Southern Hemisphere minke whales: standardised abundance estimates from the 1978/79 to 1997/98 IDCR-SOWER surveys

T.A. Branch[#+] and D.S. Butterworth[#]

Contact e-mail: tbranch@u.washington.edu

ABSTRACT

Minke whale abundance estimates, standardised by the use of consistent methodology throughout, are presented from the IWC/IDCR and SOWER Antarctic circumpolar sightings surveys for three circumpolar sets of cruises: 1978/79–1983/84, 1985/86–1990/91 and 1991/92–1997/98 (*still incomplete). The database estimation package DESS is used to obtain these standardised estimates. Two survey modes (closing and IO) are used in the surveys; IO mode is considered to provide less biased estimates. An updated estimate for the conversion factor from closing to 'pseudo-passing' mode of $R = 0.826$ (CV = 0.089) is obtained. IO and 'pseudo-passing' estimates are then combined using inverse-variance weighting to give estimates of 608,000 (CV = 0.130), 766,000 (CV = 0.091) and 268,000* (CV = 0.093) for the three circumpolar sets of cruises. These cruises have covered approximately 65%, 81% and 68% of the ice-free area south of 60°S. As estimates of abundance for Southern Hemisphere minke whales, these are negatively biased because some areas inside the pack ice cannot be surveyed, not all whales migrate into the area south of 60°S, the assumption is made that all whales on the trackline are sighted, and minke whale sightings for which species identification is uncertain ('like minkes') are omitted. The three circumpolar estimates are extrapolated simply to account for the different areas covered in the sets of surveys, and also for the increasing proportion of 'like-minke' sightings over time. The results suggest that for comparable areas the abundance estimates for the third circumpolar set of cruises are 55% (closing mode only) and 45% (IO mode only) of those for the second set, but that the first and second set estimates are within 15% of each other. The decrease in abundance between the second and third sets is statistically significant at the 5% level. Possible reasons for this estimated decline are discussed, related both to factors that might render the estimates non-comparable, and to population dynamics effects that could have led to a real decline. Further attention should be given, in particular, to the most appropriate method for estimation of mean school size for these surveys.

KEYWORDS: ANTARCTIC MINKE WHALE; SOUTHERN HEMISPHERE; ANTARCTIC; ABUNDANCE ESTIMATE; SURVEY-VESSEL

INTRODUCTION

There has been some recent controversy over the current status of Antarctic minke whales (*Balaenoptera bonaerensis*). The best source of data to address this issue is the series of 22 consecutive annual surveys conducted almost exclusively south of 60°S between 1978/79 and 1999/2000. The first 18 surveys fell under the IWC's IDCR programmes (International Decade of Cetacean Research) and the last four under its SOWER circumpolar programme (Southern Ocean Whale and Ecosystem Research). These surveys may be divided into three circumpolar sets of cruises: 1978/79–1983/84, 1985/86–1990/91 and 1991/92–1999/2000 (incomplete). The 1984/85 cruise was devoted mainly to experiments, and is normally excluded from abundance analyses (e.g. Brown and Butterworth, 1999). The data are at present encoded and validated as far as the 1997/98 cruise, and are contained in a database package DESS (IWC Database-Estimation System Software v 3.0 - Strindberg and Burt, 2000), which automates the process of extraction and abundance estimation. This paper is deliberately restricted to estimation procedure options available in DESS, in part to ensure that the results presented are readily replicable.

Abundance estimates for minke whales have previously been calculated for each survey separately - most recently by Burt and Stahl (2000) for the 1997/98 cruise. However, the original data were thoroughly re-checked when they were being entered in DESS in recent years, resulting in minor changes to the sightings and effort data and to the areas of the open ocean regions associated with the survey strata. Furthermore several aspects of the estimation process adopted by the IWC Scientific Committee have changed over the period of the assessments (as summarised in Appendix 1). The most recent change was to the mean school size ($\bar{s}$) estimation method from the 1995/96 survey onwards (Burt and Borchers, 1997). The effective search half-width (w) has been estimated by fitting a hazard-rate function to the perpendicular distance (y) distribution data from the 1985/86 survey onwards (Butterworth and Silberbauer, 1987). In general, estimates of $\bar{s}$ and w have been calculated on a stratum- and vessel-specific basis, but in certain cases small sample size forces some pooling. The pooling rationale was *ad hoc* in the earlier assessments, but from the 1993/94 survey (Borchers and Burt, 1996) onwards, Akaike's Information Criterion was used (AIC, Akaike, 1973). A contouring method was used to convert daily density estimates into abundance for the surveys from 1978/79 to 1982/83 (e.g. Best and Butterworth, 1980) before it was supplanted by the current approach of treating segments of search effort as random and independent samples within pre-defined strata.

These changes in the assessment methodology have resulted in a growing incomparability between earlier and more recent abundance estimates. Butterworth *et al.* (1987 - see also IWC, 1988, Appendix 7) revised the estimates from the 1978/79 to 1983/84 cruises, fitting the hazard-rate function for w and also stratifying the areas surveyed. Haw corrected and extended that series to the 1988/89 survey, to provide the estimates used for the 1990 Comprehensive

[#] *MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.*
[+] Current address: *Box 355020, Department of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, 98195-5020, USA.*

Assessment of Southern Hemisphere minke whales (IWC, 1991, p.117). These were marginally further corrected in Haw (1993b). The Comprehensive Assessment selected the most recent cruise at that time in each of the six Antarctic Management Areas (see Fig. 1 and Donovan, 1991) to provide the best individual estimates of minke whale abundance. These estimates sum to the widely quoted circumpolar estimate of 760,000 (CV = 0.098) for Southern Hemisphere minke whales. This figure was considered at that time (IWC, 1991, pp.120-21, 130) to be representative of abundance in the mid-1980s, but is no longer regarded as an appropriate estimate of current abundance (IWC, 2001, p.31). Accordingly, an updated set of estimates is timely, especially given that the IWC Scientific Committee is planning a thorough review of minke whale abundance estimates commencing in 2001. This paper therefore presents revised estimates of abundance from each survey between 1978/79 and 1997/98, using methodology available in DESS applied consistently throughout this time period.

METHODS

The methodology outlined in Burt and Stahl (2000) (referred to here as the 'standard methodology' or 'standard analyses'), together with their notation, is followed here as far as possible for obtaining abundance estimates from each survey. Points of departure are expanded upon below where appropriate. This standard methodology is essentially that adopted by the IWC Scientific Committee in 1992 (IWC, 1983, p.106), except for the subsequent procedure adopted for mean school size estimation (see Appendix 1).

Survey modes and activity codes

Searching on the surveys is restricted to Beaufort states of 5 or less. The searching speed was originally 12 knots, but was reduced in 1987/88 to 11.5 knots in order to assist in fuel efficiency and reduce vibration. Further details of the survey procedures (and experiments) on the first ten cruises are summarised in Joyce *et al.* (1988); for later years, such details can be found in the annual cruise reports (e.g. Ensor *et al.*, 1998 for the 1997/98 survey).

Survey effort is divided into closing mode and IO (independent observer) mode. The first circumpolar set of surveys was conducted in closing mode only, i.e. when a school is sighted, the vessel suspends primary searching effort, turns[1] off the trackline and closes with the sighting. This mode enables better species identification and school size estimation. Later surveys (from 1984/85) alternated between closing and IO mode. In IO mode, the vessel continues steaming along the trackline after a sighting, with observers in the barrel and the IO (independent observer) platform[2] (both located on the main mast) maintaining full search effort while those on the upper bridge concentrate on tracking and identifying the sighting. IO mode was introduced because of concern about possible biases introduced into density estimation by the closing mode procedure: for example, upward bias through deviations from the trackline drawing the vessel into preferentially higher density areas, downward bias from neglect of 'secondary sightings' while the vessel closed off primary effort on an original sighting, and the many end effects that arise from frequently switching on and off primary search effort to close with sightings. IO mode was intended as the standard, with closing mode retained because of the unreliability[3] of school size estimation and species identification in IO mode (many of the sightings are not approached closely in this mode).

A number of activity codes are used to distinguish between different aspects of these main modes. The following codes are used for closing mode and IO mode in these analyses (*denotes those used in the 'standard analyses'). More details of the different codes can be found in Strindberg and Burt (2000); a summary of the amount of primary search effort under each code in each survey is given in Branch and Butterworth (2001, table 4).

Closing mode
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).

IO mode
BI*: Ice navigation in passing mode reduces the effective search effort.
BO*: Passing mode with independent observer in position (i.e. standard IO mode).
BU: Cue counting from the bridge during BO mode (1986/87 survey only).
BQ: Passing with independent observer tracking (1987/88 survey only).

Excluded activity codes
BP: Passing mode with no independent observer.
BH: High density of schools in IO mode causes difficulty in discriminating between schools.
BL: High density of schools in closing mode causes difficulty in discriminating between schools.

In the first six surveys, closing mode search effort data were always recorded under the SE code - for the later surveys this was split into BC and BR to distinguish between these two components. Almost all of the effort recorded by vessel *Shonan Maru 2* in 1986/87 was under the BU code, which is included here since the manner in which cue counting was conducted did not compromise the normal collection of sightings data. The codes BB and BQ were used only in 1987/88, where they comprised 20% of closing mode and 44% of IO mode effort respectively, so that their exclusion would compromise the representative nature of the remaining data for that survey.

In practice, no effort during closing mode survey was recorded as BL. In IO mode, the recorded school sighting rate under BH is some six times the average over the other

[1] In some of these earlier cruises, the turn was delayed until the angle between the sighting and trackline became larger, to better estimate perpendicular distance from the trackline, but this practice was later discontinued as it increased the chance of losing track of sightings.

[2] The additional observer in the IO platform in this mode was introduced to provide data for the estimation of $g(0)$, the probability that a school on the trackline is sighted (e.g. Butterworth and Borchers, 1988). The observers in the standard barrel and the IO platform are kept unaware of each others sightings.

[3] This unreliability was confirmed by 'SSII' experiments, which indicated school size estimation in passing/IO mode to be negatively biased by about one third (IWC, 1987, p.70).

codes for this mode, but since only 0.2% of the total IO effort is specified as BH, neglect thereof does not introduce any substantial bias.

Only sightings of schools comprised entirely of minke whales are used for the analyses of this paper[4]. Sightings and search effort are included only if they were recorded inside the survey region, during primary search effort, and outside periods when experiments were conducted.

Survey vessels

Up to four vessels were used in the earlier cruises. Most of the sightings data have come from the *Shonan Maru* and *Shonan Maru 2* (SM1 and SM2) which have been used in every survey since 1981/82. The *Kyo Maru 27* (K27) was used in five surveys to 1986/87, the *Toshi Maru 11* (T11) in the second and third surveys, and the *Toshi Maru 16* and *18* (T16 and T18) in the first survey only. During the 1980/81 to 1986/87 cruises, the *Vdumchivy 34* (V34) or the *Vderzhanny 36* (V36) was used predominantly to map the ice edge and for marking, so their sightings and effort data are excluded, as for previous analyses.

Species codes

The recommendations of Branch and Ensor (2001) regarding interpretation of the various species codes used for minke whales have been incorporated into DESS 3.0. Thus over 1978/79-1996/97, minke whales were recorded as code 04, and 'like minke' whales as code 39. From the 1993/94 survey, code 74 was introduced for dwarf minke whales, following recognition that this sub-species could be present in the region covered by these surveys. Dwarf minke whales have not yet been formally named, but are closer to ordinary minke whales (*Balaenoptera acutorostrata*) than to Antarctic minke whales (*B. bonaerensis*) in several respects (e.g. Best, 1985; Kato and Fujise, 2000). To distinguish whether identification was uncertain at the species or sub-species level, further codes were introduced for the 1997/98 survey. For that survey, codes 04, 90, 91 and 92 are taken to be minke whales, and code 39 is considered to be 'like minke'[5]. Estimates in this paper referring to 'minke whales' are put forward as estimates for Antarctic minke whales, although it is possible that these estimates include a very small proportion of dwarf minke whales (Kato and Fujise, 2000). Only two sightings of dwarf minke whales have been recorded in the survey regions since a code for this sub-species was introduced in 1993/94. However, it can be difficult to distinguish dwarf minke whales from Antarctic minke whales, particularly for distant sightings made in IO mode (P. Best, pers. comm.).

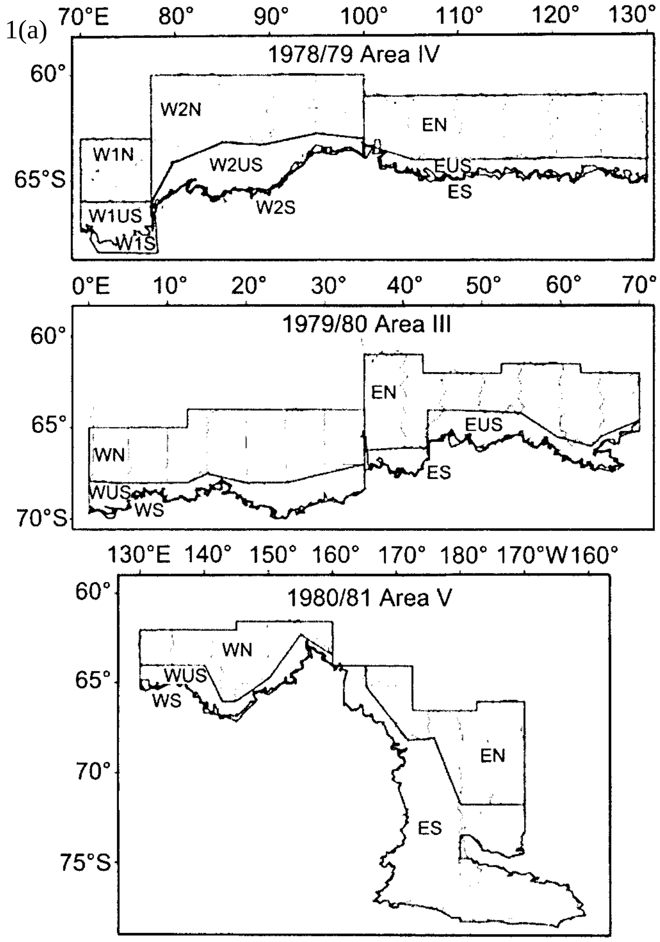


Fig. 1a. Strata surveyed in each year from 1978/79 to 1980/81. The southern boundary for each survey was the ice edge. Bold lines indicate the stratum boundaries, whilst cruise tracks are indicated by lighter lines. Only primary search effort (closing mode and IO mode data are combined) is indicated; 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.

Note that Figs 1b–f are given on the following two pages.

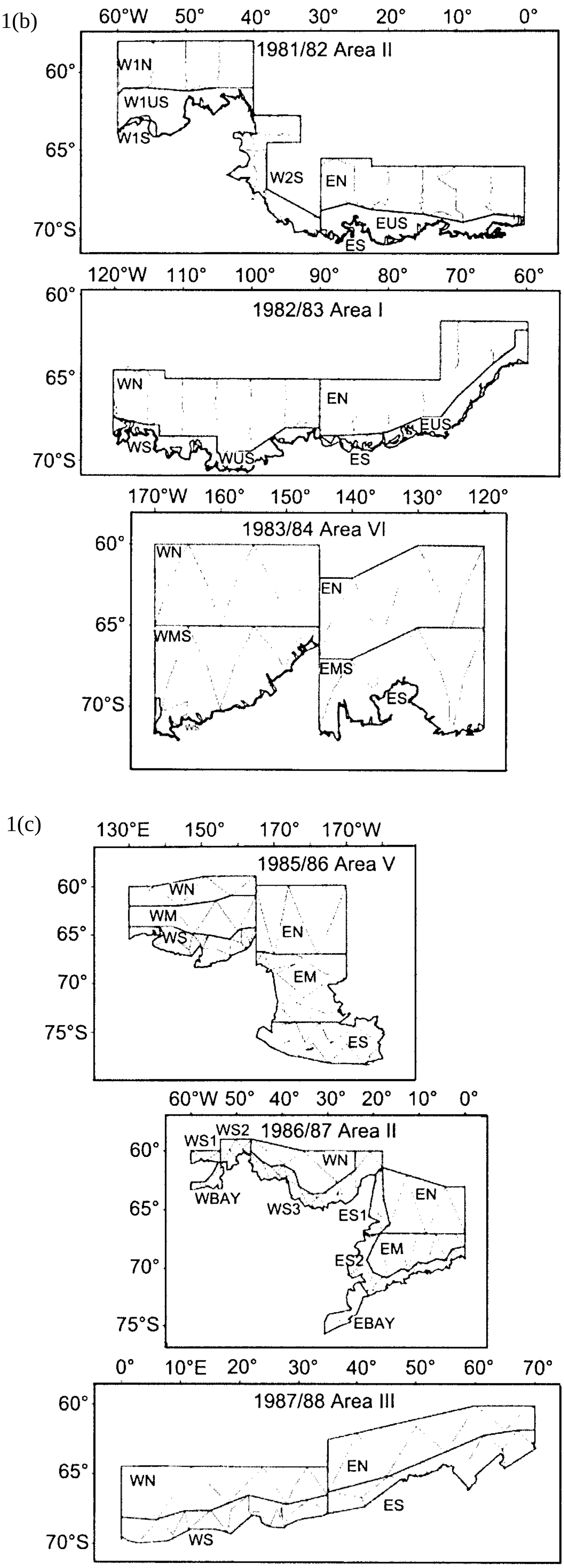
Strata and cruise tracks

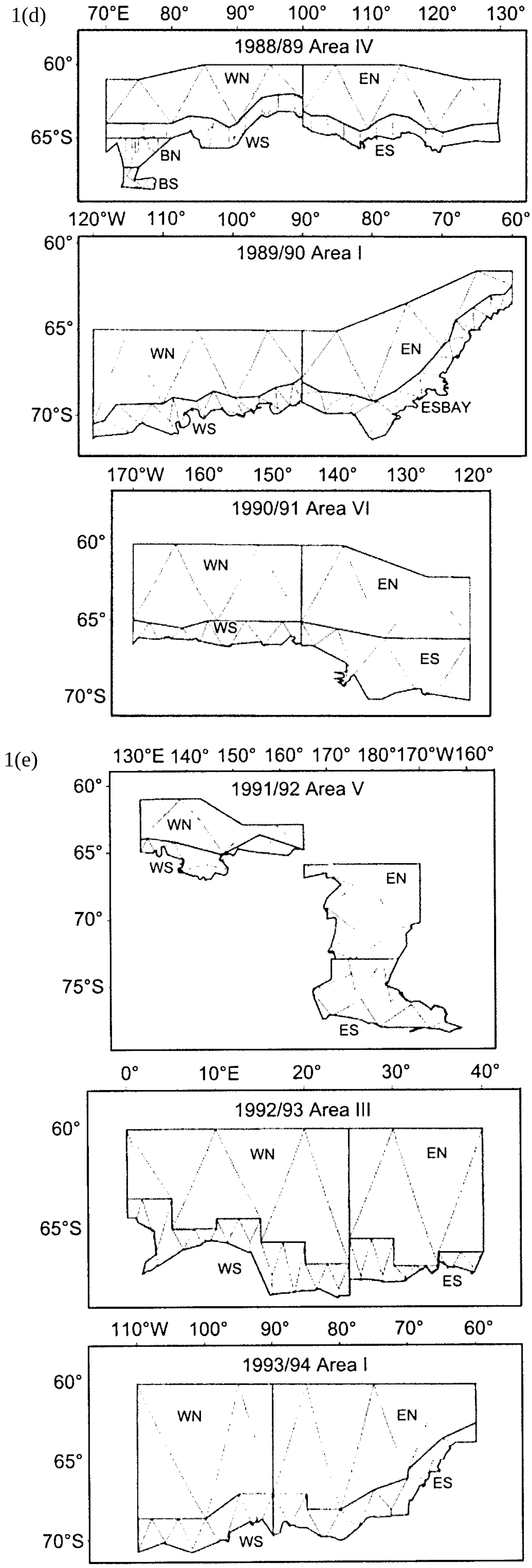
When these IDCR surveys were first planned in 1978, mark-recapture methods were conceived as the primary basis to estimate abundance, with sightings playing a secondary role only. This required marking as many whales as possible, so that the effort of one of the two survey vessels was concentrated close to the ice-edge where the greatest minke whale densities were expected. This changed from the 1983/84 cruise for two reasons: (1) minke whale abundance turned out to be considerably larger than anticipated when the programme was planned such that the resultant low number of recaptures gave estimates with notably worse precision than had been expected from these surveys; (2) the decision taken in 1982 to impose a moratorium on commercial whaling three years thereafter removed the basis to obtain recaptures. As a result, sightings became the primary data source to estimate abundance.

