mode, the vessel continues steaming on the trackline after the sighting, with observers in the barrel (situated high on the main mast) maintaining full searching effort while those on the upper bridge concentrate on tracking and identifying the sighting. In this mode, most of the effort was conducted with an additional Independent Observer (IO) on a separate platform on the main mast, and is termed IO mode. A number of effort codes have arisen to distinguish between different aspects of closing and passing modes, as discussed later.

Sightings were also recorded during experiments and during other non-primary activities such as closing on a sighting to confirm school size, drifting, or steaming with the topmen down. Neither these sightings nor any associated non-primary search effort are included in these analyses.

Changes to data in DESS

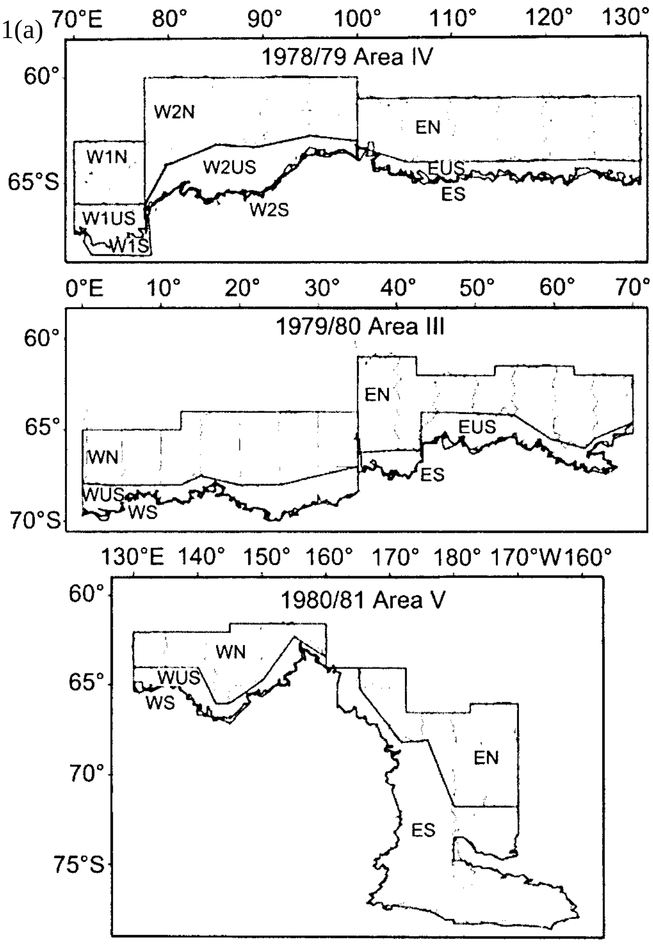
In order to preserve consistency in data storage throughout the surveys, changes to existing data in DESS have occasionally become necessary, as recorded in the appendices of Strindberg and Burt (2000). In addition, a thorough review of species codes has led to some changes, especially in the ‘like species’ codes (used in instances where species identification was uncertain) in the database, following the recommendations of Branch and Ensor (2001).

Previous assessments

A number of studies have used the IDCR-SOWER data to estimate cetacean abundances in the Southern Ocean. The most recent estimates for fin, sei, pilot and killer whales are from Butterworth *et al.* (1994), but that analysis failed to include sightings during 1990/91 in Area VI because of an error noted at the time (Butterworth *et al.*, 1994). In addition, the methods of analysis have changed over time (Branch and Butterworth, 2001), most notably with the adoption of a new method for mean school size estimation in 1995/96. Sperm whales were assessed by Brown and Butterworth (1998) and blue and humpback whales by Brown and Butterworth (1999); the 1997/98 survey data are now available to update these estimates. The abundance of southern bottlenose whales has not previously been estimated, although they are frequently sighted on the surveys.

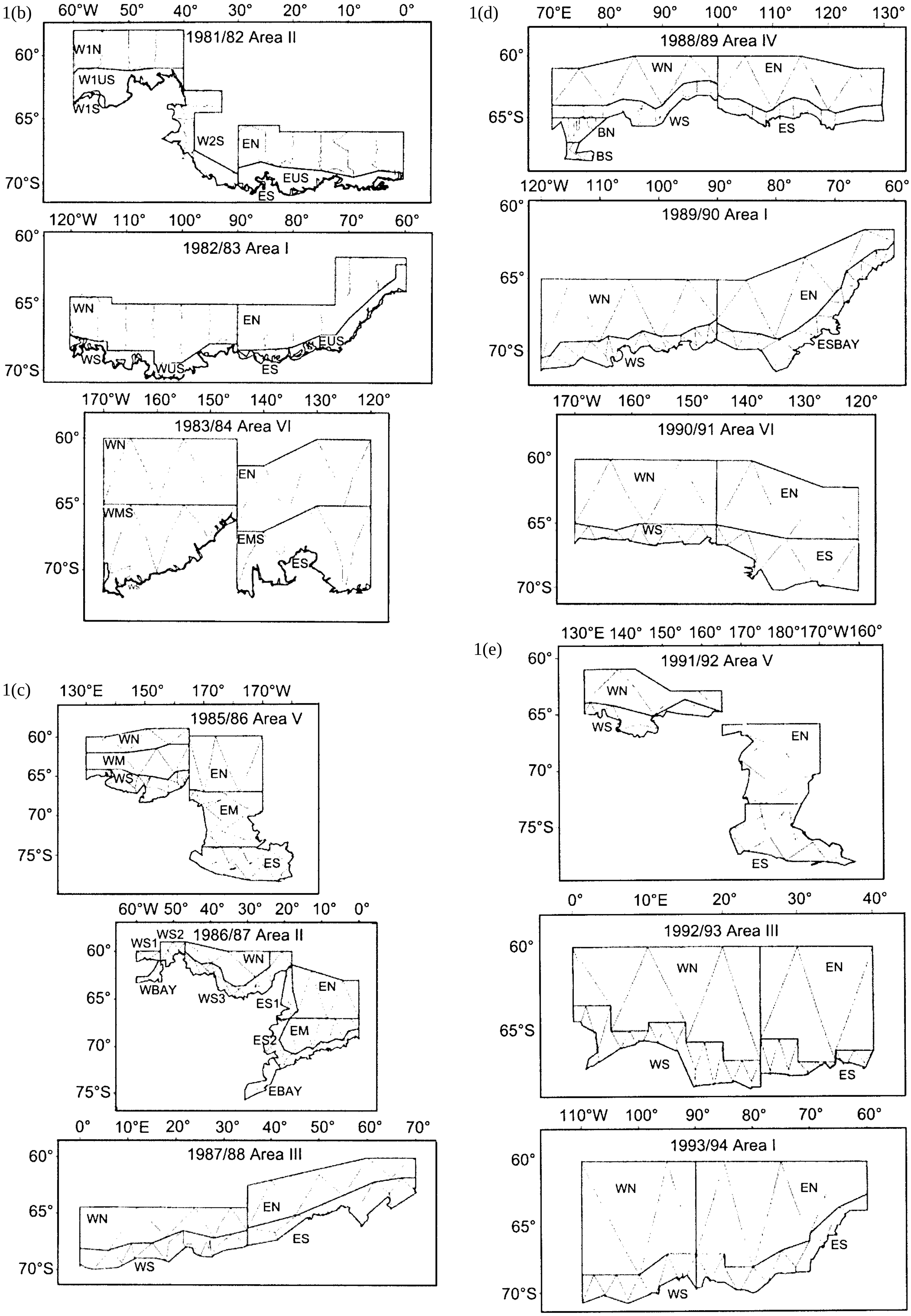
This paper provides the most up-to-date estimates available for six species: blue, fin, sperm, humpback, killer and southern bottlenose whales, broadly using the methodology developed for estimating minke whale abundance from these surveys, while also incorporating updates in the data since the Butterworth *et al.* (1994) paper. Estimates are not updated for sei whales, pilot whales or hourglass dolphins, because of concerns detailed later in this paper. Due to the low number of sightings for these species compared to minke whales, some changes (e.g. greater pooling) to this methodology are needed in order to obtain reliable abundance estimates. Sensitivity analyses are therefore presented to determine the impact of these changes on the abundance estimates.

1(a)



Figs 1a-f. Strata surveyed in each year from 1978/79-1997/98. The southern boundary for each survey was the ice edge. Bold lines indicate the stratum boundaries, whilst cruise tracks are indicated by lighter lines. Only primary search effort (closing mode and IO mode data are combined) is indicated; gaps in the cruise tracks indicate off-primary-effort steaming (e.g. because of poor weather conditions). The ‘US’ strata in the early surveys were unsurveyed regions between the south (‘S’) and north (‘N’) strata. The circular ‘bite’ missing from the WN stratum in 1996/97 falls within the EEZ of the South Georgia and South Sandwich Islands. Repeated from Branch and Butterworth (2001).

[1] The IWC divides the Antarctic waters into six Management Areas, labelled I to VI; most encompass 60° of longitude (Donovan, 1991).


1(b)
1981/82 Area II
W1N
W1US
W1S
W2S
EN
EUS
ES
1982/83 Area I
WN
WS
WUS
EN
EUS
ES
1983/84 Area VI
WN
WMS
EN
EMS
ES
1(c)
1985/86 Area V
WN
WM
WS
EN
EM
ES
1986/87 Area II
WS1
WS2
WN
WBAY
WS3
ES1
EN
ES2
EM
EBAY
1987/88 Area III
WN
WS
EN
ES
1(d)
1988/89 Area IV
WN
EN
WS
BN
BS
ES
1989/90 Area I
WN
EN
WS
ESBAY
1990/91 Area VI
WN
EN
WS
ES
1(e)
1991/92 Area V
WN
WS
EN
ES
1992/93 Area III
WN
EN
WS
ES
1993/94 Area I
WN
EN
ES
WS

Figs 1b-d

1(f)

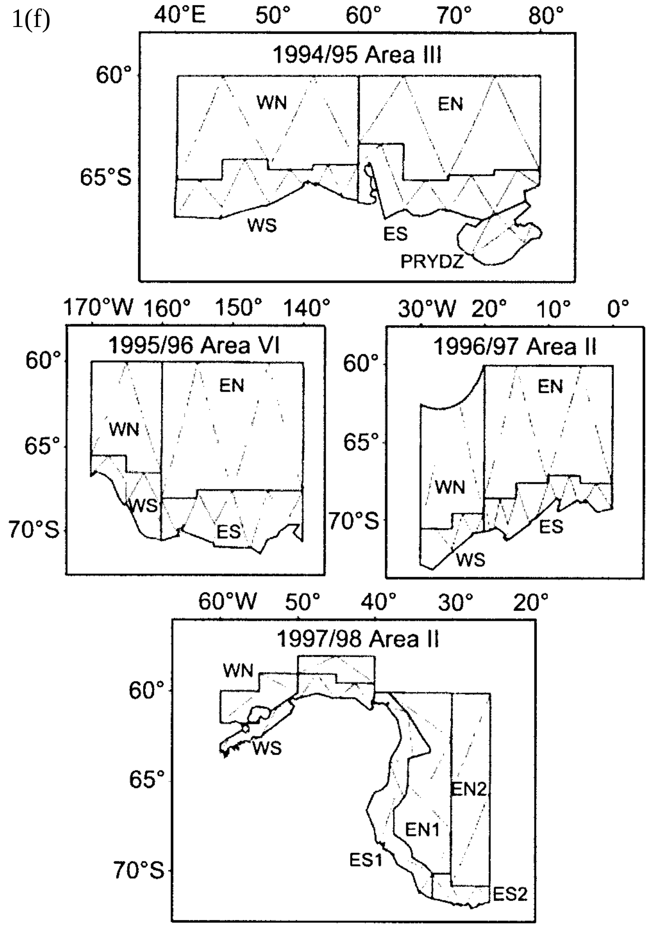
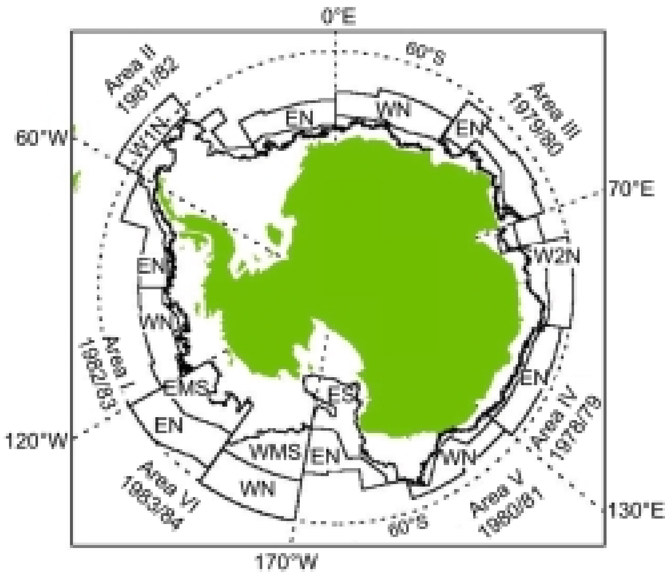


Fig. 1f



Figs 2a-c. The areas surveyed up to 1997/98 by each of the three sets of circumpolar cruises. Repeated from Branch and Butterworth (2001).

METHODS

Abundance is estimated from the perpendicular distances and school sizes of sightings, with the assumption that 100% of schools on the trackline are detected. Abundance estimation is based, where appropriate, on the 'standard methodology' adopted by the IWC Scientific Committee (e.g. IWC, 1988, pp.77-78). The 'standard methodology' and the process of adoption by the Scientific Committee are described in more detail in Branch and Butterworth (2001).

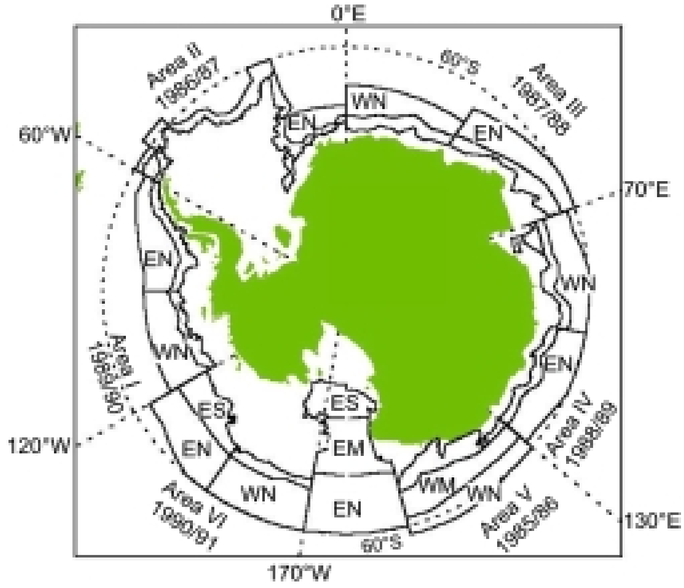


Fig. 2b

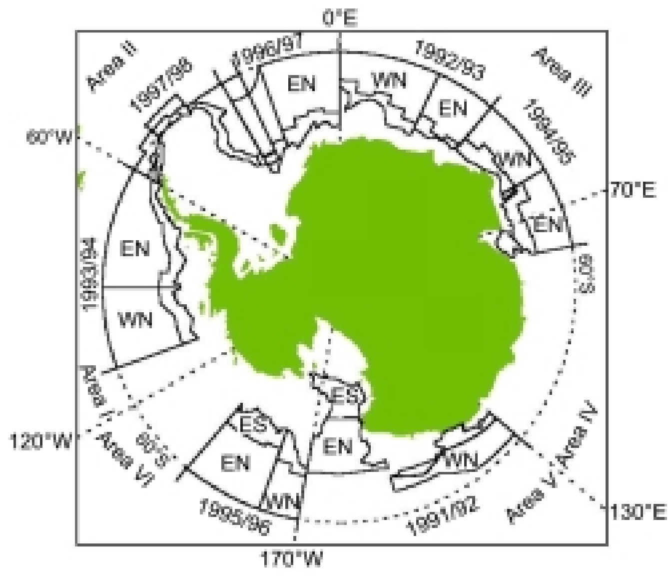


Fig. 2c

This methodology was developed primarily for minke whales (e.g. Burt and Stahl, 2000); changes that are necessary to obtain abundance estimates for the other species are highlighted below.

Abundance estimation

The basic equation used for abundance estimation is:

$$P = \frac{A \cdot \bar{s} \cdot n}{2 \cdot w_s \cdot L} \tag{1}$$

where:

- P = uncorrected abundance (assumes all schools on the trackline are sighted and makes no correction for random school movement);
- A = open ocean area of stratum;
- $\bar{s}$ = mean school size;
- n = number of schools sighted during primary search mode;
- w_s = effective search half-width for schools, equal to the inverse of the detection function intercept $f(0)$;

L = search effort (distance steamed in primary search mode).

The CV for P is calculated as follows:

$$[CV(P)]^2 = \left[CV\left(\frac{n}{L}\right)\right]^2 + [CV(\bar{s})]^2 + \left[CV\left(\frac{1}{w_s}\right)\right]^2 \quad (2)$$

Species

Eight species other than minke whales have been sighted in sufficient numbers (Table 1) to attempt abundance estimates: blue whales, *Balaenoptera musculus*; fin whales, *B. physalus*; sei whales, *B. borealis*; sperm whales, *Physeter macrocephalus*; humpback whales, *Megaptera novaeangliae*; killer whales, *Orcinus orca*; southern bottlenose whales, *Hyperoodon planifrons*; and hourglass dolphins, *Lagenorhynchus cruciger*. Note that common and scientific names used in this paper are those recommended by the IWC (IWC, 2001b).

The scientific value of the estimates produced varies (see Discussion). In particular, the values for sei whales and hourglass dolphins have high associated CVs (0.51–0.84) and little biological meaning, given that their distribution is predominately outside the study area (e.g. Mackintosh, 1965; Gaskin, 1972; Miyashita *et al.*, 1995). In addition, the number of sei whale primary sightings is small (16), and estimates for hourglass dolphins may be affected by possibly large positive bias due to vessel attraction. As a result, abundance estimates for these two species are not included in this paper. However, information about the number of sightings, estimated school size and effective search half-width is included for these two species.

Species codes for blue whales have proved problematic, with an ongoing discussion about the percentage of pygmy blue whales (*B.m. brevicauda*) that may occur in waters south of 60°S during the IDCR-SOWER surveys (IWC, 2000, pp.28–29, 174; IWC, 2001a, p.35). An additional problem is that the species codes for blue whales changed from the 1997/98 survey. In this paper, the recommended species codes of Branch and Ensor (2001), as adopted by the Scientific Committee (IWC, 2001a, p.186), are used to obtain estimates for blue whales: code 01 (blue whale) in 1978/79–1996/97, and codes 01, 98 (blue whale, probably true) and 99 (blue whale, undetermined) in 1997/98. These codes provide comparable estimates for true blue whales (*B.m. intermedia*) in all years, although these estimates may include a small proportion of pygmy blue whales. Analyses by Kato *et al*. (2000) and Donovan (2000) led the Scientific Committee (IWC, 2001a, p.35) to decide that there was no unequivocal evidence that pygmy blue whales were caught south of 60°S, but that if they were present, pygmy blue whales were unlikely to constitute more than 5% of the recorded historical catch of blue whales in the region of the IDCR-SOWER surveys.

Identification of beaked whale species (family Ziphiidae) in DESS is problematic because of the high number of sightings classified as code 11 (beaked whale) and code 38 (*Mesoplodon* spp.), particularly in the first few surveys. For this reason, only data from the second and third circumpolar sets of surveys were used to obtain estimates for ziphiid species. In those surveys, 97% of the ziphiid sightings identified to species level were southern bottlenose whales (code 24), which is therefore the only beaked whale species for which estimates are provided in this paper. As a possible alternative, all of the ziphiids could have been pooled into one group, an approach adopted by Kasamatsu (2000). The sightings data on the IDCR-SOWER surveys could then be used to estimate the proportion of this 'ziphiid' abundance estimate to assign to southern bottlenose whales and to Arnoux's (code 25), Cuvier's (code 35), Gray's (code 36) and Layard's (code 37) beaked whales.

Estimates for long-finned pilot whales (*Globicephala melas*, codes 12 and 41), which were estimated in Butterworth *et al*. (1994) are not provided here, primarily because of the paucity of sightings for this species. An additional reason for their omission is that the 30 schools sighted in the 1998/99 survey (Ensor *et al.*, 1999) would increase abundance estimates fourfold, but those data had not been included in DESS at the time of the analyses.

Antarctic minke whale (*B. bonaerensis*) data are included in some tables so that the nature of the data available for minke whales (by far the most frequently sighted species in the surveys) can be compared with those of the other species. However, estimates of abundance from data pooled at the circumpolar level are not presented because a more stratified analysis (Branch and Butterworth, 2001) has already been conducted for this species.

Number of schools sighted: *n*

The number of schools sighted in primary search mode in each year is shown in Table 1. Note that 'like species' sightings are not included in the baseline analyses. The inclusion of such sightings would increase fin whale sightings by 14% and other species by at most 8% (Table 2).

Mixed schools (more than one cetacean species in the same school) are excluded in the 'standard methodology' for minke whales. Mixed school sightings comprise up to 7% of all sightings for the other species (Table 3), and are therefore included here because these proportions are much higher than the negligible 0.4% for minke whales.

In IO mode, many of the sightings are duplicates or even triplicates, as the same school may be independently sighted by observers in the barrel, the IO platform or the bridge. Duplicates/triplicates are assigned a qualitative probability (either 'definite', 'possible' or 'remote') that the sightings referred to the same school. In this paper both definite and possible duplicates were removed (only definite duplicates are removed under the 'standard methodology'). This amounted to the removal of an additional 0.3% of the sightings and was effected in the interests of greater certainty.

In the standard Antarctic minke whale analyses, there is an option to estimate the variance of n/L indirectly whenever the number of transects (k) in the stratum is less than five (Strindberg and Burt, 2000). These analyses have used the DESS option of a pooled variance estimation over all strata, for strata where $k < 5$, as described in Branch and Butterworth (2001). There are two reasons for this: (1) the CVs for circumpolar abundance estimates differ by no more than 0.0001 between the two methods; and (2) when the number of sightings is low, it is complicated and time-consuming to estimate separate variances in DESS.