The areas surveyed by each cruise are outlined in Figs 1a-f, together with the tracklines followed while on primary effort. It is immediately obvious that the survey design for most of the first circumpolar set of surveys (Figs 1a-b) differed from that in later cruises. In the first five of these

[4] Since 1993/94, schools of more than one species have been recorded using different sighting forms for each species, so that such 'mixed' schools are included in these analyses. Prior to that date they are excluded, as has been past analysis practice; this represented less than 0.5% of schools of minke whales only (see Branch and Butterworth, 2001, table 3), so alternative choices here would hardly impact final estimates.

[5] In the 1997/98 survey, the codes in DESS 3.0 are: 04: definitely Antarctic minke; 39: like minke: probably a minke, but not certain; 74: definitely dwarf minke; 90: definitely minke and probably dwarf minke, but not certain; 91: definitely minke, but unsure whether Antarctic or dwarf; 92: definitely minke and probably Antarctic minke, but not certain.





Figs 1b to 1e. Strata surveyed in years 1981/82 to 1993/94. Details as for Fig. 1a.

1(f)

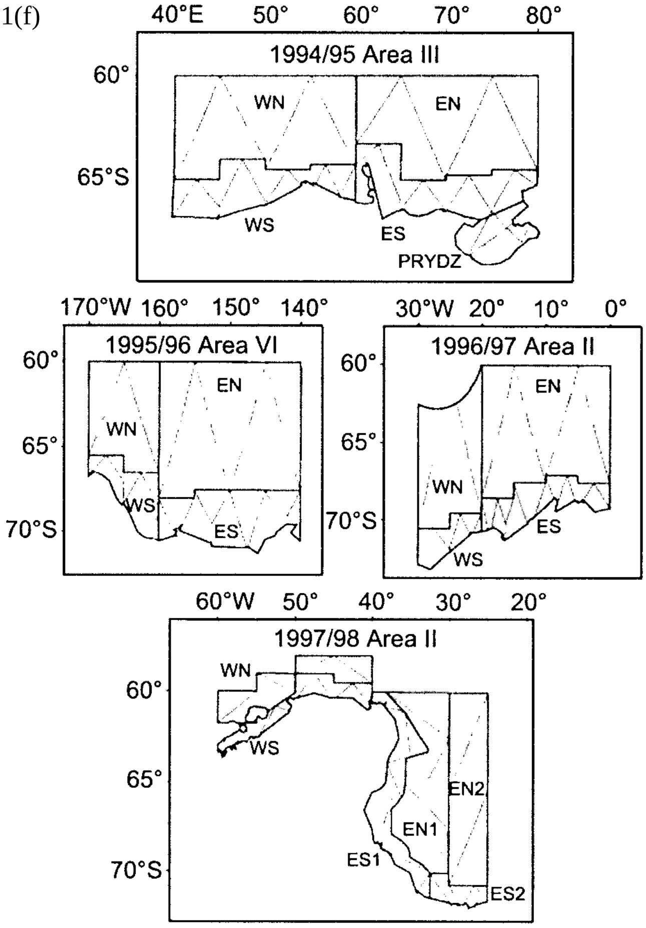


Fig. 1f. Strata surveyed in years 1994/95 to 1997/98. Details as for Fig. 1a. Note that the circular 'bite' missing from the WN stratum in 1996/97 falls within the EEZ of the South Georgia and South Sandwich Islands.

early cruises, one vessel followed the ice-edge[6] closely (the 'S' strata), while another vessel alternated between latitudinal and longitudinal legs (the 'N' strata), typically 60 n.miles or more north of the pack ice. An unsurveyed area ('US') generally remained between the 'S' and 'N' strata. The 'S' strata were considered to cover an area twice that between the ice-edge and the vessel's trackline. In 1987, the IWC Scientific Committee decided to assign the average density of whales in the 'S' and 'N' strata to this unsurveyed area, thus effectively adding half the area of each 'US' stratum to the area of the corresponding 'S' and 'N' strata (IWC, 1988, pp.77-8). This approach was considered reasonable based on 'density gradient' experiments conducted in 1980/81 and 1981/82 to check the rate of minke whale density fall off away from the ice-edge (Butterworth *et al.*, 1982; 1984a). These suggested that averaging the density estimates in this manner would not introduce substantial bias in the abundance estimates. Typically (see Figs 1a-f) the 'S' strata for the second and third circumpolar sets of cruises cover comparable latitudinal ranges to the 'S' and 'US' strata combined for the first five cruises. These later cruises thus contain further information about the pattern of minke whale density with distance from the ice-edge in the 'US' regions, which could be used to refine this 1987 decision.

[6] The 'ice-edge' is generally the edge of the pack ice. In the first two circumpolar sets of surveys, the ice-edge was determined by dedicated vessels, but the JIC satellite system was used to map the ice-edge in later cruises. There are often large areas of open water inside the ice-edge which are not accessible to the survey vessels, but would be suitable habitat for minke whales.

There are two exceptions to this general pattern in the first six cruises. First, the 1980/81 ES stratum and the 1981/82 W2S stratum are not divided into 'S' and 'US' portions since there was some search effort in the centre of each of these areas. Secondly, for the 1983/84 survey, the data from the vessel following the ice edge are not used in the standard DESS stratification (for convenience) since the middle vessel covered the entire region south of the 'N' strata (i.e. the WMS and EMS strata are included, but the WS and ES strata are omitted, in abundance estimation). In addition, in the 1983/84 cruise, vessels off the ice edge followed the zigzag cruise-track design that was to be used in subsequent cruises.

The second and third sets of circumpolar cruises followed a zigzag cruise-track design within each stratum (Figs 1c-f)[7]. The survey region was typically divided into four strata: WN, WS, EN and ES. Exceptions occur when there are bays in the south strata (e.g. the Ross Sea in Area V).

There are differences in the latitudinal coverage of the survey regions (Figs 2a-c). In the first and second circumpolar sets of cruises, coverage between the ice edge and 60°S was not complete (except for Area V in 1985/86). In contrast, in the third circumpolar set of cruises, the entire area south of 60°S was always surveyed (except for Area V in 1991/92). The three sets of surveys reflect coverage of roughly 65%, 81% and 68% of the open ocean area south of 60°S respectively; the last figure reflects the incomplete nature of the third circumpolar set of cruises as at 1997/98. This raises problems of comparability between abundance estimates from the three different sets of cruises, as discussed later.

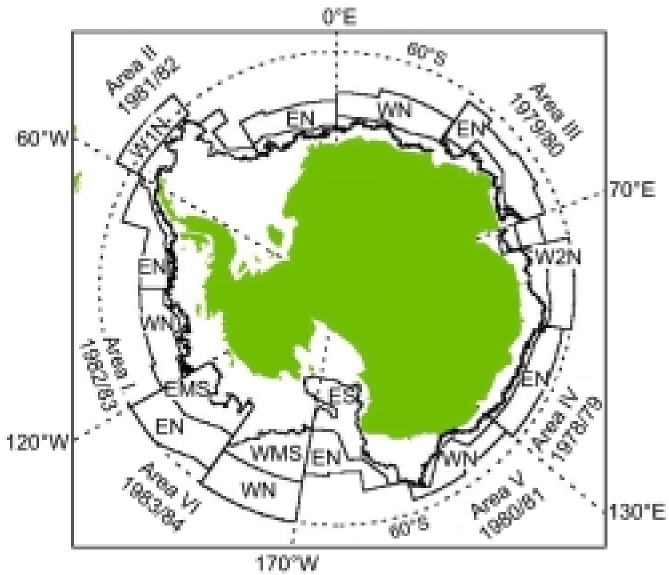
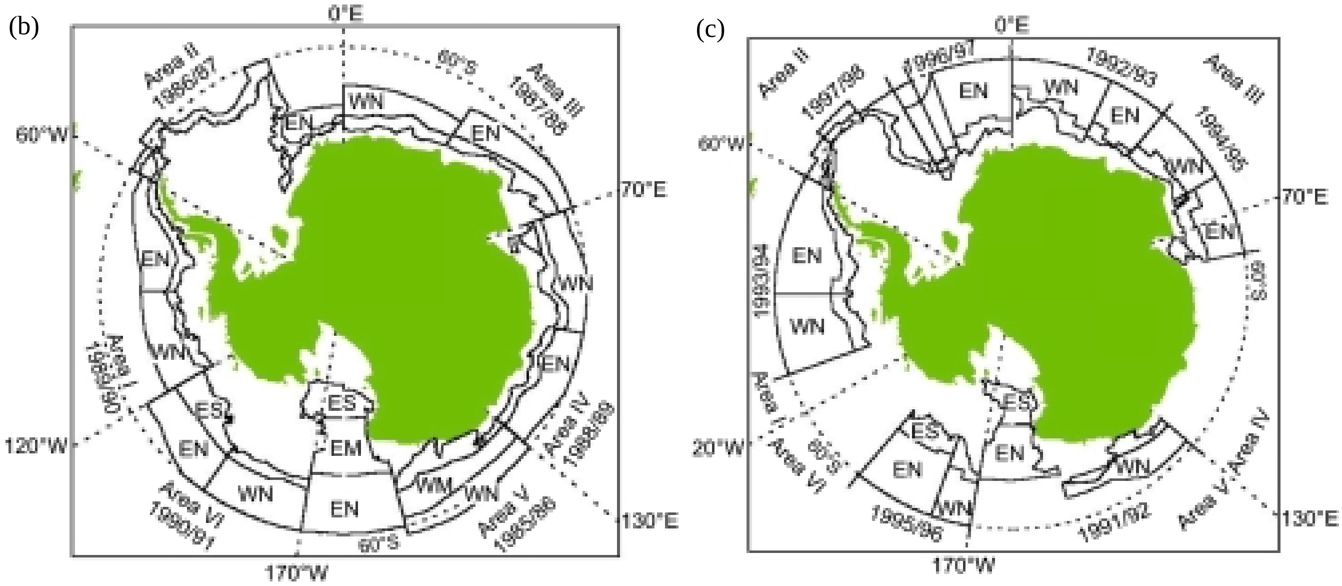


Fig. 2a. The area surveyed by the first circumpolar cruise.

[7] Although the cruise tracks shown in Figs 1c-f may seem to reflect similar designs, there was in fact an underlying change effected from the 1992/93 cruise. Between 1984/85 and 1991/92, the track design algorithm used as the cruise proceeded was developed to enable subsequent abundance computation using a Horvitz-Thompson estimator approach. This required the ability to separately estimate the probability of sighting each school (e.g. Cooke, 1987). Later, however, with the prospect of abundance estimates being required for 5º longitude sectors to relate to the *Small Areas* adopted by the IWC Scientific Committee for the Revised Management Procedure (IWC, 1994b), the track design was changed to give more representative coverage of the 5° sectors.



Figs 2b-c. The areas surveyed on the second and third (up to 1997/98) circumpolar cruises.

In addition to differences in cruise track design and in the areal coverage of the surveys, there were also some changes in the timing of the surveys (Fig. 3). In particular, as recommended by the Scientific Committee (IWC, 1994c), the surveys from 1994/95 onwards started about 2-3 weeks later than all the earlier surveys, in order to improve the chances of the ice edge receding before the start of the survey, and thus ease the task of cruise track design (Ensor *et al.*, 1995).

Duplicate and triplicate sightings

In IO mode, duplicate and even triplicate sightings are a common occurrence. The same school may be sighted from the IO platform, from the barrel or from the upper bridge. Each pair/triplet is assigned a probability status (‘definite’, ‘possible’, or ‘remote’) that the same school has been sighted. In the standard analyses (and in this paper), only one sighting from each pair/triplet in the ‘definite’ duplicates is retained when estimating abundance. Normally, the sighting

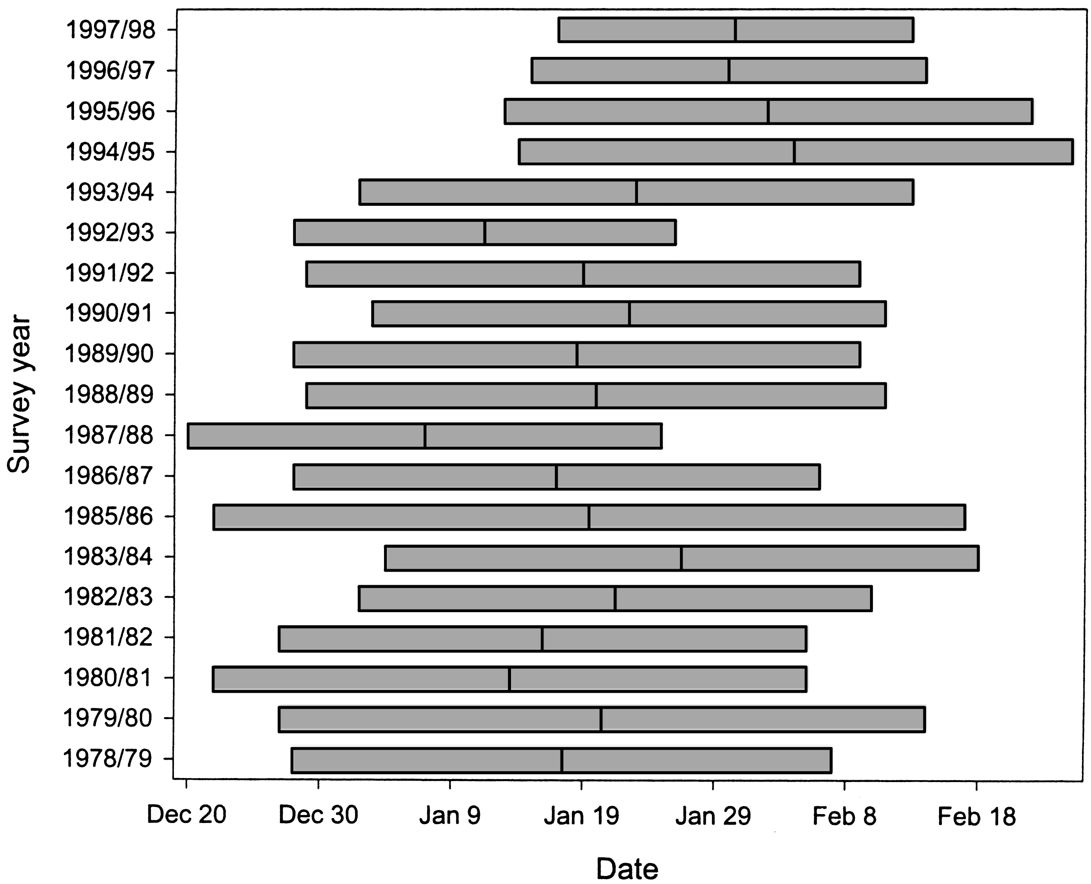


Fig. 3. Start and end dates of each survey, with the mid-point of the survey indicated by a solid line.

made first in time is the one retained, although data from this sighting may be combined with a school size estimate or species identification from one of the other sightings in the pair/triplet (Strindberg and Burt, 2000). 'Possible' and 'remote' duplicates/triplicates are treated as separate schools.

ABUNDANCE ESTIMATION

The basic equation used for abundance estimation is:

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

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[8]:

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

Strictly this formula is correct only in the limit of very small CVs. It is applied here as its use has been standard practice in the past analyses of these surveys, and it is the formula built into DESS. Although it is generally a reasonable approximation, larger CVs reported for abundance estimates in this paper are consequently slightly negatively biased.

The transect is the sampling unit used to estimate the variance of the sighting rate (n/L), with transects defined by a waypoint file which records instances of changes in mode and major changes in course[9]. For the first five surveys, however, for which the cruise track design does not readily admit such an interpretation, the sampling unit adopted was a survey day. The variance estimate is effort weighted[10], i.e. if survey in the stratum consisted of $i = 1, 2 \ldots k$ units of length l_i and with n_i schools sighted, then:

$$\mathrm{var}\left(\frac{n}{L}\right) = \frac{1}{k-1} \sum_{i=1}^{k} \frac{\ell_i}{L}\left(\frac{n_i}{\ell_i} - \frac{n}{L}\right)^2 \quad (3)$$

where

$$n = \sum_{i=1}^{k} n_i \quad \text{and} \quad L = \sum_{i=1}^{k} \ell_i$$

[8] Equation 2 makes no allowance for uncertainty in stratum area A, which arises because of difficulties in demarcating the position of the ice-edge (which can change quite rapidly during the period of the surveys). The only quantitative analysis reported on this matter is that by Butterworth and Silberbauer (1987) for the 1985/86 cruise in Area V. This found that the most conservative and most generous specifications of the ice-edge led to differences of only ~1-2% in the total minke whale abundance estimate for the Area. Such differences are dwarfed by the typical sizes of the other contributors to CV(P). The conclusion by Butterworth and Silberbauer (1987) at that time that uncertainties about ice-edge definition did not therefore seem to be a serious concern for estimates of abundance is likely the reason for the absence of any further attention to this issue.

Confirmed and unconfirmed school sizes

School size is 'confirmed' if the number of whales in a school is determined reliably, as assessed by observers on the vessels who take account of the time for which the school was observable. Furthermore, during data validation for the earlier (1978/79 to 1987/88) surveys, the condition was imposed that minke school size could only be classified as 'confirmed' if the school was closed to within 0.3 n.miles. This restriction was relaxed for the later surveys although on average 86% of all confirmed sightings were still approached to within 0.3 n.miles. Thus school size confirmation is usually achieved in closing, but seldom in IO mode. For convenience, in the text following, a sighting for which school size is confirmed is referred to as a 'confirmed sighting'.