Primary search length: *L*

A number of activity codes have been used to record search effort; these codes can be grouped into closing mode, passing mode and other (non-primary effort). Most passing mode effort was conducted in IO mode (codes BI, BO, BU, BQ). In these analyses, the following effort codes are included (*denotes those used by Branch and Butterworth (2001) for minke whales).

Table 1

Number of schools sighted for each species code in the IWC/IDCR-SOWER surveys. Only primary sightings made during the survey are included. Definite and possible duplicates have been removed. No perpendicular truncation distance is applied. Species codes with zero primary sightings are excluded from this table.

		First circumpolar (years)						Expt	Second circumpolar (years)						Third circumpolar (years)							
Code	Common name	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	Total
01	Blue whale	1	5	2	2	2	2	2	8	5	4		3	2	4	7	3	7	5	5	6	75
02	Fin whale	2		3	3	8	8	2	4	8	8		3	10	2		3		18		20	102
03	Sei whale	1	1		3	2	1			1		1	4	1		1	4		5		6	31
04	Minke whale	567	462	662	507	617	195	328	1,125	849	319	454	508	155	573	345	234	224	181	147	118	8,570
05	Sperm whale	27	11	32	13	3	5	88	82	37	65	123	11	31	79	109	13	44	17	13	1	804
07	Humpback whale	20	20	6	3	8	17	22	6	12	12	47	24	23	23	7	18	34	17	14	9	342
08	(Great/southern) right whale				1	2				3		1								1	9	17
09	Unidentified whale	49	44	18	74	56	29	58	62	113	90	42	43	8	12	17	17	5	10	6	4	757
10	Killer whale	31	20	24	14	17	11	16	19	22	5	30	14	8	26	9	7	8	6	4	8	299
11	Akabo/beaked whale	96	123	21	31	50	9	113	25	115	64	38	31	5	1	21	29	15	5	18	40	850
12	Pilot whale											1		1								2
13	Cruciger (hourglass) dolphin	4		2	1	8	4	17	31			1	3	4	2		6	6	11	1	4	105
15	Unidentified dolphin						1	1	2				1				4		1		2	12
16	Unidentified whale or dolphin	1	18		1		2	1	8	1				1			6	7				46
24	Southern bottlenose whale	7		2	2	5	2	70	22	123	74	116	72	45	45	165	36	54	30	90	80	1,040
25	Arnoux's beaked whale							2	3	4			2	1		1				2	3	18
35	Cuvier's beaked whale						1														1	2
36	Gray's beaked whale									1			3				3			1		8
37	Layard's beaked whale								2			1							1		1	5
38	Mesoplodon							1	3	9		1	13	6		3	9	1	1	5	5	57
39	Like minke/?minke			2	1			46	129	74	53	18	96	34	154	49	80	51	49	47	41	924
41	Long finned pilot whale	4			4		1	6				1										16
51	Baleen whale												1	3				1				5
56	Pygmy blue whale																				2	2
57	Like killer whale						1															1
60	Like sei whale																				2	2
61	Like southern bottlenose whale									1	1		6	8	7	26		6	2	7	12	76
62	Like sperm whale									1	1	1	2	3	5	2	5	4	2	1		27
63	Unidentified small whale															24	6	5	37	24	19	115
64	Unidentified large baleen whale													2	6		2	6	19	3	19	57
66	Like fin whale													3					11			14
68	Like hourglass dolphin						2		1													3
71	Like humpback											1		2	6			2	3	1	2	17
72	Like beaked whale														7	2		2				11
73	Unidentified large whale													5		12	7	2	5	3	2	36
74	Dwarf minke whale																	1	1			2
76	Unidentified small cetacean																7	1				8
91	Minke whale (undetermined)																				43	43
94	Like blue whale													2	1	1		1		1		6
Total		810	704	774	660	778	291	773	1,532	1,379	696	877	840	363	953	801	499	487	437	394	459	14,507

Table 2

Number and percentage of 'like species' sightings. Sightings were extracted as follows: primary sightings during surveys; passing and closing modes; 1984/85 survey excluded (not used for abundance estimation); no perpendicular truncation distance applied; definite and possible duplicates excluded.

Species	Species code	Like code	Sightings	Like sightings	% Like sightings
Blue[1]	1, 96, 98, 99	94	73	6	8.2
Fin	2	66	100	14	14.0
Sei	3	60	31	2	6.5
Minke[2]	4, 90, 91, 92	39	8,285	924	11.2
Sperm	5	62	716	27	3.8
Humpback	7	71	320	17	5.3
Killer	10	57	283	1	0.4
Hourglass dolphin	13	68	88	1	1.1
Southern bottlenose[3]	24	61	952	76	8.0

[1] Blue whale codes (recommendations of Branch and Ensor 2001) are:
1 = blue whale (73 sightings)
96 = blue whale, like pygmy (0)
98 = blue whale, like true (0)
99 = blue whale, undetermined (0)
94 = like blue whale (6)

[2] Minke whale codes (recommendations of Branch and Ensor 2001) are:
4 = minke whale (before 1997/98, 8124 sightings), Antarctic minke whale (1997/98, 118)
90 = minke whale, probably dwarf (0)
91 = minke whale, undetermined (43)
92 = minke whale, probably Antarctic (0)
39 = like minke whale (924)

[3] Southern bottlenose sightings in the first circumpolar set of surveys are excluded since they were often recorded as 'akabo' during this period.

Table 3

Number and percentage of mixed species school sightings in the surveys from 1978/79 to 1992/93. Sightings were extracted as follows: primary sightings during surveys; passing and closing modes; 1984/85 survey excluded (not used for abundance estimation); no perpendicular truncation distance applied; definite and possible duplicates excluded. Note that the designation of mixed schools was discontinued from 1993/94 onwards, with the different species in such schools being instead recorded on separate forms as separate sightings. For this reason there is only one code that appears in this table for blue and minke whales.

Species	Code	Sightings	Mixed schools	% Mixed
Blue	1	47	5	10.6
Fin	2	59	5	8.5
Sei	3	16	2	12.5
Minke	4	7,338	30	0.4
Sperm	5	628	4	0.6
Humpback	7	228	8	3.5
Killer	10	250	18	7.2
Hourglass dolphin	13	60	5	8.3
Southern bottlenose[1]	24	662	5	0.8

[1] Sightings in the first circumpolar set of surveys are excluded for southern bottlenose whales since they were often recorded as 'akabo' during this period.

Closing mode effort codes
BA*: Ice navigation during closing mode reduces the effective search effort.
BC*: Searching on the trackline.
BR*: Returning to the trackline after closing with a sighting.
SE*: Closing mode, no distinction between BC and BR.
BB*: Closing with independent observer tracking (1987/88 survey only).
BL: High density of schools in closing mode causes difficulty in discriminating between schools.

Passing mode effort codes
BO*: Passing mode with independent observer in position (i.e. standard IO mode).
BI*: Ice navigation in IO mode reduces the effective search effort.
BU*: Cue counting from the bridge during BO mode (1986/87 survey only).
BQ*: Passing with independent observer tracking (1987/88 survey only).
BP: Passing mode with no independent observer.
BH: High density of schools in passing mode causes difficulty in discriminating between schools.
BV: Cue counting in BP mode with duplicate cue counts from IO platform (1986/87 survey only).

More detailed descriptions of the effort codes can be found in Strindberg and Burt (2000). Codes SE, BC and BR account for 99% of all closing mode effort; codes BO and BP account for 96% of all passing mode effort (Table 4). Note that although the overall proportion of effort under the other codes is small overall, it can be substantial for certain surveys (e.g. 1987/88, Table 4). For the Antarctic minke whale analyses, separate estimates are obtained from closing and passing mode (only IO codes are used). In this analysis, the closing and passing mode efforts are grouped, and minor effort codes are also included. A less restrictive approach is followed here than for minke whales since the small number of sightings available for many species dictates the need to include as many data as possible.

Truncation distance (for n, w_s, $\bar{s}$)
The estimation process for the effective search half-width (w_s) requires data to be truncated at a particular perpendicular distance from the trackline. The choice of the most appropriate truncation distance involves a trade-off between increasing sample size to improve precision, and reducing the possibility of biasing estimates of the detection function intercept $f(0)$ (from which w_s is calculated) through undue influence of observations far from the trackline. The

Table 4

Amount of primary search effort (in n.miles) achieved in each year. Only search effort inside the survey areas is included. Occasionally, two effort codes were assigned to the same period of effort; this consisted mostly of cue counting (BV, BU) in addition to one of the other primary effort codes. In such instances, only the main effort code is included.

Code	Description of search code		Code	Description of search code	
SE	Searching (closing)[1]	Closing mode	BO	IO mode	Passing mode
BC	Closing mode		BP	Passing mode	
BR	Return to trackline		BQ	Passing IO-tracking	
BB	Closing IO-tracking		BI	Passing in ice	
BA	Closing in ice		BH	High density of schools	
BL	High density of schools		BV	Cue counting with IO	

	First circumpolar (years)						Expt	Second circumpolar (years)						Third circumpolar (years)							
Code	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	Total
SE[1]	7,764	6,966	5,300	6,582	4,823	4,191	5,932														41,558
BC								3,539	2,947	1,406	3,156	2,186	1,343	1,490	2,316	1,935	1,943	1,503	1,475	1,261	26,499
BR								463	424	231	401	283	102	186	174	428	105	145	94	107	3,143
BB										414											414
BA								49	13	19	28		8	26	59		4			9	214
BL																					0
BO								4,162	3,598	1,164	2,379	2,967	2,160	2,027	2,733	2,475	2,242	1,730	1,762	1,685	31,084
BP								617	1,038	129				83	161	21					2,050
BQ										1,025											1,025
BI								66	35		42	42		2	33	2	6	4	7	3	242
BH								33				6		14			9				61
BV																					0
BU																					0
Total	7,764	6,966	5,300	6,582	4,823	4,191	5,932	8,930	8,055	4,387	6,006	5,483	3,613	3,829	5,475	4,861	4,309	3,381	3,338	3,065	106,291

[1] After the 1984/85 survey (which was mainly devoted to experiments), SE mode was split into two components - BC and BR - to allow the BR component of returning to the trackline after confirming a sighting to be distinguished from searching on the trackline (BC).

truncation distance used for Antarctic minke whales is 1.5 n.miles. However, because of their size, blue whales can be spotted much further from the vessels than, say, southern bottlenose whales. The mean perpendicular distance of sightings for the species considered here varies from 0.28 n.miles for hourglass dolphins to 1.32 n.miles for blue whales (Table 5). The rule of thumb advocated in Buckland *et al*. (1993, p.106), to truncate about 5% of the data, is therefore applied in this paper and the result rounded to the nearest 0.3 n.miles. The truncation distances obtained using this rule range from 0.6 n.miles for hourglass dolphins to 3.0 n.miles for blue and fin whales (Table 5).

Table 5

Statistics for perpendicular distance (y) from the trackline for each species. The mean distance and the distance at which only 5% of sightings would be excluded, are indicated. The truncation distance is obtained by rounding the latter to the nearest 0.3 n.miles for each species.