Number of schools sighted

The radial distance and angle data associated with each sighting are smeared using Method II of Buckland and Anganuzzi (1988), which uses the sightings data themselves to estimate the extent of rounding by observers to favoured distance and angle values. A sighting at radial distance r and angle to the trackline θ is smeared over radial distance $[r(1\text{-}s),\ r(1+s)]$ and angular $[\theta\text{-}\phi,\ \theta+\phi]$ ranges[11]. These definitions of s and ϕ are as used in DESS but differ from s and ϕ as defined in Fig. 2 of Buckland and Anganuzzi (1988): $s_{\mathrm{BA}} = r(1+s_{\mathrm{DESS}})$ and $\phi_{\mathrm{BA}} = 2\phi_{\mathrm{DESS}}$. After smearing, the perpendicular distance distribution is truncated at 1.5 nmi, which overall excludes slightly more than 5% of the minke school sightings. The number of schools sighted after truncation and smearing is denoted n_s, and this includes both confirmed and unconfirmed sightings. Population estimates are calculated with n_s substituted for n in equation 1.

[9] For the longer transects in the N strata, during which survey mode might change between closing and IO on more than one occasion, the mode alternation procedure was effected to ensure a balanced design if these full transects were treated as single sampling units for variance estimation. DESS, however, does not have this combination capability, so that every change in survey mode or major change in course is taken to define the start of an additional sampling unit for variance estimation purposes.

[10] In cases where k is too small to allow reliable estimation of variance in this manner (taken as $k < 5$), neighbouring strata (j) are pooled to estimate an overall sighting rate $S = \sum_j n_j / \sum_j L_j$ with CV(S) being estimated by application of equation 3. The sighting rate CV for an individual stratum j, CV(S_j), is then estimated by $\sqrt{\sum_p L_p / L_j}\,$CV($S$), i.e. a Poisson-like variance structure is assumed.

[11] While angles between the direction to the whale school when first sighted and the vessel trackline have always been based on observers' estimates (though with the assistance of angle boards which were first introduced for the 1983/84 survey), the practice used to provide radial distance measures has changed over time. Originally these distance estimates were based upon the product of vessel speed and the time taken to close with the sighting after the whales were first sighted and the vessel deviated from the trackline. Observer estimates of such distances upon first sighting were originally mistrusted as too subjective. However, the use of graticuled binoculars with distance scales (based upon the angle between the sighting and the horizon), together with satisfactory results from annual 'estimated distance' experiments that were first introduced on the 1981/82 cruise, enhanced confidence in these estimates. In 1986 use of observer estimates of radial distance became standard, particularly because for IO mode the other approach required specification of the time the vessel came abeam of the school sighted, and this proved difficult to judge for a transitory target (Butterworth, 1986). The 'estimated distance' experiment (conducted on every cruise since 1981/82 for each vessel) involves

Effective search half-width

The smeared and truncated sightings of schools are grouped into intervals (or 'bins') of 0.1 n.miles to estimate the detection function intercept, $f(0)$, where $f(y)$ is the probability density function for the sightings distribution in relation to perpendicular distance from the trackline (y). Both confirmed and unconfirmed sightings are included in this estimation process. The hazard rate model (accepted by the Scientific Committee [IWC, 1988, p.77] based on Buckland [1987a]), defined by the following equation, is fitted to these data:

$$f(y) = f(0)\, g(y)$$
$$= f(0)\left[1-\exp\left(-\left[\frac{y}{a}\right]^{-b}\right)\right] \tag{4}$$

where: $g(y)$ is the probability that a school at a perpendicular distance y from the trackline will be sighted, and a, b are parameters estimated in the fitting process, subject to the constraints[12]:

$a \geq 0.0001$ n.miles
$b \geq 1$.

The analyses conducted here make the 'standard analyses' assumption that all schools on the trackline are seen, and hence that $g(0) = 1$[13].

The effective search half-width is then given by:

$$w_s = \frac{1}{f(0)} \tag{5}$$

Mean school size $\bar{s}$

Mean school size is based on confirmed schools sighted during closing mode only, because of the low number of confirmed sightings in IO mode. In some instances, there is evidence of observed school sizes (s) tending to increase with perpendicular sighting distance y, reflecting a faster drop with y in the probability of sighting smaller schools. DESS compares the results of two methods for estimating mean school size: the actual mean for schools sighted within the truncation distance, and the regression estimate for $y = 0$ of a $\ell n\ s$ vs. $g(y)$ regression (the method proposed by Buckland *et al.*, 1993), with the latter used if the regression is significant at the 15% level and has a slope in the direction expected. Estimates of mean school size ($\bar{s}$ in equation 1) obtained in this manner are denoted $E[s_{sc}]$. The basis for use of 15%, rather than the usual 5% criterion, is discussed by Buckland *et al.* (1993, p.75-6). Essentially it is to lessen the risk of biased estimates of abundance and negatively biased estimates of variance in situations of low sample size and hence low power to detect trends with $g(y)$. In one instance, the 1983/84 cruise stratum EN, the regression method obtains $E[s_{sc}] = 0.71$ (CV = 0.202). As a mean school size less than unity is not plausible, this has been replaced by the actual mean school size for that stratum.

Pooling to estimate effective search half-width and mean school size

Due to small sample sizes in some strata, it is necessary to pool strata in order to estimate w_s and $E[s_{sc}]$. In the standard analyses, AIC is used as a basis to determine the level of pooling. On the surface, AIC appears to provide a convenient and statistically defensible basis for determining how to best pool across strata within a survey. AIC values were therefore calculated for each survey for the following pooling combinations: all strata pooled, all strata separate, strata surveyed by the same vessel pooled, north and south strata pooled separately, and east and west strata pooled separately. However, a number of problems, as listed below, were encountered in using AIC as the basis for choice between these options.

(1) The standard analyses compute AIC values based upon w_s estimation, which uses both confirmed and unconfirmed sightings. However, estimates of $E[s_{sc}]$ use confirmed sightings only, so there is no guarantee that this approach will leave enough sightings to determine $E[s_{sc}]$ reliably.

(2) Separate estimates of w_s (and hence AIC values) are obtained for closing and for IO mode analyses. In the interests of simplicity, data for the two modes on the same survey should be pooled in the same way, but for eight of the 13 surveys concerned, the recommended pooling option on the basis of AIC values is different for closing and IO modes.

Footnote 11 continued from previous page
comparing observer estimates of the distance and angle to a radar-reflecting buoy with radar readings (Butterworth *et al.*, 1984a). If bias (statistically significant at the 5% level) is detected in observer estimates, these estimates are corrected by the bias factor estimated before perpendicular distances y are computed. Originally the variance of the observations in these experiments about the radar readings was used to specify the extent of smearing. However, concerns arose that this approach might produce smearing factor estimates that were too low, because of the greater ease of reliably estimating distance and particularly angle to a continuously visible target (the buoy) compared to a transient whale cue (usually a blow). Smearing of angles has a much greater effect than that of distances on abundance estimates, especially because of observations recorded as $\theta = 0$ (hence $y = 0$), the proportion of which was quite large for the earlier cruises. This led to the Buckland-Anganuzzi approach being preferred. Allowing only for rounding to estimate the extent of smearing in this approach would be of concern if the actual observation errors greatly exceeded the extent of rounding. However, comparison of smearing factors estimated from the 'estimated distance' experiment, as calculated for the 1983/84 (Butterworth *et al.*, 1984b) and for the 1984/85 cruises (Butterworth and McQuaid, 1985), with those from the Buckland-Anganuzzi approach (see Fig. 5) indicates rough similarity.

[12] Analyses pre-dating DESS specified $a \geq 0.1$ n.miles and $b \geq 2$ (IWC, 1988, p.77). The constraint for b above does not, however, reflect a change. Earlier convention, e.g. Buckland (1987b), in the Scientific Committee was to write the power in equation 4 as 1-b. More recently, however, the DISTANCE package used in DESS has adopted the convention of Buckland *et al.* (1993) of writing this power as $-b$.

[13] Historically, over the period 1981 to 1983, the Scientific Committee used results of analyses of variable speed and parallel ship experiments to select $g(0)$ values that were less than 1 in computing minke whale abundance estimates (see, for example, Butterworth *et al.*, 1982; 1984a and Joyce *et al.*, 1988 for more details of these experiments and their analysis). However, at the 1984 Scientific Committee meeting, methodological questions about these approaches were raised, and in the absence then of their resolution, the Committee effectively decided to set $g(0) = 1$ (linked to the use of the negative exponential form for the detection function $g(y)$). Despite considerable efforts to obtain a satisfactory estimate of $g(0)$ from these experiments and from IO mode duplicate sightings data over the next six years, problems in interpreting the data continued (see, e.g., IWC, 1988, p.78; IWC, 1989, p.72-3). In the absence of any agreed estimate of $g(0)$, use of the value $g(0) = 1$ was continued for abundance estimation purposes. Finally, during the 1990 Comprehensive Assessment of Southern Hemisphere minke whales, the results of a review (Butterworth, 1991) of estimates of $g(0)$ for the barrel from IO survey data were noted, together with the fact that applying these to sightings from the barrel alone yielded density estimates not much different from these based on sightings from all platforms linked to the assumption $g(0) = 1$ (IWC, 1991, p.116). This was followed by agreement to continue use of the value $g(0) = 1$, a decision reconfirmed two years later (IWC, 1993, p.106).

(3) AIC can be applied only to model fits to the unsmeared perpendicular distance data, since its computation requires independence of the grouped data in each of the 0.1 n.miles bins chosen to fit the $f(y)$ model. However, for the actual abundance estimation, the detection function is applied to bins of smeared data, which are not independent so that the AIC values computed are not really applicable. This could be a problem for the early surveys in particular, for which the unsmeared data (although not necessarily the smeared data) frequently show large peaks close to the trackline that the hazard rate function has difficulty fitting, thus perhaps unduly penalising the associated AIC value.

(4) When actually applying the AIC criterion, some further problems immediately become apparent. For example, in 1988/89 the minimum AIC value for closing mode is obtained when all the strata are separate. Yet for IO mode, one stratum (SM2, WN) has only one sighting, so that some pooling is essential. In most of the early surveys, there are certainly sufficient sightings to render stratum-specific estimation viable, but the AIC values always indicate some pooling. An extreme example occurs in 1982/83, where the smallest number of sightings in any stratum is 64, yet the AIC criterion suggests pooling all the strata. This runs counter to the view that pooling should be kept to a minimum, because of the possibility that the true values of w_s and $\bar{s}$ did indeed differ among the strata concerned.

Based on these considerations, the consistent use of AIC throughout the time series as a basis to select between pooling options does not seem reasonable. In these analyses therefore, the following rules for pooling have been applied.

(i) If there are more than a total of 15 confirmed and unconfirmed sightings in each stratum, do not pool. This criterion is satisfied for the 1978/79–1985/86 and 1989/90 surveys, for which all w_s and $E[s_{sc}]$ estimates used are stratum-specific.

(ii) If there are too few sightings in either IO or closing mode to meet the criterion in (i), then pool all strata that were surveyed by the same vessel. When applied to the remaining surveys, nearly all such 'super-strata' contain more than 15 sightings.

(iii) Two cases are not covered by the criteria above. In 1978/79, the strata surveyed by T16 are pooled by combining north and south strata, but the strata surveyed by T18 include sufficient sightings to remain separate. In 1981/82, the perpendicular distance distribution of the sightings data for W1N stratum was anomalous and poorly fitted by the detection function; the strata surveyed by SM1 were therefore pooled, but those surveyed by SM2 remain separate.

The choice of a total of 15 sightings in a stratum as the minimum required to avoid pooling is somewhat *ad hoc*. It is based primarily on the considerations that a lesser number would likely create difficulties in fitting the two-parameter hazard rate function reliably and would also compromise the procedure used to estimate stratum-specific smearing parameters. On the other hand, a number not much larger than 15 would have substantially increased the extent of pooling.

Averaging where strata were surveyed by two vessels

Occasionally, two vessels surveyed the same stratum. In such cases, the two density estimates are combined using an effort-weighted average.

Factors applied to the uncorrected abundance estimate

Two multiplicative correction factors are applied to the abundance estimates in the standard analyses. The correction factor m makes allowance for random whale movement, and the factor h for schools on the trackline that were missed. The standard analyses assume $h = 1.0$, i.e. that the probability of detection on the trackline is one, and that $m = 0.985$, with both assumed to be known exactly (i.e. CV = 0). The latter value is based on Koopman's (1956) model of a fixed detection radius within which every school is definitely seen. It results from an average whale swimming to vessel surveying speed ratio of 3 knots : 12 knots = 0.25 (Best and Butterworth, 1980; IWC, 1983, p.95). In the analyses of this paper, neither m nor h are taken into account; m has been neglected because the model previously used to estimate this is simplistic and the quantitative effect in any case rather small. The abundance estimates of this paper are accordingly termed 'uncorrected'.

Combining IO and closing mode abundance estimates

IO mode survey involves greater search effort because of the additional observer in the IO platform (Haw, 1991b), so that the assumption that all schools on the trackline are seen is likely to introduce less bias than for closing mode survey. Furthermore, closing mode involves other potential biases as discussed earlier. The IO-based abundance estimates are therefore taken as the standard. Under the standard methodology, the closing mode estimates (P_{closing}) are therefore converted to 'pseudo-passing' estimates (P_{pseudo}) by dividing them by a calibration factor R, which reflects the ratio of minke whale school density estimates in closing mode compared to IO mode:

$$P_{\text{pseudo}} = P_{\text{closing}} / R \tag{6}$$

$$CV(P_{\text{pseudo}}) = \sqrt{\left[CV(P_{\text{closing}})\right]^2 + \left[CV(R)\right]^2} \tag{7}$$

The IO mode and the pseudo-passing mode estimates are then combined by taking an inverse-variance weighted average, to obtain the final abundance estimate (P_{average}):

$$a = \frac{\text{var}(P_{\text{IO}})}{\text{var}(P_{\text{pseudo}}) + \text{var}(P_{\text{IO}})}$$

$$b = \frac{\text{var}(P_{\text{pseudo}})}{\text{var}(P_{\text{pseudo}}) + \text{var}(P_{\text{IO}})}$$

$$P_{\text{average}} = a \cdot P_{\text{pseudo}} + b \cdot P_{\text{IO}} \tag{8}$$

$$CV(P_{\text{average}}) = \frac{\sqrt{a^2 \cdot \text{var}(P_{\text{pseudo}}) + b^2 \cdot \text{var}(P_{\text{IO}})}}{P_{\text{average}}} \tag{9}$$

In the interests of simplicity, this does not take into account the covariance between the pseudo-passing and IO estimates that occurs because they use common estimates of mean school size. The variances given for the combined estimates are therefore slightly negatively biased.

Updated estimate of R

The standard analyses use $R = 0.751$ (CV = 0.152), obtained by Haw (1991b) from the 1985/86-1988/89 surveys. Burt and Stahl (2000) obtain an estimate for R of 0.893 (CV = 0.109) from the more recent 1989/90-1997/98 surveys only, but they continue to use the older value of R in combining closing and IO estimates[14]. However, both these estimates for R are problematic because they are not based on consistent estimates of density from the two modes over all the surveys. The consistent estimates obtained in this study therefore provide a convenient opportunity to update R.

An estimate (assumed to be lognormally distributed) of the density of schools:

$$D_s = \frac{n_s}{2 \cdot w_s \cdot L} \qquad (10)$$

can be obtained for each stratum surveyed from 1985/86 onwards for both closing and IO mode, and hence an estimate of R provided for each of those strata. Two strata were excluded from this process because one of the school density estimates was zero. The equations in Borchers and Butterworth (1990) were used to calculate an inverse-variance weighted average of the individual estimates of R from each stratum:

$$\overline{\ln R} = \sum_i V_i \ln R_i$$

$$\mathrm{var}\left(\overline{\ln R}\right) = 1 / \sum_i \left[\mathrm{se}\left(\ln R_i\right)\right]^{-2} \qquad (11)$$

$$R = \exp\left(\overline{\ln R} + \mathrm{var}\left(\overline{\ln R}\right)/2\right)$$

$$\mathrm{se}(R) = \sqrt{\left[\exp\left\{\mathrm{var}\left(\overline{\ln R}\right)\right\} - 1\right]} R$$

where $V_i = \left[\mathrm{se}\left(\ln R_i\right)\right]^{-2} / \sum_j \left[\mathrm{se}\left(\ln R_j\right)\right]^{-2}$

$$CV(R_i) = \sqrt{CV(D_{i\,\mathrm{closing}})^2 + CV(D_{i\,\mathrm{IO}})^2}$$

$$\mathrm{se}(\ln R_i) = \sqrt{\ln[CV(R_i)^2 + 1]}$$

Where strata had been pooled for the estimation of w_s and $E[s_{sc}]$, the sightings rates were also combined (to compute school density and hence R) according to the 'super-stratum' method of Haw (1991b) that was subsequently adopted by the Scientific Committee (IWC, 1991, p.117). In this method n_s/L and an estimate of $CV(n_s/L)$ are provided separately for each stratum by DESS. Given further common w_s and $E[s_{sc}]$ estimates over strata $i = 1 \ldots m$, which are to be combined into a 'super-stratum' for which R is to be estimated, the area of each stratum as a proportion of that of the 'super-stratum' is first calculated:

$$W_i = \frac{A_i}{\sum_{j=1}^{m} A_j} \qquad (12)$$

The average density of minke whale schools in the 'super-stratum' for the survey mode under consideration is then estimated using an area-weighted average of the sighting rate:

$$\overline{D} = \frac{1}{2\hat{w}_s} \sum_{j=1}^{m} W_j \cdot \left(\frac{n}{L}\right)_j$$

[14] Burt and Stahl (2000) reports $R = 0.832$ (CV = 0.0953), but these authors have revised this figure on rechecking their computations (M.L. Burt, pers. comm.).

$$CV\left(\overline{D}\right) = \sqrt{\left[CV\left(\frac{1}{\hat{w}_s}\right)\right]^2 + \frac{\sum_{i=1}^{m} W_i^2 \left(\frac{n}{L}\right)_i^2 \cdot \left[CV\left(\frac{n}{L}\right)_i\right]^2}{\left[\sum_{i=1}^{m} W_i \cdot \left(\frac{n}{L}\right)_i\right]^2}} \qquad (13)$$

The impact of 'like minke' sightings

More sightings have been recorded as 'like minke' in the third circumpolar set than in the second set of surveys, whereas almost no such sightings were recorded in the first circumpolar set. This difference does not arise only from the introduction of IO mode after the first circumpolar set of surveys. Although 'like minke' sightings are more frequent in IO than closing mode, there has also been an increase in the proportion recorded in closing mode since the first circumpolar set was completed (Fig. 3). This suggests a change in species-classification over time (possibly resulting from the use of topmen with increasingly less identification experience from whaling operations as the surveys progressed). This change would probably confound comparisons of results from the three sets of surveys that are based on minke sightings only. Uncorrected abundance estimates are therefore also calculated with 'like minke' sightings included, to investigate the influence of this factor.