Species	Code	Mean (n.miles)	Exclude 5% (n.miles)	Truncation distance (n.miles)
Blue whale	1, 96, 98, 99	1.32	3.15	3.0
Fin whale	2	1.25	3.22	3.0[1]
Sei whale	3	0.89	1.86	1.8
Minke whale	4, 90, 91, 92	0.51	1.57	1.5
Sperm whale	5	0.99	2.56	2.7
Humpback whale	7	0.85	2.32	2.4
Killer whale	10	0.72	1.88	1.8
Hourglass dolphin	13	0.28	0.72	0.6[2]
Southern bottlenose	24	0.49	1.39	1.5

[1] The maximum possible truncation distance considered is 3 n.miles.
[2] Intervals of 0.05 n.miles were used for grouping data when fitting the detection function $f(y)$ for hourglass dolphins; 0.1 n.miles for other species.

Smearing parameters (for n, w_s, $\bar{s}$)

The truncated sightings data are smeared before their use in the estimation of w_s and $\bar{s}$. Radial distance and angle data are conventionally smeared using Method II of Buckland and Anganuzzi (1988) and then grouped into intervals of 0.1 n.miles for estimating w_s values. The only point of departure here is that intervals of 0.05 n.miles were used for hourglass dolphins because of the very narrow distribution of their sightings around the trackline. For minke whales, smearing parameters are normally estimated separately for each stratum from the data. However, due to the lower numbers of sightings for the species in this paper, some pooling is necessary to apply the Buckland and Anganuzzi method. Smearing parameters are thus obtained from pooled sightings (irrespective of whether school size was confirmed or not) separately for each circumpolar set of surveys, except for the infrequently sighted sei whales, which were pooled over all surveys for this purpose. In some cases, there were too few sightings to estimate the smearing parameters; they were then set to values of 4.0° (angle) and 0.30 (relative distance), which are typical of those obtained when estimation is possible.

Effective search half-width (w_s)

Effective search half-width (w_s) is obtained by fitting a hazard rate function to smeared and truncated frequencies of sightings in perpendicular-distance intervals from the trackline. It is often necessary to pool sightings from different strata to obtain an estimate of w_s, even for Antarctic minke whales where the number of sightings is relatively high. More extensive pooling is necessary for less frequently sighted species. In this paper, all sightings within a circumpolar set were pooled to estimate w_s, except for sei whales where data from all surveys combined were used to obtain a single w_s value, because of very low numbers of sightings. Had it been decided to present estimates for sei whales, this would have been problematic in examining trends over time (see Discussion).

The program DISTANCE 2.2 (Laake *et al.*, 1996) is called from inside DESS for line transect estimation and is used to obtain estimates of w_s (and indirectly $\bar{s}$). In this paper, for comparative purposes, estimates of w_s and $\bar{s}$ for minke whales are presented on a circumpolar basis, rather than on the much more disaggregated basis used for the standardised minke whale abundance estimates in Branch and Butterworth (2001). The sample sizes for minke whales were too large for computation with DESS, so that a recompiled version of the smearing program and DISTANCE 3.5 (Thomas *et al.*, 1998) running outside DESS, were used.

Mean school size: $\bar{s}$

Only sightings made during closing mode for which school size was confirmed are used to obtain the mean school size ($\bar{s}$). This follows from the SSII experiments conducted during the mid-1980s, which showed that school sizes estimated in passing mode, when schools are not approached closely, are substantially negatively biased (IWC, 1987, p.70). Pooling was more extensive than for Antarctic minke whale assessments: as for w_s, sightings within a circumpolar set were pooled to estimate a circumpolar-specific $\bar{s}$ for all species except sei whales where data from all surveys combined were used to obtain a single $\bar{s}$ value. The regression method of Buckland *et al*. (1993), as implemented in DESS, was used to estimate the mean school size. This involves a regression of *ln*(school size) against the detection function $f(y)$; for further details of this procedure and its implications, see Branch and Butterworth (2001).

Adjustments for regions that have been surveyed twice, or were not surveyed

In the early surveys (1978/79-1982/83), an unsurveyed 'U' area remained between the 'N' and 'S' strata. Following the 'standard methodology', the average density of whales in the 'S' and 'N' strata is assigned to this unsurveyed area, thus effectively adding half the area of each 'U' stratum to the area of the corresponding 'S' and 'N' strata.

In some years, the same stratum was surveyed by two vessels. In such cases (following the 'standard methodology' as in Branch and Butterworth, 2001), an effort-weighted average of the density estimates is used to calculate the stratum abundance. The 'Average' columns in Tables 6a-c reflect the strata that were averaged in this manner.

An adjustment is also needed for the third circumpolar set of surveys, where a 5° longitudinal strip (30°W-25°W in Area II) was surveyed in both 1996/97 and 1997/98. Since coverage of this strip was less intensive in 1996/97 (Ensor *et al.*, 1997), the simple approach adopted by Branch and Butterworth (2001) is used here to account for this region. This involves multiplying the estimates for the WN and WS strata in 1996/97 by 0.51 and 0.23 respectively - the areal percentage of those strata not surveyed in 1997/98. Overall CVs are adjusted accordingly.

Trends in abundance

Fully comparable estimates for the three circumpolar sets of surveys require that the differing areas surveyed south of 60°S are taken into account. Problems arise because (1) the first two circumpolar sets of surveys did not completely

Table 6a

Statistics for strata for the first circumpolar set of surveys. The search effort (L) and number of transects (k) in each stratum are shown. For the first five surveys, the trackline was not a zigzag design, so that each day is treated as a separate transect. Sightings for each species are the number of schools within the truncation distance, after smearing. Smearing sometimes results in a fractional number of sightings within this distance. Strata with the same number in the 'Average' column were surveyed by two vessels; an effort-weighted average of the corresponding density estimates is used to calculate abundance for such strata. Stratum areas have been adjusted upwards to account for the unsurveyed portion between the South and the North strata in the first five surveys (see text).

								Number of schools (after smearing and truncation)								
Year	Area	Vessel	Stratum area (n.mile^2)	Stratum	L (n.mile)	k	Average	Blue	Fin	Sei	Minke	Sperm	Humpback	Killer	Hourglass	S. Bottle[1]
1978/79	IV	T16	156,766	EN	2,155.5	18				1.0	70.6	4.0	5.0	4.0	4.0	
			39,256	W1N	222.2	2	1				9.0	1.0				
			20,389	W1S	200.6	5					56.3					
			153,914	W2N	384.7	3	2				5.0	1.0	1.0	1.0		
			29,600	W2S	1,073.3	12	3	1.0			84.0		4.0	1.0		
		T18	27,571	ES	1,436.6	16					169.2	11.0	4.0	19.0		
			39,256	W1N	685.3	6	1				35.9	5.6		3.0		
			153,914	W2N	1,212.5	11	2		2.0		26.3	3.0	2.4			
			29,600	W2S	393.4	4	3				42.0	1.0	2.0	1.0		
1979/80	III	K27	41,772	ES	1,346.5	20		3.0			167.9		4.0	4.0		
			200,724	WN	2,014.9	16		1.0			54.7	8.0	4.0	1.4		
		T11	217,865	EN	2,636.7	20		1.0			57.5	1.0	2.0	7.9		
			33,619	WS	968.2	19		1.0			139.2		7.0	4.0		
1980/81	V	K27	208,159	EN	877.3	14					78.7	3.0	2.0	2.0	1.0	
			98,766	ES	439.6	5	4				55.9	5.9		5.8		
			34,164	WS	698.1	17					74.0			5.0		
		T11	98,766	ES	2,133.3	21	4	1.0	2.0		291.9	21.0	1.0	9.7		
			139,191	WN	1,151.6	15		1.0	1.0		44.2		3.0	0.8		
1981/82	II	SM1	29,633	ES	1,162.9	18		1.0			169.3			5.0		
			135,504	W1N	1,064.9	10			2.0	3.0	21.0		1.0		2.0	
			52,096	W2S	920.6	10	5				76.2			1.0		
		SM2	145,063	EN	1,748.8	17					55.0	10.7	1.0	2.0		
			35,725	W1S	872.2	9			1.0		31.4		0.5	3.0		
			52,096	W2S	812.4	12	5	1.0			94.0			1.6		
1982/83	I	SM1	33,050	ES	928.0	15		1.0			115.6		1.9	7.0		
			163,926	WN	1,426.1	15			6.0	1.0	62.8	3.0	1.0	4.0		
		SM2	149,433	EN	1,054.4	17			1.0	1.0	83.9		3.0	3.0	7.2	
			25,596	WS	1,414.8	19		1.0	1.0		314.0			2.0		
1983/84	VI	K27	158,893	EMS	1,094.4	5		1.0			48.4	2.0	4.0	5.0		
			207,721	WN	875.6	5			2.0	1.0	52.0		7.9	3.0	5.0	
		SM1	202,108	EN	911.6	5			2.0		20.0	1.0	1.0	1.0		
		SM2	156,457	WMS	1,309.0	5		2.0	2.0		69.8	2.0	2.1	2.0		

[1] Southern bottlenose whales are omitted for the first circumpolar set of surveys.

cover the latitudinal range from the ice edge to 60°S; (2) the third circumpolar set of cruises surveyed the full latitudinal range but did not cover the longitudinal ranges of 140°W-110°W and 80°E-130°E (Figs 2a-c); and (3) the proportion of 'like species' sightings has increased over time (Table 1).

One simple way of obtaining comparable estimates is outlined in Branch and Butterworth (2001) and applied here. This method has three steps:

(1) assume that the unsurveyed northern areas have the same density of whales as the northern surveyed strata in each survey, to scale estimates to 60°S;
(2) estimate the abundance within the longitudinal regions covered by all three circumpolar sets (i.e. exclude estimates from 140°W-110°W and 80°E-130°E);
(3) include like species sightings in the estimates.

Sensitivity analyses

A number of modifications have been made above to the 'standard methodology' used for Antarctic minke whale abundance estimates. The impact of these modifications on the abundance estimates is examined in a series of sensitivity analyses.

(1) Change the truncation distance to 1.5 n.miles for all species, the distance used in previous analyses for minke whales and for other species (e.g. Butterworth *et al.*, 1994). In addition, for blue and humpback whales, the truncation distances are changed in increments of 0.3 n.miles from 1.2 n.miles to 3.0 n.miles, to determine whether there is any trend in the estimates (or their precision) with increasing truncation distances.
(2) Include 'like species'. The proportions of 'like species' have increased over time, which may bias perceived trends in abundance. Note that DESS 3.0 incorporates changes to blue whale species codes recommended by Branch and Ensor (2001).
(3) Exclude sightings recorded in mixed species schools. Note however that the mixed species designation was discontinued from the 1993/94 survey, with the different species in such schools being recorded separately from then onwards.
(4) Exclude only definite duplicates instead of excluding both definite and possible duplicates.

Table 6b

Statistics for strata in the second circumpolar set of surveys. The search effort (L) and number of transects (k) in each stratum are shown. Sightings for each species are the number of schools within the truncation distance, after smearing. Smearing sometimes results in a fractional number of sightings within this distance. Strata with the same number in the 'Average' column were surveyed by two vessels; an effort-weighted average of the corresponding density estimates was used to calculate abundance for such strata.

								Number of schools (after smearing and truncation)								
Year	Area	Vessel	Stratum area (n.mile^2)	Stratum	L (n.mile)	k	Average	Blue	Fin	Sei	Minke	Sperm	Humpback	Killer	Hourglass	S. Bottle
1985/86	V	K27	279,611	EN	1,757.7	16					110.4	14.6			25.4	11.0
			104,814	WS	1,596.8	28		2.9			162.7	30.3	2.0	9.7		3.0
		SM1	165,912	EM	1,866.4	20		2.0			286.0	32.7	2.0	2.7		1.0
			166,349	WM	850.0	8					68.3		2.0	1.0		3.0
		SM2	107,717	ES	1,737.8	22		1.0			360.4			4.0		
			139,065	WN	1,121.5	10			4.0		68.0	1.0		1.0	2.0	3.0
1986/87	II	K27	23,142	ES1	527.6	8					32.0	1.0	1.0	2.0		3.0
			10,270	WS1	185.5	4		1.0	1.0		21.0		2.0			
			21,143	WS2	239.7	4	6		2.0		7.0		1.0			7.0
			79,605	WS3	1,014.8	15	7		1.0		83.4		3.0	4.0		20.0
			124,057	EN	965.9	7		1.0	2.0		110.0	9.0		3.0		8.0
		SM1	15,242	EBAY	232.2	7					48.0			2.0		
			44,975	ES2	1,287.8	29		3.0	1.0		138.3	9.5	1.0	2.0		6.0
			11,505	WBAY	166.4	3					47.0					
			95,361	WN	516.6	6			1.7		3.0		1.0			7.0
		SM2	69,908	EM	1,444.2	9					182.4	16.9		4.0		19.0
			21,143	WS2	234.6	3	6			1.0	3.0		2.0			8.0
			79,605	WS3	1,119.8	19	7		1.0		105.7			5.0		40.9
1987/88	III	SM1	87,677	ES	1,196.0	15		1.0	6.5		48.7	18.5	5.9	1.0		22.0
			148,821	WN	857.3	13					36.5	5.0	1.0			24.5
		SM2	168,881	EN	1,086.7	14			0.5		12.0	9.8	1.0	2.0		12.0
			74,351	WS	1,247.3	21		3.0			203.2	28.8	4.0	2.0		15.9
1988/89	IV	SM1	6,520	BS	231.9	4					62.5	2.0		1.0		
			181,166	EN	1,116.3	12				1.0	24.0	26.0	2.0	3.0	1.0	27.7
			58,693	WS	1,312.2	22					150.0	45.6	10.0	6.0		30.9
		SM2	17,486	BN	627.7	15					32.0	14.0		6.0		3.0
			52,441	ES	1,260.9	21					140.2	18.5	3.0	6.0	1.0	25.2
			156,617	WN	1,431.9	12					14.0	14.3	29.9	5.0		25.0
1989/90	I	SM1	62,594	ESB	1,416.8	26			2.0	2.0	100.2		8.0	2.0		12.7
			168,761	WN	1,167.1	13		1.0		1.0	58.1	3.0	7.0	3.0	2.7	8.0
		SM2	153,029	EN	1,429.8	14					80.4	3.0	1.5	5.4	1.0	40.0
			45,128	WS	1,433.1	30		1.5	1.0	0.7	248.8	5.0	7.0	2.9		10.0
1990/91	VI	SM1	191,954	EN	666.6	7			3.8		29.2	5.0	3.0	1.0		4.0
			45,414	WS	950.1	14		1.0	1.0		41.4	11.1	7.3			18.0
		SM2	108,268	ES	952.9	9			4.7		59.0	6.0	1.0	6.0		6.0
			211,788	WN	1,043.4	9				1.0	17.0	4.0	9.0	1.0	4.0	15.0

(5) Obtain separate estimates from closing and passing mode data for sperm, killer, humpback and southern bottlenose whales (for which there are sufficient sightings to do so). In the analyses above, passing and closing mode data are pooled to increase the number of sightings and hence reduce estimation variance.

RESULTS

A summary of the number of sightings in each stratum, after smearing and truncation, is given in Tables 6a-c, which also contain details of the strata names, vessels, strata areas and the amounts of search effort in each stratum.

Smearing parameters for the different species generally decrease from the first to the third circumpolar set of surveys (Table 7), although in many cases there were insufficient sightings to estimate the smearing parameters.

For all of the more frequently sighted species (minke, southern bottlenose, sperm, humpback and killer whales), the estimates for w_s increased from the first circumpolar to the second circumpolar set of surveys, and again from the second circumpolar set to the third (Table 8). The fits of the hazard rate model used in obtaining the w_s estimates are shown in Figs 3a-b. For the more frequently sighted species, the width of the 'shoulder' adjacent to the trackline increases from one circumpolar survey to the next (Figs 3a-b).

There are no consistent trends in estimates of $\bar{s}$ from one circumpolar set of surveys to the next. However, $\bar{s}$ estimates for killer whales decrease from 17.11 in the first circumpolar set to 7.17 in the second, and then increase to 12.30 in the third circumpolar set (Table 9). The mean school size for fin whales increases from 2.04 and 1.62 in the first two circumpolar sets to 4.06 in the third. Interestingly, sperm whale sightings were almost all of single animals in the second and third circumpolar sets, though larger schools were recorded in the first circumpolar set of surveys.

Abundance estimates are given in Table 10, and shown alongside those of previous analyses in Table 11. Separate estimates are available for the three circumpolar sets of surveys except for southern bottlenose whales, for which estimates are possible for the last two circumpolar sets only. Only for sperm, humpback, killer and southern bottlenose whales are estimates reasonably precise (i.e. CVs < 0.30). Given the large associated CVs, presenting the estimates at a smaller spatial scale (e.g. by IWC Management Areas – see Donovan, 1991) would have limited meaning.

Table 6c[1]

Statistics for strata in the third circumpolar set of surveys. The search effort (L) and number of transects (k) in each stratum are shown. Sightings for each species are the number of schools within the truncation distance, after smearing. Smearing sometimes results in a fractional number of sightings within this distance. Strata with the same number in the 'Average' column were surveyed by two vessels; an effort-weighted average of the corresponding density estimates was used to calculate abundance for such strata.

Year	Area	Vessel	Stratum area (n.mile^2)	Stratum	L (n.mile)	k	Average	Number of schools (after smearing and truncation): Blue	Fin	Sei	Minke	Sperm	Humpback	Killer	Hourglass	S. Bottle
1991/92	V	SM1	165,429	EN	1,008.8	17		1.6	1.0		191.8	29.3	7.5	2.0		9.6
	130°E-170°W		58,643	WS	748.2	15		1.0	1.0		148.9	25.0	13.8	16.5		26.5
		SM2	82,039	ES	1,416.4	22					182.2			9.0		
			137,734	WN	655.3	9		1.0			13.0	14.6	2.0		2.0	4.0
1992/93	III	SM1	23,207	ES	893.4	23					31.7	7.0	1.0	2.7		58.5
	0-40°E		210,035	WN	1,404.5	15	8				42.0	24.0				24.0
			61,527	WS	143.0	3	9				5.0	3.0	1.0			2.0
		SM2	150,547	EN	1,101.2	9				1.0	18.0	9.0	1.0	2.0		29.0
			61,527	WS	1,774.6	31	9	5.0			228.9	50.8	3.0	4.0		46.0
			210,035	WN	134.2	1	8					9.0				1.0
1993/94	I	SM1	50,596	WS	1,068.3	23		3.0			76.8	4.0	10.0	2.0		2.0
	110-70°W		293,196	EN	1,581.8	22			2.0		15.0	1.9	2.0	3.0	4.0	10.0
		SM2	251,735	WN	1,134.0	16					25.0	3.0	1.0	1.0	2.0	15.0
			72,249	ES	1,076.4	20				3.5	107.5	2.0	4.5	2.8		8.9
1994/95	III	SM1	51,938	WS	919.6	23		3.6			59.5	28.9	14.0	2.0		32.0
	40-80°E		146,681	EN	1,154.5	15		2.0			25.0	4.7	1.0	2.0	5.8	7.0
		SM2	148,803	WN	921.6	14					18.6	2.0	16.0	1.0		6.0
			60,046	ES	899.2	17		1.0			57.0	7.0	3.0	2.0		6.0
			21,096	PRYD	414.2	8					56.0					
1995/96	VI	SM1	34,051	WS	738.9	19					35.9	6.0	4.0	1.0		7.0
	170-140°W		242,073	EN	1,045.3	21		4.0	11.9	2.9	48.5	3.0	7.4	1.0	5.0	1.0
		SM2	97,945	WN	528.5	9			1.0		17.0		2.0	1.0	4.5	2.0
			72,349	ES	1,068.5	19		1.0			72.6	8.0	1.0	3.0		19.7
1996/97	II	SM1	67,072	ES	1,229.2	38		2.0			56.2	7.0	5.7	2.0		52.1
	30-0°W		113,687	WN	463.9	10					16.0		2.7	1.0		4.0
		SM2	241,928	EN	1,260.4	32					28.0	6.0	3.0	1.0	1.0	25.1
			23,028	WS	384.5	15		2.0			31.0		2.0			3.0
1997/98	II	SM1	32,620	WS	490.3	17			5.1	1.0	4.0		7.5	4.5		36.4
	60-25°W		84,726	EN1	581.1	12		1.0			16.0			1.0		7.0
			10,451	ES2	226.3	9					40.7					
			44,064	EN2	202.1	4					11.0					8.7
		SM2	52,135	WN	493.3	8		1.0	9.7	4.0	7.0	1.0	1.0		1.0	5.8
			47,036	ES1	741.5	16		3.8			61.0					17.0
			35,949	EN2	330.8	4					14.0					1.0

Table 7

Smearing parameters used in obtaining the estimates. These are computed by DESS from the raw angle and distance data, using Method II of Buckland and Anganuzzi (1988). The angle parameter is an absolute value (in degrees), but the distance parameter is a relative value - see Branch and Butterworth (2001) for further details.

Species	First circumpolar: Angle	Distance	Second circumpolar: Angle	Distance	Third circumpolar: Angle	Distance
Blue	4.00[1]	0.30[1]	4.00[1]	0.30[1]	3.24	0.267
Fin	6.00	0.333	4.00[1]	0.30[1]	3.75	0.327
Sei[2]	3.66	0.205	3.66	0.205	3.66	0.205
Minke	6.63	0.336	4.47	0.223	3.25	0.151
Sperm	5.20	0.260	4.10	0.209	2.90	0.172
Humpback	6.13	0.341	2.88	0.190	2.66	0.198
Killer	7.08	0.318	3.26	0.240	3.31	0.273
Hourglass dolphin	4.00[1]	0.30[1]	4.00[1]	0.30[1]	4.00[1]	0.30[1]
Southern bottlenose	-	-	5.15	0.214	4.02	0.167

[1] Due to low sample size, the smearing parameters are set at 4.0 (angle) and 0.3 (distance), these values being typical of those for the remaining species.
[2] Smearing parameters obtained by pooling data from all three circumpolar sets of surveys

Table 8

Effective search half-width (w_s), in n.miles, estimated for each species.

Species	First circumpolar		Second circumpolar		Third circumpolar	
	w_s	CV	w_s	CV	w_s	CV
Blue	1.966	0.11	1.569	0.30	2.078	0.34
Fin	1.333	0.17	1.378	0.25	1.831	0.37
Sei[1]	1.181	0.40	1.181	0.40	1.181	0.40
Minke	0.376	0.05	0.523	0.03	0.577	0.04
Sperm	0.710	0.30	1.392	0.08	1.516	0.06
Humpback	0.746	0.33	0.948	0.18	1.299	0.10
Killer	0.651	0.24	0.957	0.13	1.453	0.09
Hourglass dolphin	0.170	0.71	0.279	0.39	0.161	0.46
Southern bottlenose	-	-	0.529	0.07	0.698	0.07

[1] Calculated by pooling data from all three circumpolar sets of surveys.