Comparing abundance estimates for the different circumpolar sets of surveys

A great deal of interest has been expressed in determining trends in abundance, particularly for minke whales, from the IDCR-SOWER circumpolar surveys. However, problems arise because of non-comparability of areal coverage between the circumpolar sets of surveys. These are of two kinds: first, most surveys in the first two circumpolar sets did not completely cover the full latitudinal range to 60°S; secondly, the third circumpolar set of cruises has not yet completed a full circuit of the Antarctic - the longitudinal ranges of 140°W-110°W and 80°E-130°E have yet to be surveyed (Figs 2a-c).

Previous attempts to compare abundance estimates for the same region from surveys in different years (e.g. Punt *et al.*, 1997) have been based upon scaling estimates down to a 'common northern boundary', so that abundance contributions from northerly areas not surveyed by all the cruises under comparison are not taken into account. However, as the number of cruises has increased, this approach is proving problematic as the highly variable nature of the ice-edge from year to year has led to instances where sections of the ice-edge for one cruise were north of the northernmost area surveyed in another (i.e. no common area for such sectors).

Pending the development of more sophisticated approaches to obtain comparable estimates of abundance over time in these circumstances, a simpler approach has been pursued here to allow initial comparisons to be made. The unsurveyed northern areas are assumed to have the same density of whales as the northern surveyed strata in each survey (Tables 5a-c), in order to extrapolate all abundance estimates to a common area south of 60°S[15]. In some cases,

[15] This assumption probably introduces some positive bias into the resultant estimates, as minke whale density tends to decrease with movement north away from the ice-edge. In turn, this could bias estimates of trend in abundance, as the sizes of the unsurveyed areas tend to decrease over time.

the surveys covered areas north of this range, in which case the abundance estimates from the northern strata are scaled down proportionately. Abundance estimates from each Management Area not as yet fully covered during the third circumpolar set of cruises are decreased according to the fraction of the area of each stratum that falls outside the longitudinal range covered to date by the third set[16].

The areas of the unsurveyed regions (and those surveyed north of 60°S) were obtained from table 3b of Butterworth *et al.* (1994) for 1978/79–1990/91. *MapInfo* 5.5 (which is incorporated into DESS) was used to obtain the corresponding areas for the remaining surveys and to re-check the original values. *MapInfo* was also used to calculate the areas needed to evaluate proportional coverage by the third circumpolar set of cruises.

The effects of increasing proportions of ‘like species’ sightings in the later surveys must also be taken into account when comparing abundance estimates across the circumpolar sets of surveys. The proportional increase (or decrease) in abundance estimates when ‘like minke’ sightings are included (obtained as described above) is therefore used to modify the corresponding extrapolated estimates above, to investigate this source of bias.

[16] DESS has the capability of computing abundance estimates based only upon the sightings and effort within a user-defined new stratum. This option could have been used here in place of area-based pro-ratio, but the latter was preferred as this paper is based upon the more straightforward features of DESS, for simplicity.

RESULTS

Abundance estimates

Revised abundance estimates, and the values of the parameters used to compute these estimates in the consistent manner described above, are presented for closing mode (Table 1a-c) and IO mode (Tables 1d-e). Plots showing the fit of the hazard rate function to the perpendicular distance distributions for the sightings data are given in Figs 4a-c, and show no obvious indications of model mis-specification. There is no obvious trend towards distributions with sharper peaks near the trackline in the earlier years, as is evident when estimated detection functions for some other species are examined (Branch and Butterworth, 2001). The smearing parameters are markedly higher at the start of the first circumpolar set of cruises than for the two later sets (Fig. 5). The decrease in smearing parameters over time relates to the introduction of angle boards and graticuled binoculars, with a consequent improvement in the precision of the recorded angles and distances.

Sensitivity to duplicate identification

Uncertainties about duplicate identification affect only the abundance estimates for IO mode. If instead of the ‘standard analyses’ practice of considering only ‘definite’ duplicate pairs/triplets as single sightings, the ‘probable’ duplicates are also treated in this manner, the number of sightings in IO mode in the second and third circumpolar sets of surveys decrease by 1.6% and 1.2% respectively, and the corresponding abundance estimates decrease by 0.2% and 1.0%.

Tables 1a-e, Figs 4a-c and Fig. 5 occur on the following 9 pages.
Text continues on p. 163

Table 1a

Abundance estimates of minke whales obtained from closing mode data for the first circumpolar set of cruises (1978/79 to 1983/84) - CPI. Strata with the same number in the 'Ave' column were surveyed by two vessels and the resulting abundance estimates were combined using an effort-weighted average. The symbols used here and in subsequent Tables denote the following:

A - stratum area (n.miles²);

N_L - number of transects;

n_s - number of schools sighted (primary effort), after smearing and truncation at a perpendicular distance of 1.5 n.miles;

L - primary search effort (n.miles);

w_s - effective search half-width for schools (n.miles);

$E[s_{sc}]$ - estimated mean school size (based on schools with confirmed school size in closing mode only);

D_w - density of whales (per n.miles²);

P - uncorrected abundance estimate.

The complete longitudinal extent of the Management Area (I-VI) associated with each cruise, as indicated in this and subsequent Tables, was covered unless an asterisk is appended to the Area number.

Year	Vessel	Stratum	A	N_L	n_s	L	n_s/L	CV	w_s	CV	$E[s_{sc}]$	CV	D_w	CV	P	CV	Ave	Total	CV
1978/79	T16	EN	156,766	18	68.0	2,155.5	0.032	0.321					0.1473	36.6	23,099	0.366			
(IV)		W1N	39,256	2	9.0	222.2	0.018	0.784	0.295	0.137	2.75	0.113	0.1891	80.4	7,423	0.804	1		
		W2N	153,914	3	5.0	384.7	0.013	0.298					0.0607	34.7	9,337	0.347	2		
		W1S	20,389	5	56.0	200.6	0.279	0.187	0.374	0.190	2.81	0.086	1.0511	28.0	21,430	0.280			
		W2S	29,600	12	83.3	1,073.3	0.078	0.141					0.2923	25.1	8,653	0.251	3		
	T18	ES	27,571	16	167.0	1,436.6	0.116	0.160	0.393	0.181	5.89	0.105	0.8710	26.3	24,014	0.263			
		W1N	39,256	6	35.6	685.3	0.052	0.266	0.238	0.341	2.36	0.167	0.2572	46.4	10,096	0.464	1		
		W2N	153,914	11	25.8	1,212.5	0.021	0.363	0.530	0.223	2.05	0.131	0.0412	44.6	6,343	0.446	2		
		W2S	29,600	4	40.8	393.4	0.104	0.222	0.314	0.357	1.85	0.124	0.3057	43.8	9,048	0.438	3	93,808	0.147
1979/80	K27	ES	41,772	20	166.3	1,346.5	0.124	0.194	0.254	0.257	2.43	0.088	0.5905	33.4	24,668	0.334			
(III)		WN	200,724	16	53.0	2,014.9	0.026	0.249	0.261	0.336	2.36	0.127	0.1193	43.7	23,950	0.437			
	T11	EN	217,865	20	56.4	2,636.7	0.021	0.188	0.263	0.516	3.23	0.123	0.1314	56.3	28,627	0.563			
		WS	33,619	19	138.2	968.2	0.143	0.211	0.303	0.214	3.15	0.080	0.7420	31.1	24,944	0.311		102,188	0.218
1980/81	K27	EN	208,159	14	77.7	877.3	0.089	0.141	0.331	0.378	1.87	0.093	0.2506	41.4	52,172	0.414			
(V)		ES	98,766	5	54.1	439.6	0.123	0.376	0.480	0.371	3.36	0.216	0.4296	57.1	42,425	0.571	4		
		WS	34,164	17	74.0	698.1	0.106	0.240	0.262	0.366	3.41	0.114	0.6898	45.2	23,568	0.452			
	T11	ES	98,766	21	293.1	2,133.3	0.137	0.244	0.531	0.153	2.87	0.222	0.3704	36.3	36,578	0.363	4		
		WN	139,191	15	43.6	1,151.6	0.038	0.439	0.324	0.512	2.49	0.220	0.1454	70.9	20,244	0.709		133,560	0.228
1981/82	SM1	ES	29,633	18	169.4	1,162.9	0.146	0.174					0.2938	22.8	8,705	0.228			
(II)		W1N	135,504	10	18.7	1,064.9	0.018	0.691	0.515	0.136	2.08	0.059	0.0361	70.0	4,885	0.700			
		W2S	52,096	10	76.0	920.6	0.083	0.317					0.1671	35.0	8,704	0.350	5		
	SM2	EN	145,063	17	54.9	1,748.8	0.031	0.331	0.428	0.389	1.63	0.100	0.0596	52.0	8,647	0.520			
		W1S	35,725	9	30.9	872.2	0.035	0.318	0.359	0.571	2.70	0.140	0.1333	66.8	4,763	0.668			
		W2S	52,096	12	94.7	812.4	0.117	0.189	0.501	0.276	2.12	0.089	0.2468	34.6	12,856	0.346	5	37,649	0.202
1982/83	SM1	ES	33,050	15	114.6	928.0	0.123	0.214	0.396	0.280	2.57	0.071	0.4005	36.0	13,235	0.360			
(I)		WN	163,926	15	62.7	1,426.1	0.044	0.217	0.804	0.162	1.63	0.106	0.0445	29.1	7,288	0.291			
	SM2	EN	149,433	17	84.3	1,054.4	0.080	0.303	0.862	0.137	3.55	0.114	0.1646	35.2	24,598	0.352			
		WS	25,596	19	314.5	1,414.8	0.222	0.176	0.615	0.098	1.66	0.043	0.3004	20.6	7,688	0.206		52,808	0.194
1983/84	K27	EMS	158,893	5	47.4	1,094.4	0.043	0.394	0.422	0.229	1.52	0.136	0.0778	47.6	12,355	0.476			
(VI)		WN	207,721	5	49.9	875.6	0.057	0.142	0.489	0.191	2.11	0.127	0.1229	27.0	25,536	0.270			
	SM1	EN	202,108	5	19.0	911.6	0.021	0.584	0.328	0.533	2.27	0.238	0.0722	82.6	14,593	0.826			
	SM2	WMS	156,457	5	69.8	1,309.0	0.053	0.187	0.309	0.236	2.22	0.140	0.1914	33.2	29,939	0.332		82,423	0.261

Table 1b

Abundance estimates of minke whales obtained from closing mode data for the second circumpolar set of cruises (1985/86 to 1990/91) - CPII.

Year	Vessel	Stratum	A	N_L	n_s	L	n_s/L	CV	w_s	CV	$E[s_{sc}]$	CV	D_w	CV	P	CV	Ave	Total	CV
1985/86 (V)	K27	EN	279,611	8	38.0	865.3	0.044	0.413	0.362	0.260	3.20	0.222	0.1942	53.7	54,314	0.537			
		WS	104,814	14	44.6	767.6	0.058	0.248	0.625	0.140	3.55	0.216	0.1647	35.8	17,267	0.358			
	SM1	EM	165,912	10	96.3	735.0	0.131	0.255	0.605	0.152	2.69	0.143	0.2907	33.0	48,238	0.330			
		WM	166,349	4	27.5	354.0	0.078	0.498	0.458	0.355	1.91	0.196	0.1624	64.2	27,007	0.642			
	SM2	ES	107,717	11	137.5	763.4	0.180	0.189	0.479	0.150	3.33	0.113	0.6272	26.6	67,562	0.266			
		WN	139,065	5	19.0	566.7	0.034	0.516	0.304	0.297	1.93	0.184	0.1063	62.4	14,787	0.624		229,175	0.188
1986/87 (II)	K27	ES1	23,142	3	7.0	179.0	0.039	0.548					0.1492	58.5	3,453	0.585			
		WS1	10,270	2	11.0	81.8	0.134	0.275					0.5130	34.4	5,268	0.344			
		WS2	21,143	2	3.0	111.0	0.027	0.121	0.369	0.173	2.82	0.113	0.1031	23.9	2,180	0.239	6		
		WS3	79,605	8	41.0	544.4	0.075	0.510					0.2873	55.0	22,869	0.550	7		
		EN	124,057	4	62.4	538.2	0.116	0.342					0.4422	40.0	54,864	0.400			
	SM1	EBAY	15,242	3	13.0	106.4	0.122	0.382					0.2466	49.7	3,758	0.497			
		ES2	44,975	13	42.6	565.8	0.075	0.301	0.551	0.293	2.23	0.122	0.1520	43.8	6,834	0.438			
		WBAY	11,505	2	18.6	92.2	0.202	0.741					0.4079	80.6	4,693	0.806			
		WN	95,361	4	3.0	315.6	0.010	0.444					0.0192	54.6	1,829	0.546			
	SM2	EM	69,908	3	33.7	473.0	0.071	0.307					0.1298	35.6	9,073	0.356			
		WS2	21,143	1	1.0	82.8	0.012	1.000	0.526	0.144	1.92	0.109	0.0220	101.6	465	1.016	6		
		WS3	79,605	5	21.0	239.4	0.088	0.415					0.1596	45.2	12,706	0.452	7	110,984	0.249
1987/88 (III)	SM1	ES	87,677	7	8.0	454.9	0.018	1.038	0.280	0.785	5.31	0.275	0.1668	133.0	14,625	1.330			
		WN	148,821	6	10.7	450.4	0.024	0.928					0.2252	125.4	33,513	1.254			
	SM2	EN	168,881	7	3.0	540.7	0.006	0.416	0.336	0.379	4.00	0.282	0.0330	63.0	5,571	0.630			
		WS	74,351	12	59.7	623.5	0.096	0.429					0.5694	63.8	42,334	0.638		96,043	0.631
1988/89 (IV)	SM1	BS	6,520	1	14.0	87.4	0.160	0.267					0.8276	68.6	5,396	0.686			
		EN	181,166	6	7.0	498.8	0.014	0.333	0.237	0.625	2.44	0.094	0.0725	71.4	13,137	0.714			
		WS	58,693	5	22.9	237.8	0.096	0.324					0.4976	71.0	29,204	0.710			
	SM2	BN	17,486	6	7.0	231.0	0.030	0.719					0.1174	78.5	2,053	0.785			
		ES	52,441	5	26.9	310.3	0.087	0.339	0.550	0.247	4.26	0.198	0.3362	46.3	17,630	0.463			
		WN	156,617	6	13.0	701.9	0.019	0.761					0.0718	82.4	11,239	0.824		78,660	0.445
1989/90 (I)	SM1	ESB	62,594	11	23.7	587.9	0.040	0.324	0.450	0.419	1.79	0.144	0.0803	54.9	5,026	0.549			
		WN	168,761	7	26.6	560.4	0.047	0.292	0.510	0.264	2.25	0.249	0.1044	46.5	17,621	0.465			
	SM2	EN	153,029	7	36.4	679.7	0.054	0.263	0.221	0.570	1.77	0.122	0.2136	64.0	32,687	0.640			
		WS	45,128	15	64.0	602.2	0.106	0.201	0.573	0.132	2.67	0.094	0.2481	25.8	11,195	0.258		66,529	0.343
1990/91 (VI)	SM1	EN	191,954	3	6.5	193.0	0.034	0.458	0.413	0.835	2.50	0.191	0.1025	97.2	19,676	0.972			
		WS	45,414	5	5.8	304.1	0.019	0.438					0.0582	96.2	2,642	0.962			
	SM2	ES	108,268	5	40.0	476.6	0.084	0.281	0.536	0.170	2.92	0.182	0.2287	37.5	24,758	0.375			
		WN	211,788	5	5.0	479.7	0.010	0.232					0.0284	34.0	6,016	0.340		53,091	0.445

Table 1c

Abundance estimates of minke whales obtained from closing mode data for the as-yet incomplete third circumpolar set of cruises (1991/92 to 1997/98) - CPIII.

Year	Vessel	Stratum	A	N_L	n_s	L	n_s/L	CV	w_s	CV	$E[s_{sc}]$	CV	D_w	CV	P	CV	Ave	Total	CV
1991/92 (V)	SM1	EN	165,429	9	76.3	434.0	0.176	0.210	0.486	0.224	2.54	0.096	0.4594	32.1	76,005	0.321			
		WS	58,643	10	11.7	278.1	0.042	0.354					0.1103	42.9	6,468	0.429			
	SM2	ES	82,039	11	48.5	645.7	0.075	0.303	0.419	0.406	1.41	0.097	0.1264	51.6	10,366	0.516			
		WN	137,734	5	3.0	345.0	0.009	0.348					0.0146	54.4	2,017	0.544		94,855	0.279
1992/93 (III*)	SM1	ES	23,207	10	7.5	380.2	0.020	0.452	0.189	0.907	1.67	0.214	0.0869	103.6	2,017	1.036			
		WN	210,035	8	9.0	648.9	0.014	0.235					0.0613	96.1	12,882	0.961	8		
		WS	61,527	1	2.0	67.1	0.030	0.707					0.1317	117.0	8,105	1.170	9		
	SM2	EN	150,547	4	6.0	498.2	0.012	0.391	0.526	0.206	1.44	0.077	0.0165	44.8	2,477	0.448			
		WS	61,527	15	78.9	812.3	0.097	0.317					0.1326	38.6	8,161	0.386	9		
		WN	210,035	1	0.0	134.2	0.000	-					0.0000	-	0	-	8	23,322	0.564
1993/94 (I*)	SM1	WS	50,596	11	25.5	501.7	0.051	0.276	0.439	0.427	1.51	0.130	0.0878	52.5	4,441	0.525			
		EN	293,196	11	4.0	819.4	0.005	0.981					0.0084	107.8	2,468	1.078			
	SM2	WN	251,735	8	17.0	583.8	0.029	0.313	0.430	0.343	1.63	0.154	0.0553	48.9	13,914	0.489			
		ES	72,249	10	33.9	457.2	0.074	0.241					0.1408	44.7	10,170	0.447		30,993	0.359
1994/95 (III*+IV*)	SM1	WS	51,938	12	15.6	414.3	0.038	0.337	0.482	0.444	2.56	0.198	0.1003	59.1	5,208	0.591			
		EN	146,681	7	5.0	523.8	0.010	0.396					0.0254	62.7	3,726	0.627			
	SM2	WN	148,803	7	3.0	463.8	0.006	0.850	0.335	0.327	1.87	0.110	0.0181	91.7	2,689	0.917			
		ES	60,046	9	19.9	439.7	0.045	0.540					0.1262	64.1	7,577	0.641			
		PRYD	21,096	4	18.0	210.7	0.085	0.255					0.2386	42.9	5,034	0.429		24,234	0.359
1995/96 (VI*)	SM1	WS	34,051	10	25.8	403.3	0.064	0.299	0.925	0.104	2.33	0.094	0.0804	33.0	2,736	0.330			
		EN	242,073	10	27.5	490.8	0.056	0.369					0.0703	39.5	17,029	0.395			
	SM2	WN	97,945	4	6.0	246.6	0.024	0.775	0.499	0.249	1.76	0.131	0.0429	82.5	4,200	0.825			
		ES	72,349	9	31.7	506.7	0.063	0.290					0.1104	40.4	7,984	0.404		31,950	0.272
1996/97 (II*)	SM1	ES	67,072	20	26.4	563.6	0.047	0.383	0.835	0.269	1.72	0.117	0.0484	48.3	3,245	0.483			
		WN	113,687	5	8.0	262.3	0.030	0.331					0.0314	44.2	3,575	0.442			
	SM2	EN	241,928	15	14.0	588.2	0.024	0.541	0.306	0.372	2.06	0.104	0.0802	66.5	19,396	0.665			
		WS	23,028	7	6.0	154.5	0.039	0.844					0.1308	92.8	3,012	0.928		29,228	0.482
1997/98 (II*)	SM1	WS	32,620	7	2.0	187.0	0.011	0.751	0.612	0.355	1.79	0.126	0.0157	84.0	511	0.840			
		EN1	84,726	6	9.0	236.0	0.038	0.600					0.0558	70.8	4,730	0.708			
		ES2	10,451	4	28.9	83.5	0.346	0.235					0.5069	44.4	5,298	0.444			
		EN2	44,064	2	9.0	114.3	0.079	0.619					0.1153	72.5	5,079	0.725			
	SM2	WN	52,135	4	1.0	240.1	0.004	1.050	0.881	0.175	1.81	0.136	0.0043	107.3	223	1.073			
		ES1	47,036	8	24.0	356.3	0.067	0.697					0.0689	73.2	3,243	0.732			
		EN2	35,949	2	9.0	160.0	0.056	0.562					0.0577	60.4	2,074	0.604		21,158	0.373