Estimates of abundance for sei whales and hourglass dolphins are not included in Tables 10-11, because, as discussed previously, these estimates are not considered to be reliable.

Trends in abundance

When comparable areas and 'like species' are taken into account, there are some apparent trends in abundance (Table 12) but in only two cases are there statistically significant differences from one circumpolar set to another. Fin whales increase significantly from the second to the third circumpolar set: from 1,401 (CV = 0.48) to 8,036 (CV = 0.58); killer whales decrease significantly from the first to the second circumpolar set, from 130,867 (CV = 0.35) to 23,570 (CV = 0.26). However, as discussed later, both of these significant results may be an artefact of changes in the survey design and not necessarily a reflection of real changes in abundance.

Sensitivity analyses

Point estimates of abundance are generally unaffected when the truncation distance is set to 1.5 n.miles (instead of the baseline selections of Table 5), especially when the large CVs associated with these estimates are taken into account (Table 13). There is no pattern of greater or lesser precision in the abundance estimates. The more detailed analyses for blue whales and humpback whales (Fig. 4) generally show no trend (in either estimates or precision) with increasing truncation distance, although better precision is obtained with increasing truncation distance for the blue whale estimates for the third circumpolar set of surveys.

Whether or not possible duplicates/triplicates are included or excluded makes negligible difference to any of the abundance estimates (Table 13). The exclusion of mixed species schools has little impact on the abundances for any species (Table 13). The inclusion of 'like species' also generally affects the estimates little, although blue whales and fin whales in the third circumpolar set of surveys increase by 25% and 61% respectively.

The sensitivity tests do reveal some anomalies caused by the method of school size estimation used in the 'standard analyses'. In DESS, the simple mean school size is used unless a regression of *ln*(school size) against the detection function is significant at the $p = 0.15$ level. This can cause a discontinuous jump in the estimated school size. This effect is noticeable in the sensitivities for killer whales in the first circumpolar set, for example, the inclusion of a single 'like species' sighting changes the *p*-value of the regression from 0.128 to 0.152. In turn, this results in the simple mean (26.4) being used for the school size instead of the regression estimate (17.6), and the abundance estimate accordingly increases by 64%. Concerns about this effect were raised by Branch and Butterworth (2001). To avoid these discontinuous jumps in abundance, the regression estimate of school size was used for sensitivities for killer whales in the first circumpolar set: the 'include like species' estimate was modified from 149,443 (CV = 0.39) using the simple mean to 99,642 (CV = 0.34) using the regression method, the 'exclude mixed species' estimate from 120,188 (CV = 0.40) to 79,367 (CV = 0.34), and the 'truncate at 1.5 n.miles' estimate from 113,768 (CV = 0.40) to 75,397 (CV = 0.34).

Estimates of sperm, humpback and southern bottlenose whales obtained separately for closing and for passing mode, differ little from the pooled closing and passing mode estimates, although the closing mode estimate for killer whales in the second circumpolar set is 61% greater than the pooled estimate (Table 12). In that case, the w_s value was 1.15 for passing mode only but just 0.579 for closing mode. The CVs of the separate estimates are higher in all cases, indicating that pooling indeed achieves the stated aim of reducing the estimation variance of the estimates. Closing mode point estimates were greater than passing mode estimates in all cases except for humpback whales in the second circumpolar set of surveys.

DISCUSSION

Abundance estimates in this paper are negatively biased, primarily because of the assumption that all schools on the trackline are sighted. In addition, the estimates presented in this paper are essentially limited to the region south of 60°S. The Japanese Scouting Vessel (JSV) data have been used to extrapolate abundance estimates from the first two circumpolar sets of surveys to the area south of 30°S (Butterworth *et al.*, 1994, improved in Butterworth and Geromont, 1995). Extrapolations there were performed for blue, fin, sei, sperm and humpback whales, but the JSV data also include killer whale records. Butterworth and Geromont (1995) found that this extrapolation increased estimates by the following multiplicative factors for the second circumpolar set of surveys: blue (both true and pygmy) (7.9-3.0); fin (4.8-8.7); sei (18-15.5); sperm (15.4-13.4) and humpback (2.1-4.5). The different ratios depend on whether JSV data for 1965/66-1977/78 or 1978/79-1987/88 respectively are used. The first of these periods had relatively more effort in lower latitudes (40-60°S), and the second more in higher latitudes (south of 60°S).

It is interesting that there is an upward trend over time in estimates of search half-width (w_s) for species for which data are pooled on a circumpolar basis. The change from the first

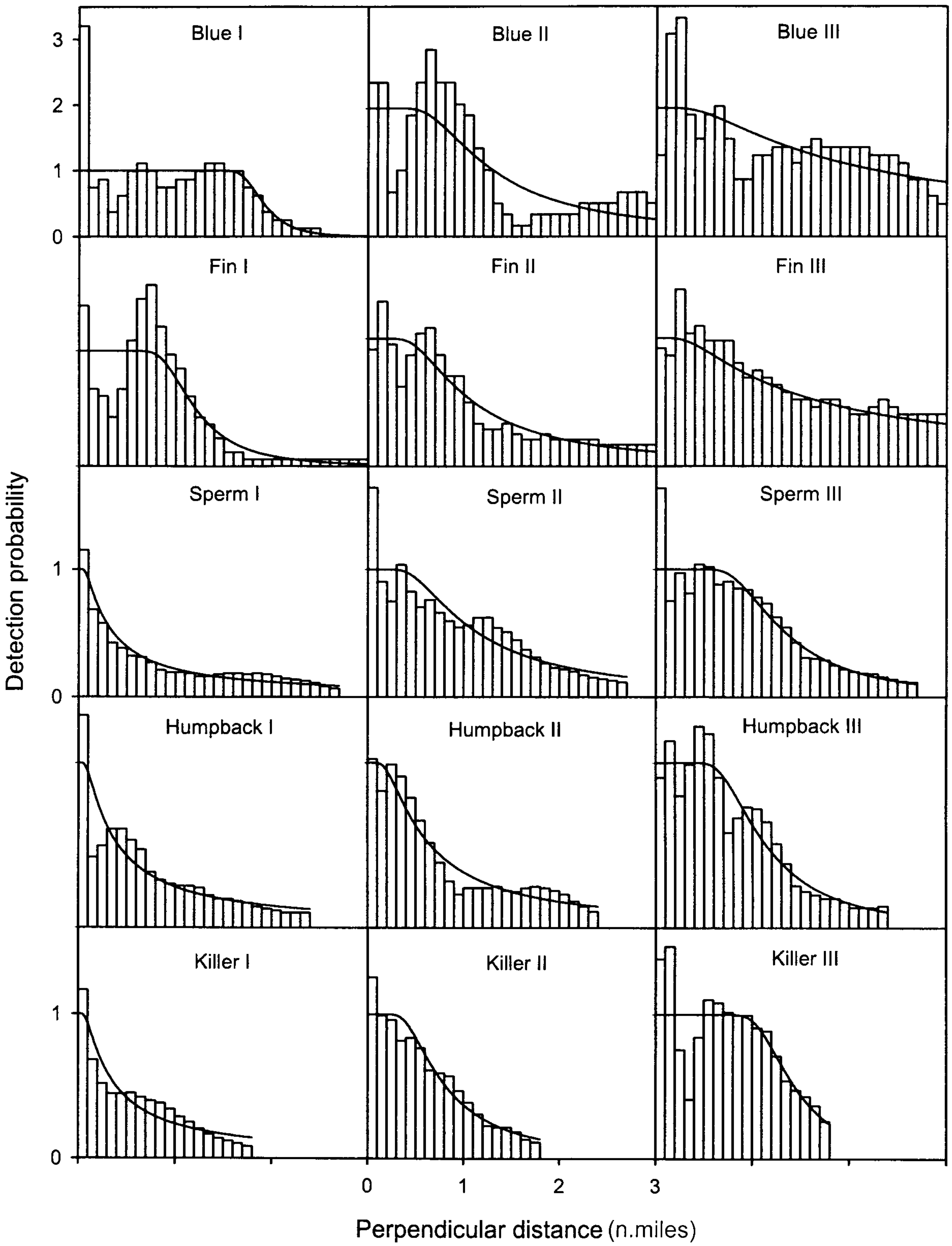


Fig. 3a. Hazard rate model for the detection function fitted to the number of schools as a function of the perpendicular distance (in n.miles) from the trackline. The individual perpendicular distances are smeared and then grouped into 0.1 n.mile perpendicular distance intervals, with truncation at species-specific distances (see Table 5). Sightings data are pooled across passing and closing modes, separately for each circumpolar set of surveys (designated I, II or III), except for sei whales where pooling is over all surveys (I+II+III).

circumpolar set to the second is easier to understand, given the different and smaller vessels used for most of the first set of surveys. Possible reasons for a change from the second to the third set (with essentially the same two vessels used throughout) are less readily advanced. The trend raises questions about the constancy over time imposed upon the estimate of w_s for sei whales, for which data had to be pooled over all surveys.

Comparison with previous estimates

There are some differences between the estimates in this paper and those of previous analyses (Table 11). In comparison with the results from the previous major conglomerate analysis (Butterworth *et al.*, 1994), the following reasons for changes should be noted: (1) the use of data from DESS; (2) correction of the earlier error in omitting 1990/91 sightings; (3) use of species-specific rather

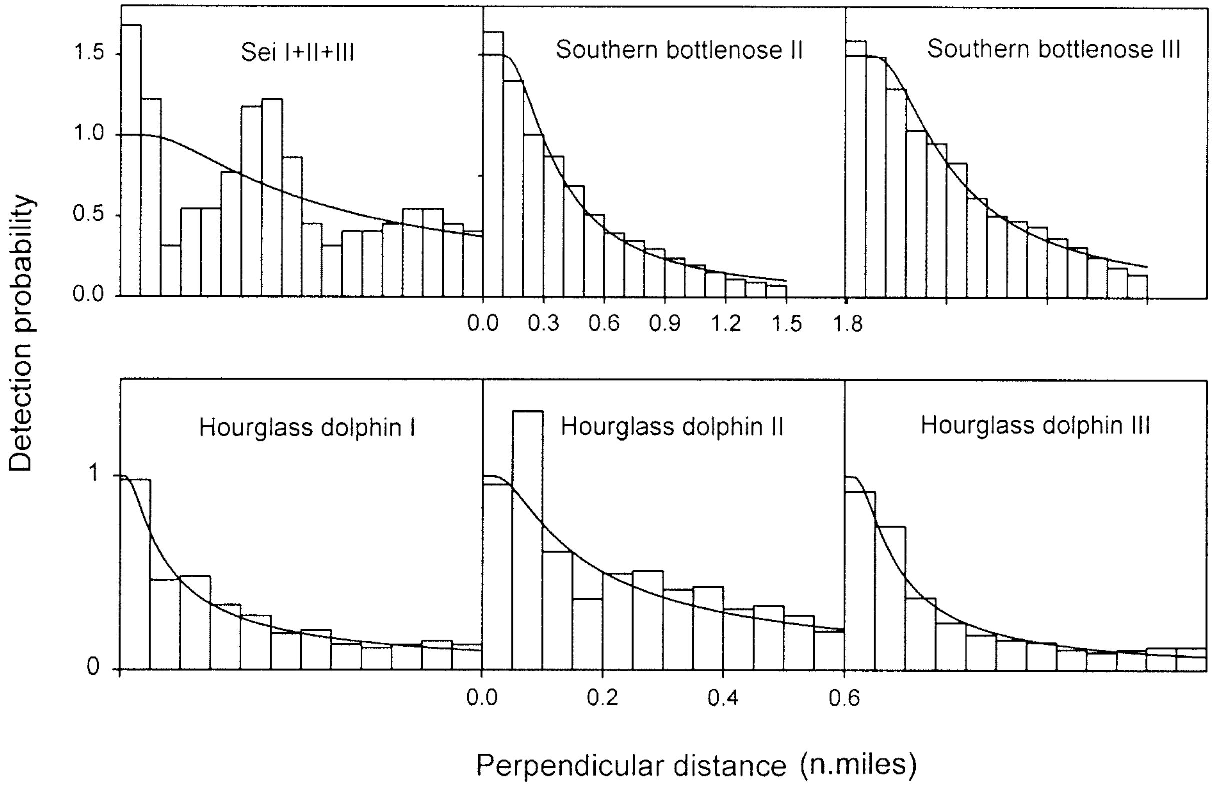


Fig. 3b. For details see the legend to Fig. 3a.