Table 1d

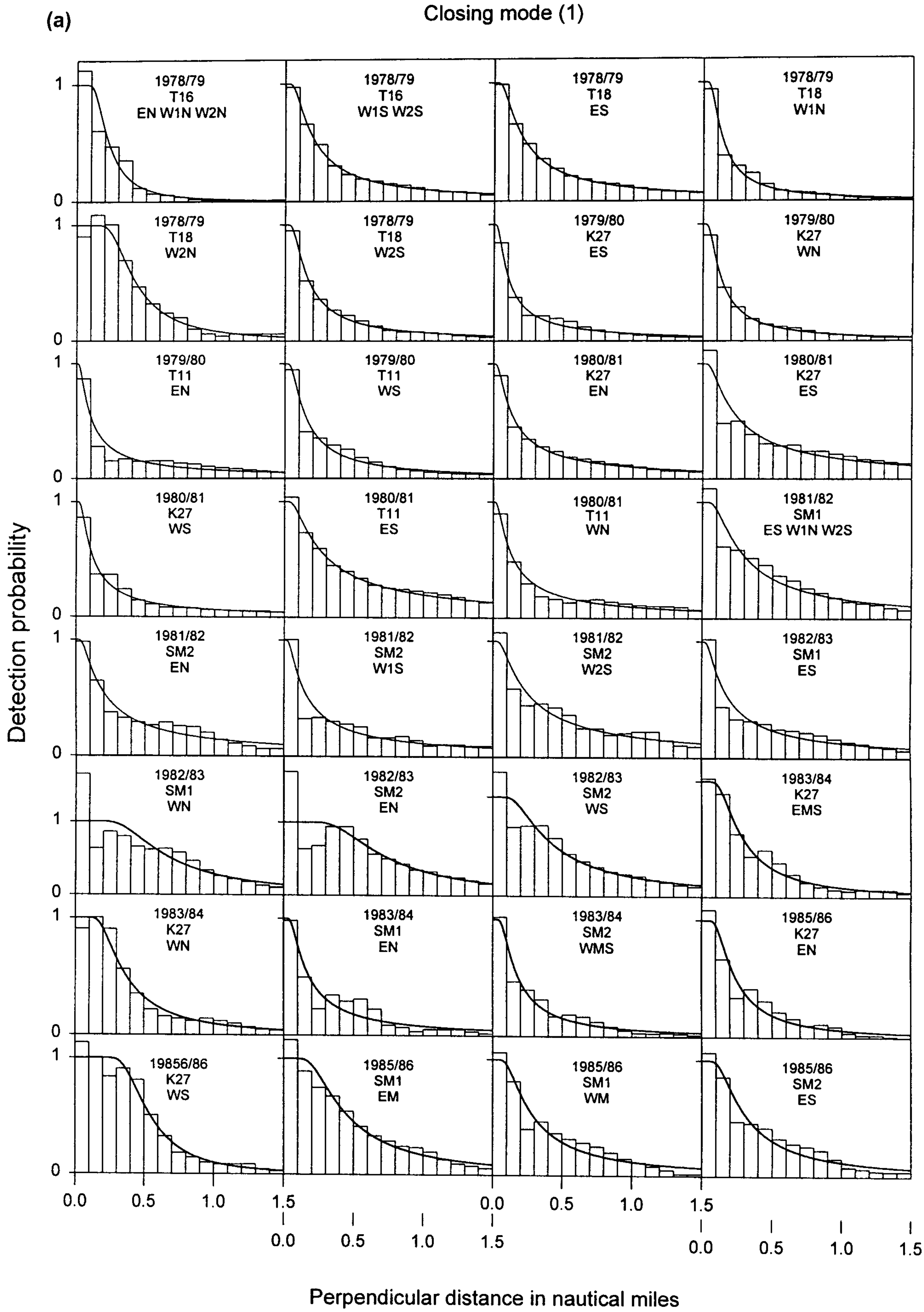
Abundance estimates of minke whales obtained from IO mode data for the second circumpolar set of cruises (1985/86 to 1990/91) - CPII.

Year	Vessel	Stratum	A	N_L	n_s	L	n_s/L	CV	w_s	CV	$E[s_{sc}]$	CV	D_w	P	CV	Ave	Total	CV
1985/86	K27	EN	279,611	8	69.3	884.4	0.078	0.325	0.702	0.157	3.20	0.222	0.1786	49,939	0.424			
(V)		WS	104,814	13	109.4	662.0	0.165	0.147	0.812	0.214	3.55	0.216	0.3615	37,886	0.338			
	SM1	EM	165,912	10	155.5	1,063.5	0.146	0.347	0.742	0.096	2.69	0.143	0.2648	43,937	0.388			
		WM	166,349	4	42.4	492.0	0.086	0.593	0.355	0.273	1.91	0.196	0.2319	38,583	0.682			
	SM2	ES	107,717	8	178.3	739.2	0.241	0.276	0.426	0.109	3.33	0.113	0.9431	101,590	0.317			
		WN	139,065	3	44.0	386.8	0.114	0.379	0.310	0.230	1.93	0.184	0.3543	49,273	0.480		321,207	0.176
1986/87	K27	ES1	23,142	5	25.0	348.6	0.072	0.526					0.2752	6,368	0.567			
(II)		WS1	10,270	2	10.0	103.7	0.096	0.384					0.3701	3,801	0.438			
		WS2	21,143	2	4.0	128.7	0.031	1.087	0.367	0.177	2.82	0.113	0.1192	2,521	1.107	6		
		WS3	79,605	7	42.4	470.4	0.090	0.251					0.3458	27,527	0.327	7		
		EN	124,057	3	47.5	427.7	0.111	0.448					0.4266	52,920	0.495			
	SM1	EBAY	15,242	4	35.8	125.8	0.284	0.367					0.4773	7,275	0.430			
		ES2	44,975	16	100.5	722.0	0.139	0.246	0.663	0.188	2.23	0.122	0.2335	10,501	0.333			
		WBAY	11,505	1	28.3	74.2	0.382	0.188					0.6404	7,368	0.645			
		WN	95,361	2	0.0	201.0	0.000	0.000					0.0000	0	0.000			
	SM2	EM	69,908	3	72.5	447.0	0.162	0.265					0.2662	18,612	0.346			
		WS2	21,143	2	2.0	151.8	0.013	0.346	0.571	0.194	1.87	0.107	0.0216	457	0.411	6		
		WS3	79,605	8	44.8	449.8	0.100	0.395					0.1634	13,010	0.453	7	128,680	0.244
1987/88	SM1	ES	87,677	8	30.7	660.1	0.046	0.512	0.514	0.280	5.31	0.275	0.2401	21,047	0.645			
(III)		WN	148,821	7	25.6	365.1	0.070	0.356					0.3623	53,914	0.530			
	SM2	EN	168,881	7	9.0	546.1	0.016	0.394	0.566	0.123	4.00	0.282	0.0583	9,840	0.500			
		WS	74,351	9	142.9	617.9	0.231	0.142					0.8177	60,799	0.339		145,600	0.300
1988/89	SM1	BS	6,520	3	48.6	144.5	0.336	0.765					0.8178	5,332	0.821			
(IV)		EN	181,166	6	17.0	617.5	0.028	0.247	0.503	0.284	2.44	0.094	0.0669	12,129	0.388			
		WS	58,693	5	23.0	245.7	0.094	0.320					0.2276	13,360	0.438			
	SM2	BN	17,486	9	24.1	396.8	0.061	0.251					0.1337	2,337	0.358			
		ES	52,441	4	43.6	244.0	0.179	0.262	0.966	0.162	4.26	0.198	0.3942	20,674	0.366			
		WN	156,617	6	1.0	730.0	0.001	1.115					0.0030	473	1.144		54,305	0.257
1989/90	SM1	ESB	62,594	13	65.7	793.1	0.083	0.466	0.838	0.139	1.79	0.144	0.0886	5,545	0.507			
(I)		WN	168,761	6	30.8	606.7	0.051	0.325	0.916	0.349	2.25	0.249	0.0623	10,522	0.537			
	SM2	EN	153,029	7	45.0	750.2	0.060	0.257	0.419	0.175	1.76	0.122	0.1262	19,318	0.334			
		WS	45,128	15	184.3	830.9	0.222	0.229	0.519	0.152	2.67	0.094	0.5713	25,783	0.291		61,169	0.192
1990/91	SM1	EN	191,954	4	22.0	473.6	0.046	0.635	0.706	0.151	2.50	0.191	0.0822	15,782	0.680			
(VI)		WS	45,414	9	36.8	645.9	0.057	0.226					0.1009	4,581	0.332			
	SM2	ES	108,268	4	19.0	476.3	0.040	0.516	0.388	0.295	2.92	0.182	0.1499	16,233	0.622			
		WN	211,788	4	12.0	563.7	0.021	0.389					0.0800	16,945	0.521		53,541	0.360

Table 1e

Abundance estimates of minke whales obtained from IO mode data for the as-yet incomplete third circumpolar set of cruises (1991/92 to 1997/98) - CPIII.

Year	Vessel	Stratum	A	N_L	n_s	L	n_s/L	CV	w_s	CV	$E[s_{sc}]$	CV	D_w	P	CV	Ave	Total	CV
1991/92 (V)	SM1	EN	165,429	8	114.6	574.8	0.199	0.230	0.812	0.097	2.54	0.096	0.3120	51,619	0.268			
		WS	58,643	5	122.8	456.4	0.269	0.457					0.4211	24,692	0.477			
	SM2	ES	82,039	10	77.0	687.5	0.112	0.417	0.588	0.151	1.41	0.097	0.1345	11,038	0.454			
		WN	137,734	4	10.0	310.3	0.032	0.691					0.0387	5,335	0.714		92,684	0.221
1992/93 (III*)	SM1	ES	23,207	11	16.9	408.8	0.041	0.341	1.003	0.136	1.67	0.214	0.0345	802	0.425			
		WN	210,035	7	32.0	755.6	0.042	0.444					0.0353	7,412	0.511	8		
		WS	61,527	2	3.0	75.8	0.040	0.050					0.0330	2,029	0.259	9		
	SM2	EN	150,547	5	12.0	603.0	0.020	0.483	0.534	0.164	1.44	0.077	0.0268	4,033	0.516			
		WS	61,527	14	148.9	905.4	0.164	0.215					0.2214	13,620	0.281	9		
		WN	210,035	0	0.0	0.0	-	-					0.0000	0	-	8	24,970	0.239
1993/94 (I*)	SM1	WS	50,596	12	52.0	566.6	0.092	0.216	0.387	0.144	1.51	0.130	0.1793	9,071	0.290			
		EN	293,196	11	11.0	762.5	0.014	0.642					0.0282	8,264	0.671			
	SM2	WN	251,735	8	8.0	550.2	0.015	0.267	0.502	0.166	1.63	0.154	0.0236	5,949	0.350			
		ES	72,249	10	72.2	598.1	0.121	0.363					0.1962	14,175	0.428		37,459	0.257
1994/95 (III*+IV*)	SM1	WS	51,938	11	35.0	496.4	0.071	0.375	0.765	0.122	2.56	0.198	0.1181	6,136	0.441			
		EN	146,681	8	20.0	630.7	0.032	0.514					0.0531	7,793	0.564			
	SM2	WN	148,803	7	15.3	457.9	0.033	0.416	0.693	0.110	1.87	0.110	0.0451	6,716	0.445			
		ES	60,046	8	37.0	459.5	0.080	0.432					0.1086	6,520	0.459			
		PRYD	21,096	4	40.0	203.5	0.197	0.296					0.2653	5,597	0.335		32,761	0.234
1995/96 (VI*)	SM1	WS	34,051	9	10.0	335.6	0.030	0.574	0.662	0.175	2.33	0.094	0.0524	1,783	0.608			
		EN	242,073	11	20.9	554.6	0.038	0.375					0.0663	16,055	0.424			
	SM2	WN	97,945	5	10.9	281.8	0.039	0.255	0.414	0.389	1.76	0.131	0.0823	8,058	0.483			
		ES	72,349	10	40.6	561.8	0.072	0.258					0.1533	11,093	0.485		36,988	0.301
1996/97 (II*)	SM1	ES	67,072	18	30.7	665.6	0.046	0.428	0.637	0.188	1.72	0.117	0.0624	4,186	0.482			
		WN	113,687	5	8.0	201.6	0.040	0.626					0.0537	6,104	0.664			
	SM2	EN	241,928	17	14.0	672.2	0.021	0.221	0.468	0.257	2.06	0.104	0.0459	11,106	0.355			
		WS	23,028	8	25.0	230.0	0.109	0.229					0.2396	5,517	0.360		26,913	0.268
1997/98 (II*)	SM1	WS	32,620	10	2.0	303.2	0.007	0.916	0.878	0.159	1.79	0.126	0.0067	219	0.939			
		EN1	84,726	6	6.7	345.1	0.020	0.419					0.0199	1,687	0.465			
		ES2	10,451	5	11.5	142.8	0.080	1.320					0.0819	856	1.335			
		EN2	44,064	2	2.0	87.8	0.023	0.954					0.0232	1,023	0.975			
	SM2	WN	52,135	4	6.0	253.3	0.024	0.434	0.672	0.128	1.81	0.136	0.0319	1,661	0.473			
		ES1	47,036	8	37.0	385.1	0.096	0.659					0.1292	6,078	0.685			
		EN2	35,949	2	5.0	170.8	0.029	0.600					0.0394	1,416	0.629		12,939	0.375



Figs 4a-c. Hazard rate model for the detection function fitted to the number of schools as a function of the perpendicular distance from the trackline. The number of schools is smeared and then grouped into 0.1 n.miles perpendicular distance intervals, with truncation at 1.5 n.miles. Some strata are pooled as discussed in the text. Graphs are provided for all detection functions estimated under closing mode (Figs 2a-b) and IO mode (Fig. 2c).

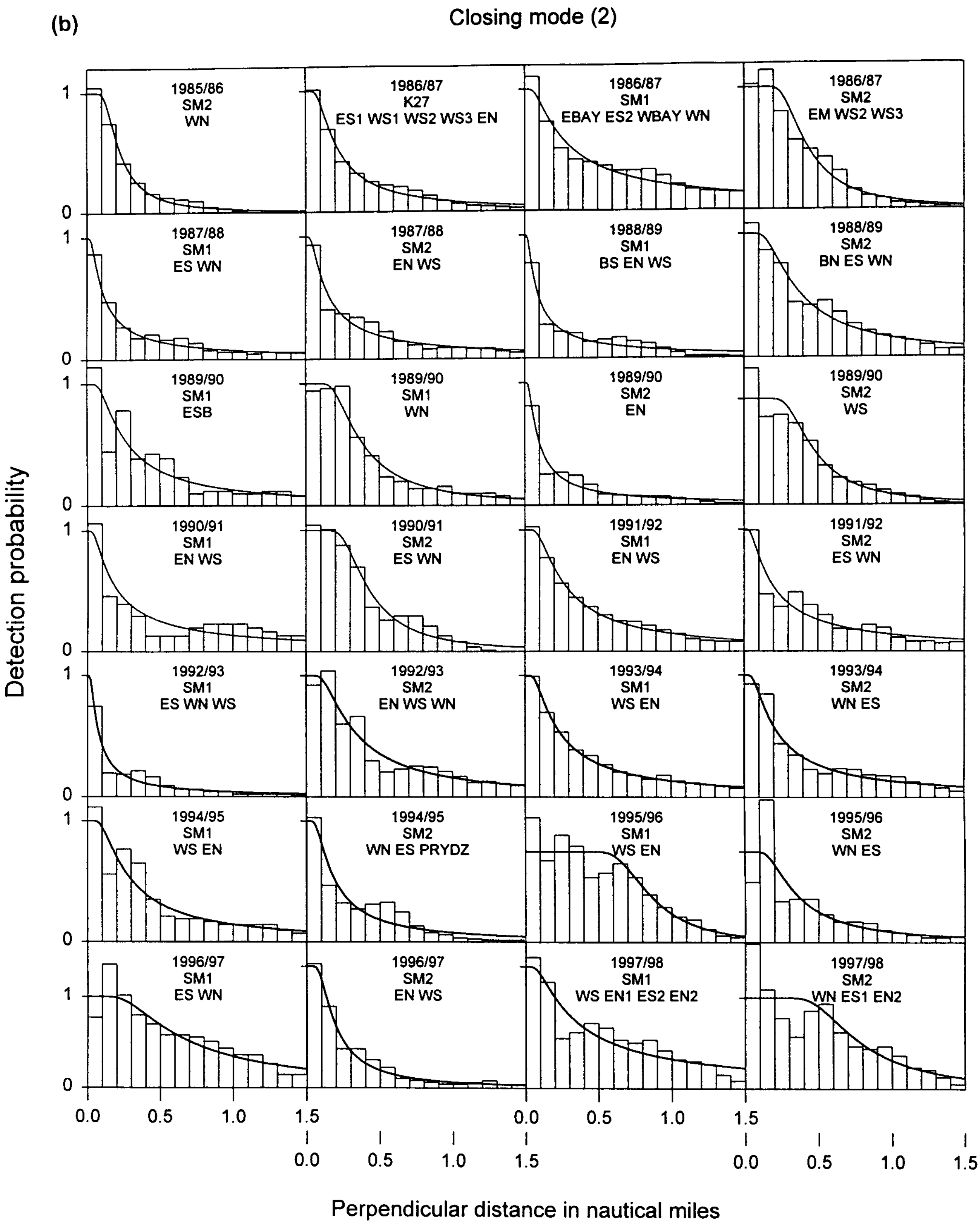

(b)
Closing mode (2)
1985/86 SM2 WN
1986/87 K27 ES1 WS1 WS2 WS3 EN
1986/87 SM1 EBAY ES2 WBAY WN
1986/87 SM2 EM WS2 WS3
1987/88 SM1 ES WN
1987/88 SM2 EN WS
1988/89 SM1 BS EN WS
1988/89 SM2 BN ES WN
1989/90 SM1 ESB
1989/90 SM1 WN
1989/90 SM2 EN
1989/90 SM2 WS
1990/91 SM1 EN WS
1990/91 SM2 ES WN
1991/92 SM1 EN WS
1991/92 SM2 ES WN
1992/93 SM1 ES WN WS
1992/93 SM2 EN WS WN
1993/94 SM1 WS EN
1993/94 SM2 WN ES
1994/95 SM1 WS EN
1994/95 SM2 WN ES PRYDZ
1995/96 SM1 WS EN
1995/96 SM2 WN ES
1996/97 SM1 ES WN
1996/97 SM2 EN WS
1997/98 SM1 WS EN1 ES2 EN2
1997/98 SM2 WN ES1 EN2
Detection probability
Perpendicular distance in nautical miles

Fig 4b.

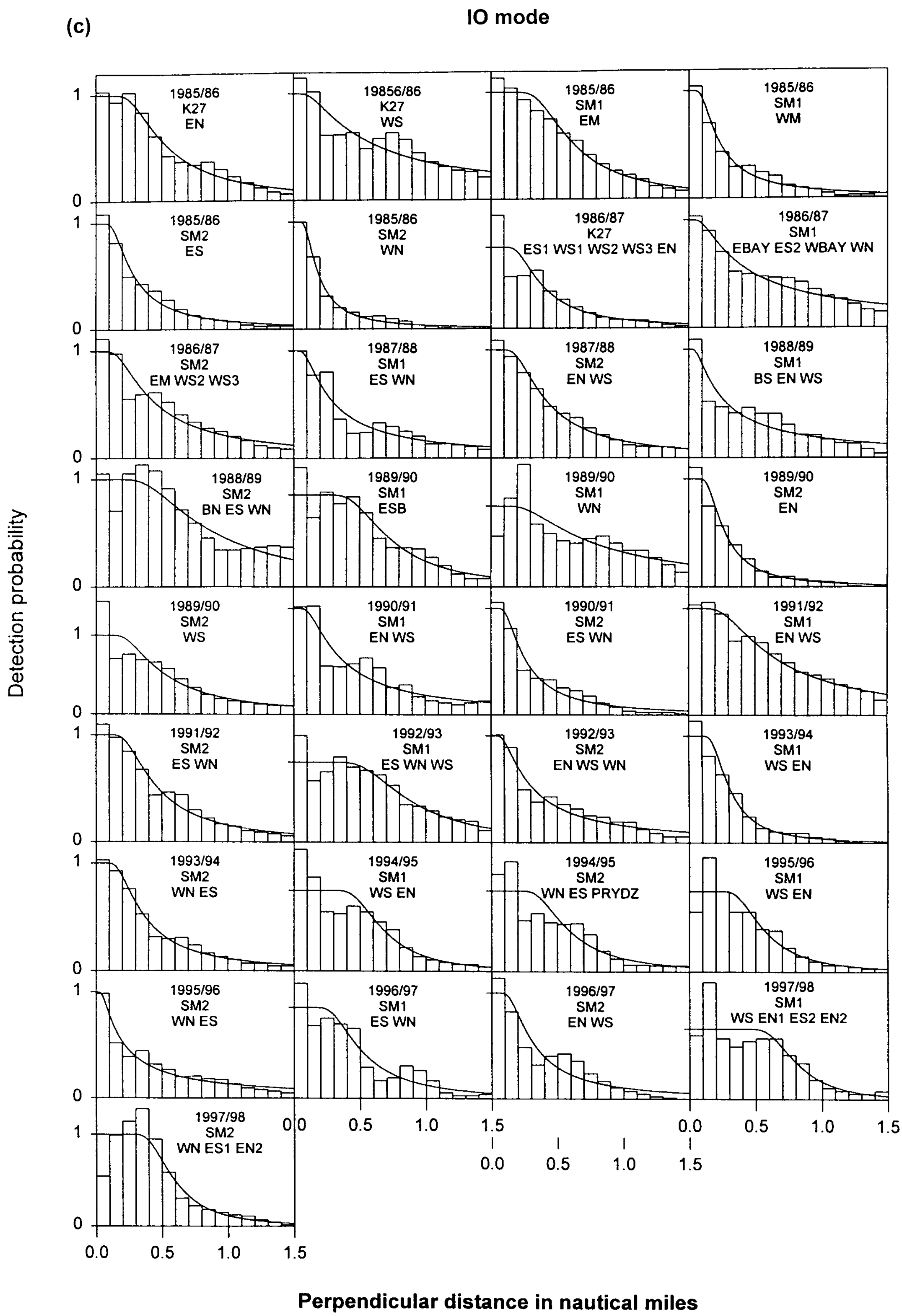

(c)
IO mode
Detection probability
1985/86 K27 EN
19856/86 K27 WS
1985/86 SM1 EM
1985/86 SM1 WM
1985/86 SM2 ES
1985/86 SM2 WN
1986/87 K27 ES1 WS1 WS2 WS3 EN
1986/87 SM1 EBAY ES2 WBAY WN
1986/87 SM2 EM WS2 WS3
1987/88 SM1 ES WN
1987/88 SM2 EN WS
1988/89 SM1 BS EN WS
1988/89 SM2 BN ES WN
1989/90 SM1 ESB
1989/90 SM1 WN
1989/90 SM2 EN
1989/90 SM2 WS
1990/91 SM1 EN WS
1990/91 SM2 ES WN
1991/92 SM1 EN WS
1991/92 SM2 ES WN
1992/93 SM1 ES WN WS
1992/93 SM2 EN WS WN
1993/94 SM1 WS EN
1993/94 SM2 WN ES
1994/95 SM1 WS EN
1994/95 SM2 WN ES PRYDZ
1995/96 SM1 WS EN
1995/96 SM2 WN ES
1996/97 SM1 ES WN
1996/97 SM2 EN WS
1997/98 SM1 WS EN1 ES2 EN2
1997/98 SM2 WN ES1 EN2
0.0 0.5 1.0 1.5
Perpendicular distance in nautical miles

Fig 4c.

Table 2

Updating the value of R, the ratio between the estimated density of minke schools (D_s) obtained during closing mode and during IO mode. Individual estimates of R are shown for each of the 'super-strata' used in obtaining the overall value.

			Closing mode		IO mode			
Year	Vessel	Strata	D_s	CV	D_s	CV	R	CV
1985/86	K27	EN	0.061	0.488	0.056	0.361	1.088	0.607
		WS	0.046	0.285	0.102	0.260	0.456	0.385
	SM1	EM	0.108	0.297	0.099	0.360	1.098	0.467
		WM	0.085	0.612	0.121	0.653	0.699	0.894
	SM2	ES	0.188	0.241	0.283	0.296	0.665	0.382
		WN	0.055	0.595	0.184	0.444	0.300	0.742
1986/87	K27	ES1 WS1 WS2 WS3 EN	0.122	0.305	0.128	0.323	0.952	0.444
	SM1	EBAY ES2 WBAY WN	0.046	0.388	0.068	0.245	0.680	0.459
	SM2	EM WS2 WS3	0.068	0.305	0.100	0.295	0.678	0.424
1987/88	SM1	ES WN	0.038	1.064	0.060	0.406	0.642	1.139
	SM2	EN WS	0.049	0.538	0.073	0.182	0.678	0.568
1988/89	SM1	BS EN WS	0.079	0.663	0.051	0.356	1.549	0.752
	SM2	BN ES WN	0.032	0.421	0.024	0.284	1.316	0.508
1989/90	SM1	ESB	0.045	0.530	0.049	0.486	0.906	0.719
		WN	0.047	0.394	0.028	0.476	1.678	0.618
	SM2	EN	0.121	0.628	0.072	0.311	1.690	0.701
		WS	0.093	0.240	0.214	0.275	0.434	0.366
1990/91	SM1	EN WS	0.037	0.929	0.034	0.518	1.091	1.063
	SM2	ES WN	0.033	0.286	0.036	0.436	0.928	0.522
1991/92	SM1	EN WS	0.145	0.297	0.134	0.236	1.080	0.379
	SM2	ES WN	0.040	0.482	0.053	0.391	0.757	0.620
1992/93	SM1	ES WN WS	0.047	0.951	0.021	0.350	2.248	1.013
	SM2	EN WS WN	0.018	0.331	0.029	0.258	0.603	0.420
1993/94	SM1	WS EN	0.013	0.580	0.033	0.356	0.398	0.681
	SM2	WN ES	0.046	0.401	0.038	0.315	1.197	0.510
1994/95	SM1	WS EN	0.018	0.513	0.027	0.353	0.641	0.623
	SM2	WN ES PRYDZ	0.036	0.456	0.044	0.253	0.813	0.522
1995/96	SM1	WS EN	0.031	0.337	0.028	0.384	1.110	0.511
	SM2	WN ES	0.041	0.412	0.064	0.430	0.636	0.595
1996/97	SM1	ES WN	0.022	0.368	0.033	0.451	0.662	0.582
	SM2	EN WS	0.041	0.609	0.030	0.306	1.348	0.681
1997/98	SM1	WS EN1 ES2 EN2	0.051	0.454	0.012	0.467	4.126	0.652
	SM2	WN ES1 EN2	0.023	0.493	0.037	0.472	0.606	0.683
All strata combined							0.826	0.089

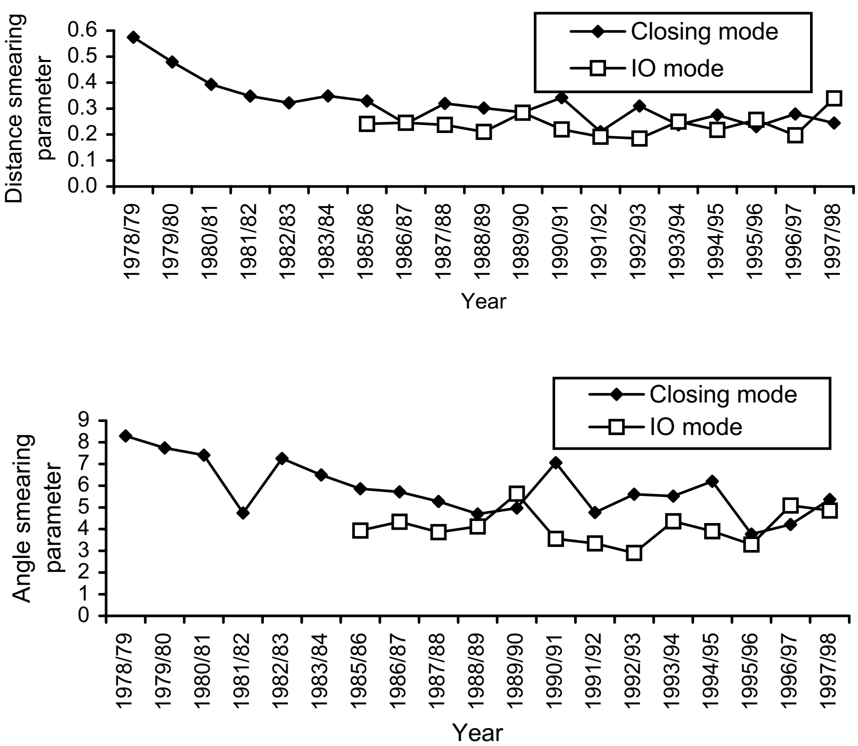


Fig. 5. The radial distance (s) and angle (ϕ) smearing factors used in estimating effective search half-width w_s. The mean value is plotted for each year separately for closing and IO mode. These factors are defined as follows: a sighting at radial distance r and angle to the trackline θ is smeared over radial distance [r(1-s), r(1+s)] and angular [θ-ϕ, θ+ϕ] ranges.

Updated estimate of R

The individual values of R for the 'super-strata' are given in Table 2. In 20 of the 33 'super-strata', the closing mode school density estimate is lower than that for IO mode. The overall inverse-variance weighted estimate of R is 0.826 (CV = 0.089).

Combined passing and closing mode estimates

The combined closing and IO mode estimates are contained in Table 3 where they are compared to previously published results. For the 1978/79 to 1988/89 surveys, these are listed in Haw (1993b); for the 1989/90 to 1997/98 cruises, they may be found respectively in Haw (1991a), Haw (1993a), Borchers (1993), Borchers and Cameron (1995), Borchers and Burt (1996), Burt and Borchers (1996), Burt and Borchers (1997), Burt and Borchers (1999) and Burt and Stahl (2000), except that an error in Burt and Stahl (2000) (in their estimates for minke and undetermined minke whales: codes 4 and 91) has been corrected.

[*Text continues overleaf*]

Table 3

Summary of abundance estimates for each survey obtained in this paper ('Revised') and those published in previous papers ('Previous'). Pseudo-passing estimates for the 'Revised' estimates are calculated by dividing the closing mode estimate by R = 0.826 (CV = 0.089). See main text (footnotes 17 and 18) for details of procedures used to obtain circumpolar estimates and their variances. The 'Previous' estimates used R = 0.751 (CV = 0.152) and were corrected for random whale movement by a multiplicative factor m = 0.985. *The third circumpolar set is incomplete. 'Previous' estimates are taken from Haw (1993a) for 1978/79 to 1988/89 and from individual assessment papers for the remaining years (see text).

	Closing mode		IO mode		Pseudo-passing		Inverse-var. weighted	
Year	Total	CV	Total	CV	Total	CV	Total	CV
Revised								
1978/79	93,808	0.147			113,569	0.172	113,569	0.172
1979/80	102,188	0.218			123,714	0.235	123,714	0.235
1980/81	133,560	0.228			161,695	0.245	161,695	0.245
1981/82	37,649	0.202			45,580	0.221	45,580	0.221
1982/83	52,808	0.194			63,932	0.213	63,932	0.213
1983/84	82,423	0.261			99,786	0.276	99,786	0.276
1985/86	229,175	0.188	321,207	0.176	277,452	0.208	299,793	0.135
1986/87	110,984	0.249	128,680	0.244	134,363	0.264	131,177	0.180
1987/88	96,043	0.631	145,600	0.300	116,275	0.637	138,022	0.273
1988/89	78,660	0.445	54,305	0.257	95,230	0.454	58,170	0.228
1989/90	66,529	0.343	61,169	0.192	80,544	0.354	63,972	0.170
1990/91	53,091	0.445	53,541	0.360	64,275	0.454	56,807	0.283
1991/92	94,855	0.279	92,684	0.221	114,837	0.293	98,682	0.177
1992/93	23,322	0.564	24,970	0.239	28,235	0.571	25,363	0.220
1993/94	30,993	0.359	37,459	0.257	37,522	0.370	37,479	0.211
1994/95	24,234	0.359	32,761	0.234	29,339	0.370	31,620	0.198
1995/96	31,950	0.272	36,988	0.301	38,680	0.286	37,839	0.207
1996/97	29,228	0.482	26,913	0.268	35,385	0.490	28,158	0.236
1997/98	21,291	0.373	12,939	0.375	25,776	0.383	15,434	0.282
CPI	502,436	0.094			608,276	0.130	608,276	0.130
CPII	634,482	0.146	764,502	0.108	768,138	0.171	765,529	0.091
CPIII*	251,805	0.149	257,479	0.109	304,849	0.174	267,881	0.093
Previous								
1978/79	72,867	0.156			97,027	0.218	97,027	0.218
1979/80	61,272	0.188			81,587	0.242	81,587	0.242
1980/81	133,382	0.216			177,606	0.264	177,606	0.264
1981/82	35,760	0.203			47,617	0.254	47,617	0.254
1982/83	55,050	0.203			73,302	0.254	73,302	0.254
1983/84	81,077	0.243			107,959	0.287	107,959	0.287
1985/86	211,150	0.174	303,284	0.172	281,158	0.231	294,610	0.138
1986/87	92,114	0.206	121,549	0.285	122,655	0.256	122,156	0.190
1987/88	51,820	0.521	102,984	0.309	69,001	0.543	88,735	0.273
1988/89	64,403	0.343	68,570	0.349	85,756	0.375	74,692	0.257
1989/90	53,236	0.258	49,592	0.197	70,887	0.299	53,314	0.166
1990/91	47,995	0.399	51,718	0.391	63,908	0.427	56,039	0.290
1991/92	78,461	0.263	87,145	0.250	104,475	0.304	92,709	0.194
1992/93	11,715	0.306	15,583	0.193	15,599	0.341	15,587	0.168
1993/94	19,076	0.335	27,505	0.271	25,401	0.368	26,687	0.218
1994/95	15,649	0.342	28,100	0.246	20,838	0.374	24,905	0.208
1995/96	31,690	0.287	35,861	0.304	42,197	0.325	38,317	0.223
1996/97	28,790	0.482	26,719	0.271	38,336	0.505	28,143	0.241
1997/98	22,258	0.365	12,056	0.346	29,638	0.395	14,033	0.280
CPI	439,408	0.093			585,097	0.178	585,097	0.178
CPII	520,718	0.113	697,697	0.111	693,366	0.190	696,579	0.096
CPIII*	203,571	0.142	225,817	0.122	271,067	0.208	234,538	0.106

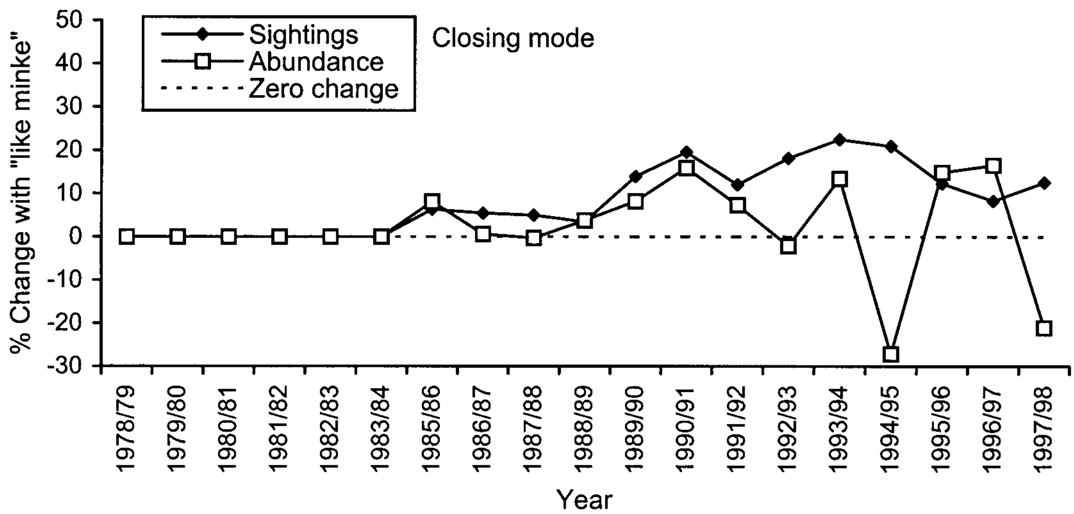
The estimates of abundance from the three circumpolar sets of cruises are 608,000 (CV = 0.130), 766,000 (CV = 0.091) and 268,000 (CV = 0.093) respectively[17,18]. These appear to be very similar to the circumpolar abundances obtained by summing previous estimates of 585,000 (CV = 0.178), 697,000 (CV = 0.096) and 235,000 (CV = 0.106). However, these previous estimates incorporated a correction factor *m* for random whale movement of 0.985, and also used Haw's (1991b) estimate of $R = 0.751$. When the updated estimate of $R = 0.826$ is applied to these previous circumpolar abundance estimates, and the adjustment factor *m* is omitted, they decrease to 540,000 (CV = 0.128), 680,000 (CV = 0.088) and 236,000 (CV = 0.099), somewhat lower than the revised estimates in all three cases.