Table 9

Estimated mean school size (w_s) for each species.

Species	First circumpolar w_s	CV	Second circumpolar w_s	CV	Third circumpolar w_s	CV
Blue	1.75	0.16	1.43	0.21	1.48	0.11
Fin	2.04	0.12	1.62	0.29	4.06	0.17
Sei[1]	1.38	0.12	1.38	0.12	1.38	0.12
Minke	2.52	0.02	2.63	0.03	1.72	0.03
Sperm	1.31	0.08	1.02	0.02	1.01	0.01
Humpback	1.63	0.05	1.54	0.06	1.96	0.05
Killer	17.11	0.17	7.17	0.18	12.30	0.15
Hourglass dolphin	6.03	0.34	10.59	0.29	3.60	0.17
Southern bottlenose	-	-	1.89	0.05	1.77	0.05

[1] Obtained by pooling data from all three circumpolar sets of surveys.

Table 10

Abundance estimates (P) for each circumpolar set of surveys. Confidence intervals are calculated according to Buckland (1992). The estimates for the third circumpolar set of surveys are adjusted to account for the 5° longitude slice surveyed in both 1996/97 and 1997/98 (see text for details).

Species	First circumpolar Abundance	CV	95% CI	Second circumpolar Abundance	CV	95% CI	Third circumpolar Abundance	CV	95% CI
Blue	438	0.41	(203; 945)	549	0.48	(230; 1,330)	1,069	0.45	(460; 2,490)
Fin	2,057	0.36	(1,040; 4,080)	2,144	0.45	(920; 4,980)	5,455	0.53	(2,000; 14,500)
Sperm	5,367	0.38	(2,600; 11,100)	10,450	0.15	(7,800; 14,000)	8,329	0.16	(6,100; 11,400)
Humpback	7,057	0.36	(3,500; 14,100)	9,236	0.29	(5,300; 16,200)	9,289	0.22	(6,000; 14,300)
Killer	91,310	0.34	(48,000; 175,000)	27,168	0.26	(16,600; 44,400)	24,790	0.23	(15,900; 38,700)
Southern bottlenose	-	-	-	71,560	0.13	(56,000; 91,400)	53,743	0.12	(42,400; 68,100)

than minke whale-based truncation distances and smearing factors; and (4) use of the subsequently adopted regression method to estimate mean school size. Estimates in Brown and Butterworth (1998) were of a preliminary nature, given that parts of DESS were still under development. Differences between the estimates in this paper and those of Brown and Butterworth (1999) arise from three factors: minor modifications to data in DESS, the inclusion of the

Table 11

Comparison of previous estimates (and associated CVs) based on the IDCR-SOWER sighting surveys with those presented in this paper. Estimates are rounded to two significant figures to ease comparisons. [1] First circumpolar set of surveys only to 1981/82. Third circumpolar set only to 1995/96. [3] Third circumpolar set only to 1996/97. [4] Third circumpolar set only to 1997/98.

Species	Circumpolar	Hammond (1984)[1]	Butterworth and Dudley (1984)	Butterworth and de Decker (1987)	Butterworth *et al.* (1994)	Brown and Butterworth (1998)[2]	Brown and Butterworth (1999)[3]	This paper (2001)[4]
Blue	I		1,000 (0.41)	500 (0.40)	450 (0.55)		500 (0.54)	440 (0.41)
	II				460 (0.41)		700 (0.45)	550 (0.48)
	III						1,300 (0.42)	1,100 (0.45)
Fin	I			2,000 (0.40)	2,300 (0.40)			2,100 (0.36)
	II				1,100 (0.50)			2,100 (0.45)
	III							5,500 (0.53)
Sperm	I			3,000 (0.30)	3,200 (0.39)	5,300 (0.39)		5,400 (0.38)
	II				14,000 (0.19)	11,400 (0.18)		10,000 (0.15)
	III					7,900 (0.19)		8,300 (0.16)
Humpback	I			4,000 (0.20)	4,500 (0.23)	5,300 (0.39)	7,400 (0.38)	7,100 (0.36)
	II				5,600 (0.28)	9,700 (0.27)	10,000 (0.27)	9,200 (0.29)
	III					8,600 (0.26)	9,300 (0.23)	9,300 (0.22)
Killer	I	180,000 (0.59)		70,000 (0.20)	64,000 (0.30)			91,000 (0.34)
	II				53,000 (0.30)			27,000 (0.26)
	III							25,000 (0.23)
Southern bottlenose	I							– (–)
	II							72,000 (0.13)
	III							54,000 (0.12)

Table 12

Comparable estimates of abundance for each circumpolar set of cruises. 'Baseline' estimates are the uncorrected abundance estimates presented in Table 10. 'Comparable area' estimates adjust the baseline estimates so that they are for comparable areas. 'Comparable + like sp.' estimates also include like species sightings in the estimates for comparable areas. See text for further details.

Species	Circumpolar set	Baseline		Comparable areas		Comparable + like sp.	
		Abundance	CV	Abundance	CV	Abundance	CV
Blue	I	438	0.41	546	0.41	546	0.41
	II	549	0.48	611	0.49	606	0.49
	III	1,069	0.45	1,250	0.45	1,555	0.46
Fin	I	2,057	0.36	2,410	0.36	2,410	0.36
	II	2,144	0.45	1,370	0.46	1,401	0.48
	III	5,455	0.53	4,850	0.54	8,036	0.58
Sperm	I	5,367	0.38	9,178	0.43	9,178	0.43
	II	10,450	0.15	8,292	0.15	8,447	0.15
	III	8,329	0.16	11,599	0.20	12,268	0.19
Humpback	I	7,057	0.36	9,242	0.37	9,242	0.37
	II	9,236	0.29	7,089	0.29	7,096	0.29
	III	9,289	0.22	10,808	0.21	11,314	0.20
Killer	I	91,310	0.34	121,134	0.35	130,867	0.35
	II	27,168	0.26	23,570	0.26	23,570	0.26
	III	24,790	0.23	26,452	0.23	26,452	0.23
Southern bottlenose	I	-	-	-	-	-	-
	II	71,560	0.13	78,008	0.13	81,067	0.13
	III	53,743	0.12	56,011	0.12	63,971	0.13

1997/98 survey data and changed truncation distances. Further species-specific aspects of these comparisons are discussed below.

Blue whale estimates

In terms of distribution, the survey coverage (designed for minke whales) is also reasonable for blue whales (e.g. Horwood, 1986). It is tempting to argue for an increase in true blue whales, given that the estimates reported increase from 440 (CV = 0.41) and 550 (CV = 0.48) in the first two circumpolar sets of surveys to 1,100 (CV = 0.45) in the most recent. The apparent increase is supported by the observation that most of the 'like blue' sightings occurred during the third circumpolar set of surveys. However, this trend is not significant when comparable areas are taken into account.

Brown and Butterworth (1999) had pooled blue whale sightings over all surveys to obtain their abundance estimates, so it is encouraging that pooling separately for each circumpolar set of surveys makes little difference to the results. The earliest estimate for the first circumpolar set by Butterworth and Dudley (1984) was higher primarily because of their use of a negative exponential rather than the hazard rate function for fitting the detection function $f(y)$ to the sightings data to estimate search half-width.

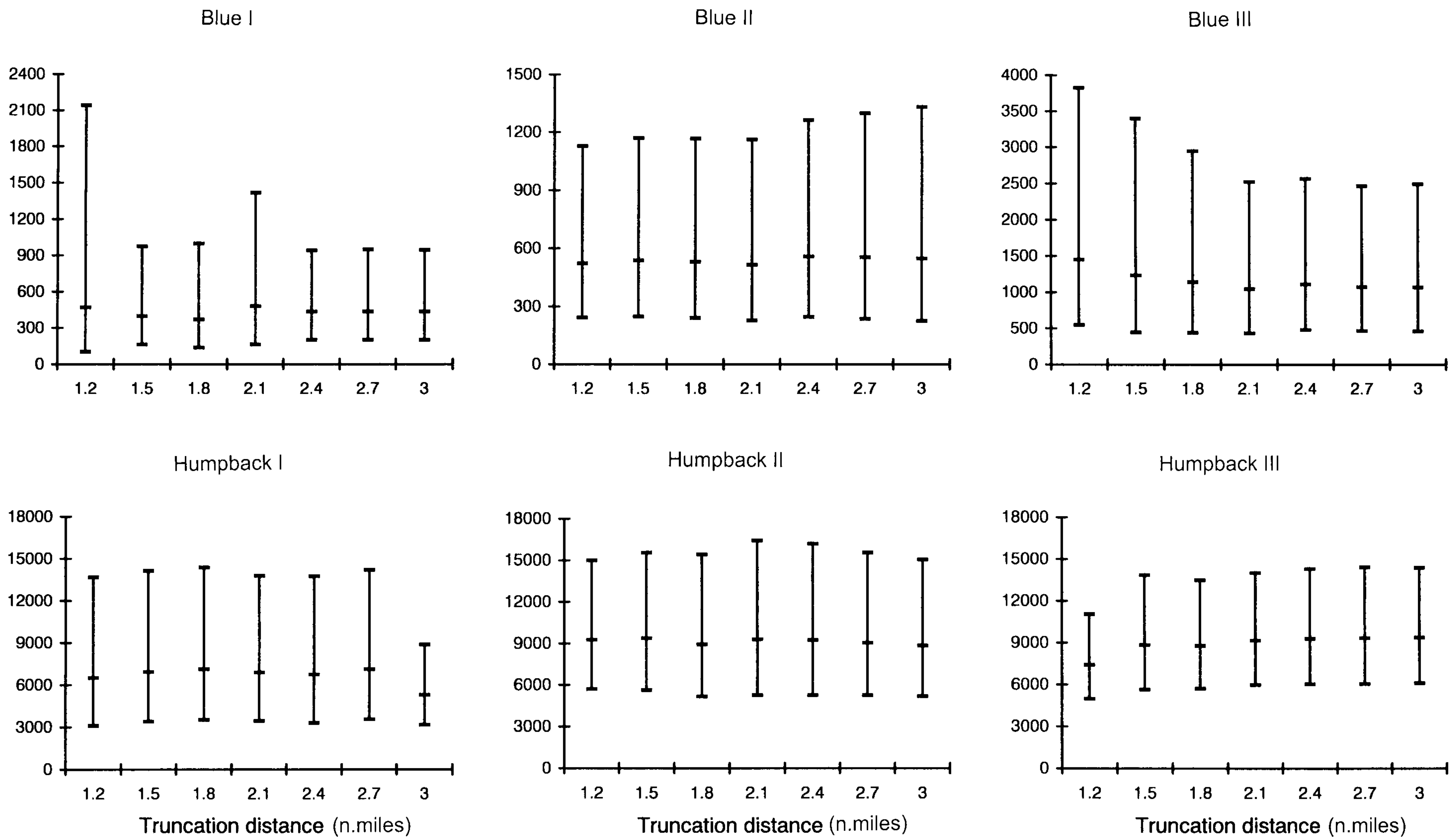


Fig. 4. Changes in abundance estimates for blue whales and humpback whales at different truncation distances (n.miles). In the baseline analyses, a truncation distance of 3 n.miles is used for blue whales and 2.4 n.miles for humpback whales. The estimates and 95% confidence intervals according to the prescription of Buckland (1992) are indicated.