Inclusion of 'like minke' sightings

Including 'like minke' sightings in the analyses has no effect on the estimates from the first circumpolar set of surveys (Table 4, Fig. 6). For closing mode, although the mean increase in sightings changes from 0% to 9% to 15% across the three circumpolar sets, the overall impact on abundance estimates is only slight, amounting to a mean increase of 6% for the second set and only 0.3% for the third circumpolar set

[17] The circumpolar estimates and their CVs in Table 3 were obtained by simply adding the estimates and variances for the individual surveys. Note, however, that in Table 3 and subsequent Tables which list 'Pseudo-passing' abundance estimates, the associated CVs for circumpolar estimates take account of the fact that a common estimate of *R* has been applied to all surveys. Furthermore, inverse-variance weighted circumpolar estimates (and their CVs) are derived by combining the associated circumpolar IO and 'Pseudo-passing' estimates. Consequently these inverse-variance weighted circumpolar estimates differ slightly from the sum of such estimates for the constituent areas. As the constituent surveys were not synoptic, but took place over a period of years, this procedure could lead to negatively biased estimates of the CVs for the circumpolar estimates. This is because of the effect of 'additional variance' arising from factors other than the sampling variability upon which the CV estimates for the constituent surveys are based. For example, one source of such additional variance could be a changed distribution of minke whales, on a scale similar to that of the individual survey coverage, from one year to the next. However, computations of the magnitude of this additional variance at the Management Area level (that typically covered by these individual surveys) by the procedure of Punt *et al.* (1997) gives a point estimate of zero (see footnote 24 of Butterworth *et al.*, 1999). Thus this potential source of bias in these CV estimates does not seem likely to be particularly large.

[18] The 1996/97 and 1997/98 cruises both covered the longitudinal range 30º-25ºW. The abundance summations for the third circumpolar set of surveys use the whole estimate for 1997/98 survey, which surveyed this region more intensively. Contributions to the summations from strata for the 1996/97 survey are pro-rated down in proportion to the fraction of their areas inside the 30º-25ºW region.



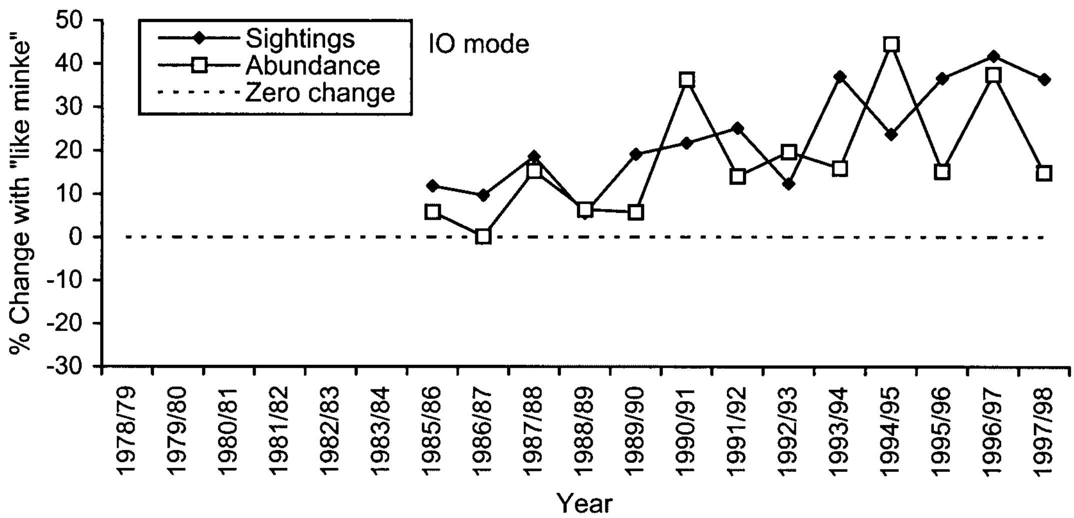


Fig. 6. Percentage changes in the number of sightings and in the uncorrected abundance estimates when 'like minke' sightings are included.

of surveys. In fact, for four of the thirteen surveys from 1985/86, the closing mode estimate decreases when 'like minke' sightings are included. For IO mode, the mean increases in sightings are 14% and 31% for the second and third circumpolar sets, and abundance estimates increase for every survey when 'like minke' sightings are included. This translates into abundance estimate increases of 12% and 23% for these two circumpolar sets of surveys.

Comparable abundance estimates from the circumpolar sets of surveys

The values of the factors used to provide comparable abundance estimates are given in Table 5a-c. Portions of the strata surveyed were north of 60°S for all Area II cruises, and for the 1985/86 cruise in Area V (see Figs 1a-f). The inverse-variance weighted estimates (Table 6) are 729,000 (CV = 0.150), 824,000 (CV = 0.117) and 359,000 (CV = 0.108) for the three circumpolar sets of surveys, when excluding longitude ranges yet to be covered in the third set from the first two. If only the first two circumpolar sets are considered, which both cover the complete circumpolar longitudinal range, the inverse-variance weighted estimates are 813,000 (CV = 0.142) and 955,000 (CV = 0.106) respectively.

After further adjustments to allow for the change in proportions of 'like minke' sightings over time, the comparable estimates for closing mode are 602,000 (CV = 0.121), 700,000 (CV = 0.205) and 384,000 (CV = 0.185) respectively (Table 7). These adjustments are made by applying factors for the proportional change in abundance when 'like species' are included ('% change (*P*)' in Table 4) to the extrapolated abundance estimates of Table 6 separately for each year and survey mode, and then summing over the surveys comprising each circumpolar set. The corresponding values for IO mode for the second and third circumpolar sets are 900,000 (CV = 0.139) and 404,000 (CV = 0.123). Pooling these estimates across modes as before would require re-computation of the calibration factor *R*, because of the differing impact of including 'like minke' sightings on closing and IO mode abundance estimates over time. If the 'minke plus like-minke' combination is assumed to reflect a more stable classification over time than 'minke' only, then such a re-computed *R* would be a more reliable estimate for this calibration factor.

Table 4

The impact of including 'like minke' sightings in the abundance estimates. The number of schools sighted in primary search mode during surveys is indicated, together with the number of sightings when 'like minkes' are included (n_{like}). The uncorrected abundance estimates for each survey are shown for both closing and IO mode. Sightings are smeared and truncated at a perpendicular distance of 1.5 n.miles. *The third circumpolar set is incomplete.

	Number of sightings			Uncorrected abundance				
Year	n	n_{like}	% change (n)	P	CV	P_{like}	CV	% change (P)
Closing mode								
1978/79	490.5	490.5	0.0	93,808	0.147	93,808	0.147	0.0
1979/80	413.9	413.9	0.0	102,188	0.218	102,188	0.218	0.0
1980/81	542.5	542.5	0.0	133,560	0.228	133,560	0.228	0.0
1981/82	444.6	444.6	0.0	37,649	0.202	37,649	0.202	0.0
1982/83	576.1	576.1	0.0	52,808	0.194	52,808	0.194	0.0
1983/84	186.1	186.1	0.0	82,423	0.261	82,423	0.261	0.0
1985/86	362.9	385.7	6.3	229,175	0.188	247,686	0.182	8.1
1986/87	257.3	271.2	5.4	110,984	0.249	111,642	0.241	0.6
1987/88	81.4	85.4	4.9	96,043	0.631	95,760	0.621	-0.3
1988/89	90.8	93.9	3.4	78,660	0.445	81,607	0.421	3.7
1989/90	150.7	171.7	13.9	66,529	0.343	71,982	0.364	8.2
1990/91	57.3	68.5	19.5	53,091	0.445	61,553	0.423	15.9
1991/92	139.5	156.3	12.0	94,855	0.279	101,793	0.276	7.3
1992/93	103.4	122.2	18.2	23,322	0.564	22,826	0.347	-2.1
1993/94	80.4	98.5	22.5	30,993	0.359	35,161	0.343	13.4
1994/95	61.5	74.4	21.0	24,234	0.359	17,650	0.285	-27.2
1995/96	91.0	102.2	12.3	31,950	0.272	36,707	0.264	14.9
1996/97	54.4	58.9	8.3	29,228	0.482	34,068	0.455	16.6
1997/98	82.9	93.3	12.5	21,158	0.373	16,696	0.256	-21.1
CPI	2,653.7	2,653.7	0.0	502,436	0.094	502,436	0.094	0.0
CPII	1,000.4	1,076.4	8.9	634,482	0.146	670,230	0.140	6.0
CPIII*	613.1	705.8	15.3	251,805	0.149	260,027	0.142	0.3
IO mode								
1985/86	598.1	668.7	11.8	321,207	0.176	339,947	0.176	5.8
1986/87	412.9	452.8	9.7	128,680	0.244	128,878	0.213	0.2
1987/88	207.9	246.5	18.6	145,600	0.300	167,806	0.320	15.3
1988/89	157.3	166.0	5.5	54,305	0.257	57,775	0.253	6.4
1989/90	325.7	387.9	19.1	61,169	0.192	64,715	0.192	5.8
1990/91	90.8	110.5	21.7	53,541	0.360	72,985	0.313	36.3
1991/92	325.6	407.5	25.2	92,684	0.221	105,704	0.215	14.0
1992/93	212.8	239.0	12.3	24,970	0.239	29,878	0.236	19.7
1993/94	143.2	196.3	37.1	37,459	0.257	43,418	0.253	15.9
1994/95	147.3	182.3	23.8	32,761	0.234	47,385	0.226	44.6
1995/96	82.4	112.6	36.7	36,988	0.301	42,613	0.223	15.2
1996/97	77.7	110.2	41.8	26,913	0.268	37,017	0.291	37.5
1997/98	70.2	95.8	36.5	12,939	0.375	14,862	0.307	14.9
CPII	1,792.7	2,032.4	14.4	764,502	0.108	832,106	0.108	11.6
CPIII*	1,059.2	1,343.7	30.5	257,479	0.109	311,520	0.102	23.1

Text continues on p. 168

Table 5a-b

Values of factors used to obtain comparable abundance estimates for each circumpolar set of surveys for closing mode. Areas are given in n.miles^2. To extrapolate the abundance estimates to 60°S, the density of whales in each unsurveyed area between a northern stratum and 60°S is assumed to be the same as that in the associated northern stratum. If a stratum extends north of 60°S, the associated abundance estimate is proportionately decreased. The fraction of each stratum area that lies within the area covered by the incomplete third circumpolar set of cruises is calculated, and the abundance estimate for the stratum multiplied by that fraction. The final result ('Total') comprises estimates of the uncorrected abundance south of 60°S in regions that correspond to those covered in the third circumpolar set of cruises to 1997/98. Note that for the WN and WS strata in 1996/97, the stratum areas have been reduced (as recorded in the 'Area overlap' column) to adjust for the fact that parts of these strata were re-surveyed in 1997/98.

(a) Comparable closing mode estimates CPI.

Year	Stratum	P	CV	Area surveyed	Area unsurveyed	Area N of 60°S	Area overlap	P (S of 60°S)	Fraction in 3rd set	P (fraction in 3rd set)	Total	CV
1978/79	W1N	9,442	0.405	39,256	38,645			18,736	1.00	18,736		
	EN	23,099	0.366	156,766	53,181			30,935	0.00	0		
	W2N	7,064	0.323	153,914				7,064	0.15	1,039		
	W1S	21,430	0.280	20,389				21,430	1.00	21,430		
	W2S	8,759	0.218	29,600				8,759	0.06	496		
	ES	24,014	0.263	27,571				24,014	0.00	0	41,701	0.232
1979/80	WN	23,950	0.437	200,724	255,938			54,488	1.00	54,488		
	EN	28,627	0.563	217,865	100,763			41,867	1.00	41,867		
	Other	49,612	0.228	75,391				49,612	1.00	49,612	145,967	0.242
1980/81	WN	20,244	0.709	139,191	91,934			33,615	1.00	33,615		
	EN	52,172	0.414	208,159	263,267			118,156	1.00	118,156		
	Other	61,145	0.260	132,930				61,145	1.00	61,145	212,916	0.266
1981/82	W1N	4,885	0.700	135,504	100,005	74,162		5,817	1.00	5,817		
	EN	8,647	0.520	145,063	288,507			25,843	1.00	25,843		
	Other	24,118	0.190	117,454				24,118	1.00	24,118	55,778	0.265
1982/83	WN	7,288	0.291	163,926	243,506			18,114	0.68	12,400		
	EN	24,598	0.352	149,433	178,386			53,962	1.00	53,962		
	WS	7,688	0.206	25,596				7,688	0.67	5,128		
	ES	13,235	0.360	33,050				13,235	1.00	13,235	84,725	0.235
1983/84	EN	14,593	0.826	202,108	35,088			17,126	0.19	3,286		
	WN	25,536	0.270	207,721				25,536	1.00	25,536		
	WMS	29,939	0.332	156,457				29,939	1.00	29,939		
	EMS	12,355	0.476	158,893				12,355	0.17	2,057	60,818	0.204

(b) Comparable closing mode estimates CPII and CPIII.

Year	Stratum	P	CV	Area surveyed	Area unsurveyed	Area N of 60°S	Area overlap	P (S of 60°S)	Fraction in 3rd set	P (fraction in 3rd set)	Total	CV
1985/86	WN	14,787	0.624	139,065		38,305		10,714	1.00	10,714		
	Other	214,388	0.196	824,403				214,388	1.00	214,388	225,102	0.189
1986/87	WS2	1,447	0.249	21,143		11,992		626	1.00	626		
	WN	1,829	0.546	95,361		10,596		1,626	1.00	1,626		
	EN	54,864	0.400	124,057	74,341			87,741	1.00	87,741		
	Other	52,844	0.211	254,647				52,844	1.00	52,844	142,837	0.258
1987/88	WN	33,513	1.254	148,821	263,930			92,947	1.00	92,947		
	EN	5,571	0.630	168,881	54,823			7,379	1.00	7,379		
	Other	56,959	0.584	162,028				56,959	1.00	56,959	157286	0.771
1988/89	WN	11,239	0.824	156,617	17,772			12,514	0.33	4,169		
	EN	13,137	0.714	181,166	17,772			14,426	0.00	0		
	BS	5,396	0.686	6,520				5,396	1.00	5,396		
	WS	29,204	0.710	58,693				29,204	0.26	7,692		
	BN	2,053	0.785	17,486				2,053	1.00	2,053		
	ES	17,630	0.463	156,617				17,630	0.00	0	19,311	0.394
1989/90	WN	17,621	0.465	168,761	249,265			43,648	0.62	27,183		
	EN	32,687	0.640	153,029	167,243			68,410	1.00	68,410		
	WS	11,195	0.258	45,128				11,195	0.64	7,176		
	ESBAY	5,026	0.549	62,594				5,026	1.00	5,026	107,795	0.424
1990/91	EN	19,676	0.972	191,954	43,706			24,156	0.23	5,435		
	WS	2,642	0.962	45,414				2,642	1.00	2,642		
	ES	24,758	0.375	108,268				24,758	0.11	2,627		
	WN	6,016	0.340	211,788				6,016	1.00	6,016	16,721	0.376
1991/92	WN	2,017	0.544	137,734	120,700			3,785	1.00	3,785		
	EN	76,005	0.321	165,429	247,210			189,584	1.00	189,584		
	Other	16,834	0.358	140,682				16,834	1.00	16,834	210,202	0.291
1992/93	All	23,322	0.564	445,316				23,322	1.00	23,322	23,322	0.564
1993/94	All	30,993	0.359	667,776				30,993	1.00	30,993	30,993	0.359

cont...

Table 5b continued.

Year	Stratum	*P*	CV	Area surveyed	Area unsurveyed	Area N of 60°S	Area overlap	*P* (S of 60°S)	Fraction in 3rd set	*P* (fraction in 3rd set)	Total	CV
1994/95	All	24,234	0.359	428,564				24,234	1.00	24,234	24,234	0.359
1995/96	All	31,950	0.272	446,418				31,950	1.00	31,950	31,950	0.272
1996/97	WN	3,575	0.442	113,687	14,510		55,590	2,283	1.00	2,283		
	WS	3,012	0.928	23,028			17,740	692	1.00	692		
	Other	22,641	0.574	309,000				22,641	1.00	22,641	25,616	0.509
1997/98	WN	223	1.073	52,135		32,722		83	1.00	83		
	WS	511	0.840	32,620		14,040		291	1.00	291		
	Other	20,424	0.300	222,226				20,424	1.00	20,424	20,798	0.295

Table 5c

Values of factors used to obtain comparable biomass estimates for the 2nd and 3rd circumpolar sets of surveys in IO mode, developed as for Tables 5a-b.

(c) Comparable IO mode CPII and CPIII.

Year	Stratum	*P*	CV	Area surveyed	Area unsurveyed	Area N of 60°S	Area overlap	*P* (S of 60°S)	Fraction in 3rd set	*P* (fraction in 3rd set)	Total	CV
1985/86	WN	49,939	0.424	139,065		38,305		36,183	1.00	36,183	307,451	0.178
	Other	271,268	0.193	824,403				271,268	1.00	271,268		
1986/87	WS2	1,404	0.915	21,143		11,992		608	1.00	608		
	WN	0	0.000	95,361		10,596		0	1.00	0	159,596	0.284
	EN	52,920	0.495	124,057	74,341			84,633	1.00	84,633		
	Other	74,355	0.233	254,647				74,355	1.00	74,355		
1987/88	WN	53,914	0.530	148,821	263,930			149,528	1.00	149,528		
	EN	9,840	0.500	168,881	54,823			13,035	1.00	13,035	244,408	0.352
	Other	81,846	0.400	162,028				81,846	1.00	81,846		
1988/89	WN	473	1.144	156,617	17,772			527	0.33	176		
	EN	12,129	0.388	181,166	17,772			13,319	0.00	0		
	BS	5,332	0.821	6,520				5,332	1.00	5,332		
	WS	13,360	0.438	58,693				13,360	0.26	3,519	11,364	0.415
	BN	2,337	0.358	17,486				2,337	1.00	2,337		
	ES	20,674	0.366	156,617				20,674	0.00	0		
1989/90	WN	10,522	0.537	168,761	249,265			26,063	0.62	16,232		
	EN	19,318	0.334	153,029	167,243			40,431	1.00	40,431	78,736	0.216
	WS	25,783	0.291	45,128				25,783	0.64	16,528		
	ESBAY	5,545	0.507	62,594				5,545	1.00	5,545		
1990/91	EN	15,782	0.680	191,954	43,706			19,376	0.23	4,360		
	WS	4,581	0.332	45,414				4,581	1.00	4,581	27,608	0.344
	ES	16,233	0.622	108,268				16,233	0.11	1,723		
	WN	16,945	0.521	211,788				16,945	1.00	16,945		
1991/92	WN	5,335	0.714	137,734	120,700			10,011	1.00	10,011		
	EN	51,619	0.268	165,429	247,210			128,756	1.00	128,756	174,496	0.218
	Other	35,730	0.410	140,682				35,730	1.00	35,730		
1992/93	All	24,970	0.239	445,316				24,970	1.00	24,970	24,970	0.239
1993/94	All	37,459	0.257	667,776				37,459	1.00	37,459	37,459	0.257
1994/95	All	32,761	0.234	428,564				32,761	1.00	32,761	32,761	0.234
1995/96	All	36,988	0.301	446,418				36,988	1.00	36,988	36,988	0.301
1996/97	WN	6,104	0.664	113,687	14,510		55,590	3,898	1.00	3,898		
	WS	5,517	0.360	23,028			17,740	1,267	1.00	1,267	20,457	0.303
	Other	15,292	0.367	309,000				15,292	1.00	15,292		
1997/98	WN	1,661	0.473	52,135		32,722		619	1.00	619		
	WS	219	0.939	32,620		14,040		125	1.00	125	11,802	0.406
	Other	11,059	0.433	222,226				11,059	1.00	11,059		

Table 6

Comparable abundance estimates for each circumpolar set of surveys, extrapolated to 60°S. The estimates do not cover the entire circumpolar range but are restricted to the longitudinal range covered in the third circumpolar set of surveys.