Table 13

Sensitivity of baseline abundance estimates to various analysis options: changing the truncation distance of 1.5 n.miles (the distance used for minke whales); the inclusion of 'like species', where the observer could not be certain of species identification; the exclusion of mixed species schools from the analysis; the exclusion of only definite duplicates/triplicates (instead of excluding both definite and possible duplicates/triplicates); and obtaining separate estimates from closing mode and passing mode data. Surveys were conducted in closing mode only for the first circumpolar set of surveys, where duplicates do not occur.

	Blue		Fin		Sperm		Humpback		Killer		S. bottlenose	
	No.	CV	No.	CV	No.	CV	No.	CV	No.	CV	No.	CV
First circumpolar												
Baseline	438	0.41	2,057	0.36	5,367	0.38	7,057	0.36	91,310	0.34	-	-
Truncate at 1.5 n.miles	399	0.48	2,198	0.36	5,367	0.38	6,948	0.38	75,397	0.34	-	-
Incl. like species	438	0.41	2,057	0.36	5,367	0.38	7,057	0.36	99,642	0.34	-	-
Excl. mixed schools	315	0.37	1,666	0.34	5,367	0.38	6,739	0.38	79,367	0.34	-	-
Second circumpolar												
Baseline	549	0.48	2,144	0.45	10,450	0.15	9,236	0.29	27,168	0.26	71,560	0.13
Truncate at 1.5 n.miles	539	0.41	2,062	0.42	7,666	0.13	9,362	0.26	28,497	0.27	71,560	0.13
Incl. like species	544	0.48	2,373	0.49	10,507	0.15	9,291	0.29	27,168	0.26	73,972	0.13
Excl. mixed schools	530	0.49	2,620	0.44	10,450	0.15	8,828	0.30	27,429	0.27	71,560	0.13
Excl. definite duplicates	559	0.47	2,173	0.44	10,510	0.15	9,236	0.29	27,168	0.26	71,908	0.12
Closing mode only	[1]	[1]	[1]	[1]	13,278	0.28	9,692	0.33	43,691	0.38	73,315	0.16
Passing mode only	[1]	[1]	[1]	[1]	11,362	0.18	9,806	0.45	24,647	0.28	67,468	0.16
Third circumpolar												
Baseline	1,069	0.45	5,455	0.53	8,329	0.16	9,289	0.22	24,790	0.23	53,743	0.12
Truncate at 1.5 n.miles	1,233	0.55	4,268	0.46	6,880	0.16	8,841	0.23	24,914	0.23	53,743	0.12
Incl. like species	1,337	0.47	8,799	0.56	8,932	0.15	9,436	0.21	24,790	0.23	61,329	0.12
Excl. mixed schools	1,108	0.47	6,923	0.55	8,142	0.16	8,801	0.22	22,402	0.24	52,906	0.12
Excl. definite duplicates	1,069	0.45	5,455	0.53	8,356	0.16	9,230	0.22	24,790	0.23	53,961	0.12
Closing mode only	[1]	[1]	[1]	[1]	9,298	0.23	9,921	0.35	21,033	0.26	57,906	0.17
Passing mode only	[1]	[1]	[1]	[1]	7,937	0.20	8,316	0.26	17,117	0.29	48,097	0.16

[1] Separate closing and passing mode estimates were obtained only for species with large numbers of sightings.

Fin whale estimates

Although fin whales are found extensively south of 50°S, they are most common north of 60°S (e.g. Miyashita *et al.*, 1995; Rice, 1998) and thus the surveyed area does not represent their complete summer distributional range. The estimates therefore represent an unknown fraction of their total abundance. Between the second and the third circumpolar sets, estimates more than doubled, related to an increase in the estimated school size from 2.04 and 1.62 in the first two sets to 4.06 in the third set. The increase in abundance is significant after accounting for 'like species' and comparable areas. It is probable that the greater latitudinal range covered in the third circumpolar set is the reason for this apparent significant difference. It is likely that for fin whales, the density in the unsurveyed northern areas is much higher than in the northern strata, but in obtaining the 'comparable estimates', the assumption is made that these densities are the same.

Sperm whale estimates

Although good precision was obtained for the two most recent sperm whale estimates, there was no significant trend in abundance for comparable areas. Most sightings in the IDCR-SOWER surveys are of solitary males because sperm whales are latitudinally segregated by size and sex, with females rarely found south of 40°S, and male school size decreasing southwards (e.g. Best, 1979). In addition, their long dive times and solitary nature in the Southern Ocean imply that many schools on the trackline are missed, although in the absence of additional information, the analysis here has assumed that 100% of the schools on the trackline are sighted. Sperm whale estimates should therefore be considered as (possibly highly) negatively biased estimates of mature males in the Southern Ocean.

Humpback whale estimates

The distribution of humpback whales during the period of the surveys largely coincides with the survey area, although some concentrations are found between 50°S and 60°S (e.g. Miyashita *et al.*, 1995). There is no clear indication of an upward trend in humpback whales for comparable areas, although the power of detecting a trend with the IDCR-SOWER surveys is low. The coverage for the third circumpolar set of surveys is incomplete primarily in regions south of Australia; perhaps when this area has been surveyed, the IDCR-SOWER data will offer clearer support for the upward trends identified in both east and west coast near-coast surveys in Australia (e.g. Bannister, 1994; Brown *et al.*, 1997).

Killer whale estimates

The significantly larger estimate of killer whale abundance for the first circumpolar set is partly a reflection of a larger mean school size estimate (17.1 vs 7.2 and 12.3 in the later circumpolar sets). Butterworth *et al.* (1994) found a significant decrease in mean school size for killer whales when moving from southern to northern strata, a feature not evident for other species. Therefore, a case exists for stratifying killer whale abundance estimates by north vs south strata, but doing so leads to little change in point estimates or precision. A plausible explanation for this trend in estimates is provided by noting that killer whales are found in much higher densities near to the ice edge, with a marked decrease in density with increasing distance from the ice edge (Kasamatsu *et al.*, 2000). The different cruise track design for the first five surveys, with the accompanying assumption to treat density in the unsurveyed 'U' strata as the average of that in the 'S' and 'N' strata, may thus have introduced a marked positive bias in the abundance estimates for the first circumpolar set of surveys for this species. The larger-still estimate for the first four surveys of this circumpolar set obtained by Hammond (1984) results from a number of factors (see Butterworth *et al.*, 1994), most importantly the use of a generalised exponential rather than a hazard rate function for the detection function $f(y)$, which resulted in a considerably smaller estimate of w_s.

Southern bottlenose whale estimates

Southern bottlenose whales are the most frequently sighted whales after minke whales on the surveys. Estimates are encouragingly precise with CVs of less than 15%, but are likely substantially downwardly biased. Bias arises because many of these whales on the trackline are missed because of their long dive times (up to two hours) and wariness of vessels (Kasamatsu, 2000). In addition, uncertain species identification has resulted in many sightings, even in the second and third circumpolar sets of surveys, being recorded as 'like southern bottlenose', 'Mesoplodon sp.' or 'beaked whale'. In the three sets of surveys, only 5%, 60% and 71% respectively of the beaked whale sightings were identified to the species level; nearly all of the unidentified sightings were probably southern bottlenose whales.

Sensitivity analyses

Excluding definite duplicates/triplicates and mixed species schools had little impact on the abundance estimates. The inclusion of 'like species' increased abundance estimates for blue whales and fin whales in the third circumpolar set of surveys by 25% and 61% respectively, but had little impact on estimates for other species.

The sensitivity tests revealed that discontinuous jumps in estimated school size are possible with the inclusion of a single extra sighting. In this paper, the regression method of estimating school size was preferred for sensitivity tests if the baseline abundance extraction had a significant correlation (at the 15% level) between *ln*(school size) and the detection function. Further work is needed on the method of school size estimation used in the 'standard analyses' but is beyond the scope of this paper.

It is surprising that when closing and passing mode estimates are obtained separately, the closing mode point estimates exceed those from passing mode in seven out of eight instances. For minke whales, the estimates from passing mode are normally higher than those from closing mode, primarily because of the extra observer during the IO variant of passing mode (Haw, 1991). An additional factor is that diverting off the trackline in closing mode to confirm species and school size may undersample areas of higher minke whale density, since sightings recorded during such diversions (secondary sightings) are not included in the analyses. If there is a negative correlation between the density of minke whales and that of the other species, closing mode could lead to undersampling of *lower* density regions for the other species. This negative correlation exists between minke and sperm whales (Kasamatsu *et al.*, 2000).

CONCLUSIONS

Estimates of summer abundance in the Southern Ocean south of 60°S were obtained for several species using 'standard methodology' developed for minke whales. Departures from this methodology were necessary because of low numbers of sightings, but these changes did not result in any major bias in the estimates. When estimates from comparable areas were calculated, only two significant trends in abundance over time were detected, but both of these can be explained by changes in latitudinal coverage and survey methods. Estimates for some species (blue, fin and humpback whales) seem reasonable, but the following specific problems afflict estimates of other species.

(1) Sperm and southern bottlenose whales have long dive times and it is likely that many schools on the trackline were missed, introducing negative bias to these estimates.
(2) Killer whale estimates in the first circumpolar should be treated as positively biased because the southern vessels followed the ice-edge in the first five surveys.
(3) The temporal and geographical coverage of the surveys was determined in order to obtain good estimates of Antarctic minke whales. To a greater or lesser extent these are less suitable for other species so that the estimates presented should not be seen as representing total Southern Hemisphere populations.

A potentially major issue affecting all the estimates is the assumption that 100% of schools on the trackline are sighted. This assumption introduces at least some negative bias into all the estimates presented. Estimating the magnitude of this factor for minke whales has proved elusive, and can be expected to be even harder for other species given their lower numbers of sightings. Future research should consider estimating the bias in estimates for each species caused by this assumption.

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