Same areas	Closing mode		IO mode		Pseudo-passing		Inverse-var. weighted	
Year	Total	CV	Total	CV	Total	CV	Total	CV
1978/79	41,701	0.232			50,485	0.248	50,485	0.248
1979/80	145,967	0.242			176,715	0.258	176,715	0.258
1980/81	212,916	0.266			257,767	0.281	257,767	0.281
1981/82	55,778	0.265			67,528	0.279	67,528	0.279
1982/83	84,725	0.235			102,572	0.252	102,572	0.252
1983/84	60,818	0.204			73,629	0.223	73,629	0.223
1985/86	225,102	0.189	307,451	0.178	272,521	0.209	290,724	0.136
1986/87	142,837	0.258	159,596	0.284	172,926	0.273	166,000	0.197
1987/88	157,286	0.771	244,408	0.352	190,419	0.776	230,755	0.322
1988/89	19,311	0.394	11,364	0.415	23,379	0.404	13,764	0.307
1989/90	107,795	0.424	78,736	0.216	130,503	0.433	83,038	0.196
1990/91	16,721	0.376	27,608	0.344	20,243	0.386	23,220	0.260
1991/92	210,202	0.291	174,496	0.218	254,482	0.304	190,081	0.180
1992/93	23,322	0.564	24,970	0.239	28,235	0.571	25,363	0.220
1993/94	30,993	0.359	37,459	0.257	37,522	0.370	37,479	0.211
1994/95	24,234	0.359	32,761	0.234	29,339	0.370	31,620	0.198
1995/96	31,950	0.272	36,988	0.301	38,680	0.286	37,839	0.207
1996/97	25,616	0.509	20,457	0.303	31,012	0.517	21,828	0.265
1997/98	20,798	0.295	11,802	0.406	25,179	0.308	15,506	0.263
CPI	601,905	0.121			728,698	0.150	728,698	0.150
CPII	669,052	0.212	829,163	0.137	809,990	0.230	823,976	0.117
CPIII*	367,115	0.181	338,933	0.126	444,449	0.201	358,504	0.108

With 'like minkes' included, for closing mode the comparable estimate of abundance for the third circumpolar set of cruises is 55% of that in the second set, whereas for IO mode the corresponding estimate is just 45%. The closing mode estimates for the first and second circumpolar sets of surveys are quite similar.

DISCUSSION

Comparison with previous estimates

The revised abundance estimates of this paper are similar to previously published estimates for most cruises, for both closing and IO modes (Table 4). There are three main reasons for differences.

(i) Corrections to the recorded data. Data are thoroughly re-checked when incorporated into DESS. Many of the minor differences in values for the components of the abundance estimation formula (e.g. stratum area A, search effort L, number of sightings n_s) can be traced to this thorough revision process. The appendices in Strindberg and Burt (2000) provide an exhaustive guide to all changes made to the data they received (which comprised the data recorded on the survey vessels, as modified in validation exercises carried out by the IWC Secretariat for the 1986/87 cruise onwards, and at the University of Cape Town for the earlier cruises).

(ii) The mean school size estimation method changed from the 1995/96 assessment. The updated method is used throughout in this paper, and often gives quite different estimates for the mean school sizes in surveys before 1995/96. In some previous assessments (e.g. those for 1991/92, 1993/94 and 1994/95), the estimated mean school size for some strata was less than one, a major reason for the methodological change made for the 1995/96 analysis.

(iii) Changes in pooling. Previous assessments made pooling decisions on either an *ad hoc* basis, or by using the AIC criterion. For many of the cruises, the pooling selected for this paper is different from that for the corresponding previous assessment. Since pooling affects estimates of both mean school size ($\bar{s}$) and search half-width (w_s), the changes in pooling explain a number of the differences between the previous and revised abundance estimates.

A brief summary of reasons (in order of importance) for such differences is given below for each cruise where the difference exceeds 25% for either closing or IO mode.

1978/79: higher $\bar{s}$ in the ES stratum, increase in sightings due to corrected data (Strindberg and Burt, 2000, appendix T)
1979/80: higher $\bar{s}$
1987/88: higher $\bar{s}$, smaller w_s in closing mode (the results of different pooling)
1992/93: higher $\bar{s}$, lower w_s (the results of different pooling)
1993/94: higher $\bar{s}$
1994/95: different pooling.

For all nine cases (for either closing or IO mode) for which the differences in abundance estimates exceeded 25%, the revised estimate is higher than the previous estimate. In most of these cases the increase can be ascribed to a larger estimate of mean school size obtained using the new method of regressing against $g(y)$. This raises concerns about the impact of the change in this methodology on the abundance estimates. In DESS, if there is a significant (at the 15% level) relationship between perpendicular distance y and school size, the regression method is used; otherwise, the mean school size within a perpendicular distance of 1.5 n.miles is adopted. This approach can result in a marked change in the estimate of $\bar{s}$ with only minor changes to the recorded data. Since obtaining a significant regression depends heavily on sample size, $\bar{s}$ is invariably set to this mean size for strata with small numbers of sightings, while those with larger numbers of sightings apply the regression method, which produces smaller $\bar{s}$ estimates. Further investigation of the most appropriate method to use to estimate mean school size is needed.

Table 7

Comparable abundance estimates with 'like minke' frequencies taken into account. The average abundance increase for each survey if 'like minkes' are included ('% change P' column in Table 4) is applied to the estimates in Table 6.

Closing mode		% Change	Closing (include like)	
Year	Total	Include like	Total	CV
1978/79	41,701	0.0	41,701	0.232
1979/80	145,967	0.0	145,967	0.242
1980/81	212,916	0.0	212,916	0.266
1981/82	55,778	0.0	55,778	0.265
1982/83	84,725	0.0	84,725	0.235
1983/84	60,818	0.0	60,818	0.204
1985/86	225,102	8.1	243,284	0.189
1986/87	142,837	0.6	143,684	0.258
1987/88	157,286	-0.3	156,823	0.770
1988/89	19,311	3.7	20,034	0.394
1989/90	107,795	8.2	116,631	0.424
1990/91	16,721	15.9	19,386	0.376
1991/92	210,202	7.3	225,577	0.291
1992/93	23,322	-2.1	22,826	0.564
1993/94	30,993	13.4	35,161	0.359
1994/95	24,234	-27.2	17,650	0.359
1995/96	31,950	14.9	36,707	0.272
1996/97	25,616	16.6	29,858	0.509
1997/98	20,798	-21.1	16,412	0.295
First circumpolar set of surveys			601,905	0.121
Second circumpolar set of surveys			699,841	0.205
Third circumpolar set of surveys			384,191	0.185
IO mode		**% Change**	**IO (include like)**	
Year	Total	Include like	Total	CV
1985/86	307,451	5.8	325,389	0.178
1986/87	159,596	0.2	159,841	0.284
1987/88	244,408	15.3	281,684	0.352
1988/89	11,364	6.4	12,090	0.415
1989/90	78,736	5.8	83,301	0.216
1990/91	27,608	36.3	37,634	0.344
1991/92	174,496	14.0	199,009	0.218
1992/93	24,970	19.7	29,878	0.239
1993/94	37,459	15.9	43,418	0.257
1994/95	32,761	44.6	47,385	0.234
1995/96	36,988	15.2	42,613	0.301
1996/97	20,457	37.5	28,137	0.303
1997/98	11,802	14.9	13,556	0.406
Second circumpolar set of surveys			899,939	0.139
Third circumpolar set of surveys			403,995	0.123

Updating the value of the calibration factor R

Previous intent was that the estimate of the closing/IO mode calibration factor *R* would be updated annually as further data became available. This, however, has not been done, and a fully updated estimate of *R* is now long overdue. The updated estimate of $R = 0.826$ (CV = 0.089) is somewhat higher than the previous estimate: $R = 0.751$ (CV = 0.152) (Haw, 1991b; 1985/86 to 1988/89 surveys). The changing proportions of 'like minke' sightings over time (different for closing and IO mode, Table 4) suggest that changes in classification practice may have led to changes over time in the closing/IO mode density estimate ratio, hence rendering global averaging to estimate *R* a questionable procedure.

Combined passing and closing estimates

The final inverse-variance weighted abundance estimates (see Table 3) for the areas covered in the surveys (i.e. no extrapolation) are 608,000 (CV = 0.130) for the first circumpolar set, 766,000 (CV = 0.091) for the second, and 268,000 (CV = 0.093) for the incomplete third set. As estimates of total Southern Hemisphere minke whale abundance, these are negatively biased for reasons that include the following.

(i) The surveys cover (most of) the area between 60°S and the ice edge. However, as has been emphasised in the cruise reports (e.g. IWC, 2000), there are often large areas of open water (polynyas) within the pack ice that are inaccessible to the survey vessels. Naito (1982) reports observations of minke whales made in summer from an ice-breaker vessel operating inside the pack ice. Minke whales are found in highest densities in and around the pack ice, so that large numbers may be missed in surveys of some parts of the Antarctic where polynyas occur.

(ii) The analyses assume that no schools on the trackline are missed. In principle, the extent of this bias can be determined from the duplicate sightings data recorded under IO mode, but attempts to date to estimate this bias from these data are probably substantially positively biased because of unmodelled heterogeneity (Ashbridge *et al.*, 1998).

(iii) The numbers south of 60°S constitute only part of the total abundance of minke whales in the Southern Hemisphere, because a proportion of the whales (particularly the younger animals) do not migrate as far south as 60°S. The relative under-representation of younger animals has in the past been argued from the relatively high proportion of takeable minke whales (> 8.2m) reported in the IDCR sightings surveys, but has since been more reliably demonstrated by the lower selectivities estimated for animals below about seven years of age from analyses of age composition data provided by the JARPA programme (Butterworth *et al.*, 1999). Japanese sighting vessel (JSV) sighting rate information for lower latitudes at the same time of the year as the IDCR-SOWER surveys does indicate minke whales (a proportion of which would be dwarf minke whales) north of 60°S, but in relatively low densities, such as would add only some 10% to the abundance estimates for the area south of 60°S (Borchers *et al.*, 1990).

(iv) A number of sightings are recorded as 'like minke', 'whale' or even 'cetacean'. It is probable that some of these sightings (especially 'like minke') were actually minke whales, but these are not included in the baseline estimates quoted above. Furthermore, the proportion of these unassigned sightings has increased in the later surveys (Table 4, Fig. 6; Branch and Butterworth, 2001, table 1). If the 'like minke' sightings are included in the analyses, closing mode estimates increase on average by only 6% and 0.3% for the second and third circumpolar sets of surveys, but IO mode estimates increase by rather more substantial amounts of 12% and 23% respectively. Sightings recorded under more general codes than 'like minke' which were, in reality, minke whales seem unlikely to constitute a major source of potential further negative bias in abundance estimates because the number of such sightings (for which the species was not identified) is relatively low.

Comparability among circumpolar sets of cruises

Last year (IWC, 2001), initial rough extrapolations of the incomplete third circumpolar set of surveys led to a point estimate of abundance that was considered 'appreciably lower' than the total of the previously agreed (IWC, 1991) point estimates by Area. This paper has made proportional coverage adjustments and also accounted for the increase in the proportion of 'like minke' sightings in the later surveys in a manner that provides estimates that are more defensible (in the context of making temporal comparisons) than those presented last year. The resultant estimates for comparable areas for the three sets of circumpolar surveys (Table 7) are in the ratio 0.86 : 1.00 : 0.55 for closing mode and 1.00 : 0.45 for IO mode. The associated CVs indicate that the drop between the second and third sets of surveys is of borderline significance at the 5% level for the closing mode estimates, but definitely significant for the IO mode estimates.

These comparisons suggest a notable decrease in minke whale abundance between the mid-1980s and mid-1990s. It is important to try to determine whether this reflects a true decrease rather than a failure above to take all necessary factors into account in attempting to produce comparable abundance estimates. Three reasons that the latter might be the case are:

(1) decreased sighting efficiency, as younger less experienced observers were introduced onto the vessels during the later surveys[19], which could have led to a decrease in $g(0)$ over time[20];
(2) a changed minke whale distribution pattern, such that a considerably smaller proportion of the population has been present in the area surveyed during the third circumpolar set of surveys than the second;
(3) a change in the timing of the surveys, so that the surveys no longer span the peak of minke whale abundance in the Southern Ocean.

The increased sighting rates for some other species in the IDCR/SOWER surveys over the same period (Branch and Butterworth, 2001) do not provide immediate support for the possibility that decreased sighting efficiency could be playing a major role, but quantitative analysis of this effect would be of interest.

The second possibility does not seem supported by past analyses of the JSV data (as discussed above), which do not suggest a large component of the population north of 60°S during the months the surveys are conducted. Both a very large density of minke whales, and a substantial increase in the area within the pack ice that is accessible to these whales, would be needed to explain the extent of the decrease in the abundance estimates above. It might be that minke whale distribution patterns have changed since the time of the JSV surveys, with a smaller proportion now migrating to the Southern Ocean. This could be in response to possible changes in the abundance of their primary food source, krill, which Loeb *et al.* (1997) report to have shown a declining trend (based upon trawl surveys) in the Elephant Island region off the Antarctic Peninsula area (i.e. in the neighbourhood of the boundary between Areas I and II) over the 1976-1996 period. They suggest that this may be linked to a longer trend, since the 1940s, of warming and associated decreased sea-ice cover in this region. However, the two synoptic acoustic surveys of krill that have taken place over a rather larger part of this region in 1981 and 2000 reflect an increase in krill abundance (SC-CAMLR, 2000).

Since 1994/95, the surveys have started some 2-3 weeks later than in earlier years, so that a greater proportion of these later surveys has taken place in February. From data from Japanese surveys south of 50°S (including IDCR surveys) from 1976/77 to 1987/88, Kasamatsu *et al.* (1996) reported a decrease in minke whale sighting rates of about 50% from late January to late February. Analyses by Free (1983, plot 18) similarly show a decrease of about the same size in commercial minke whale catch rates from their peak in January to February. Thus some of the decrease in abundance estimates for the last four (though not the earlier three) surveys of the third circumpolar set analysed here may arise from their lesser coverage of the period of peak minke abundance off Antarctica.

To the extent that the decrease in abundance is real, it must reflect some combination of an increased mortality rate and a decreased birth rate (where birth rate is considered to be a product of pregnancy rate and natural survival over the first few years of life).

(i) Large recent fishing mortality hardly seems a plausible candidate for the first of these possibilities. The combined effect of the research catches of some 400 minke whales per year taken since the 1987/88 season is more than an order of magnitude too small to explain this reduction in abundance. An increase in natural mortality rate could be postulated, but there is no independent evidence for this.

(ii) There is some evidence pointing to a decrease in the birth rate. Analyses of minke whale catch-at-age data for Areas IV and V by Butterworth *et al.* (1999) indicate a recruitment trend for both Areas that first increases over the 1950s and 1960s, but then drops again from about 1970. This would lead to a lower overall abundance in due course.

Butterworth and Punt (1999, table 4a) fit a variant of the Baleen II population model which allows for time trends in minke whale carrying capacity to these recruitment estimates for Area IV. Their results suggest a total minke whale abundance for this Area which drops by about 40% from a maximum in the early 1970s to a minimum in the late 1980s, and is relatively steady during the 1990s. This decrease in abundance results from the combined effect of the commercial catches of the 1970s and early 1980s, supercompensation[21] and a recent decrease in carrying capacity[22].

[19] During the second circumpolar set of surveys, every topman had participated in at least 10 previous sighting survey cruises. However, from the 1992/93 cruises onwards, about 40% of the topmen had previous experience from less than six earlier surveys (K. Matsuoka, pers. comm.).

[20] Even without this consideration, comparability of abundance estimates over time could be compromised if the assumption of the standard methodology that $g(0)$ is constant over time and equal to one is invalid. Existing analyses do not rule out this possibility. There has, however, been a tendency to suspect that $g(0)$ is close to 1 for minke whales on these surveys, so that any change in $g(0)$ could not be that large. This has been based on the high intensity of searching effort in IO mode (which is the standard for abundance estimates), with two observers in the barrel, one in the IO platform, and at least one dedicated observer on the upper bridge. Given vessel searching speeds (11-12 knots), and typical minke whale blow rates (48 per hour, Ward, 1988) and radial distances at first sighting (~1.5 n.miles, e.g. Butterworth and Best, 1982, table 8), there are a fair number of opportunities (typically six) to sight a minke whale on the trackline. Attempts to estimate $g(0)$ from duplicate sightings data recorded in IO mode (Butterworth and Borchers, 1988; Butterworth, 1991; Ashbridge *et al.*, 1998) have seemed to support the contention that $g(0)$ (for all platforms combined) must be close to 1, but such inferences are not conclusive because the methods used likely give substantially positively biased estimates of $g(0)$ as a result of unmodelled heterogeneity. Furthermore, consideration of the estimated detection functions (Fig. 3) and estimates of effective search half-width (w_s, Table 1) does not suggest any obvious reason to suspect marked trends in $g(0)$ over time. Average w_s values for IO mode for the second and third circumpolar sets of cruises scarcely differ. For closing mode, such averages are similar for the first and second circumpolar sets of cruises, increasing by about 20% for the third. Closing mode detection functions are typically narrower than those for IO mode (average w_s about 20% less), but any relationship which that difference might have to a possible lower $g(0)$ value for closing mode is taken into account through the closing/IO mode calibration factor R.

[21] The phenomenon of a sufficiently high level of density-dependence coming into play as a population approaches (and possibly also overshoots) its carrying capacity level, that recruitment in absolute terms falls as the mature component of the population increases further.

Point estimates of abundance for Area IV in Table 3, which decrease notably although not significantly (at the 5% level) between the 1978/79 and 1988/89 cruises, are compatible with the results from this model. However, the results of this paper point to a decrease of minke abundance in a combination of the other Antarctic Areas that occurs a little later - roughly speaking between the mid-1980s and mid-1990s. Further modelling studies would be needed to ascertain to what extent this later response might be explained by the differing commercial catch histories in those Areas and slight temporal shifts in patterns of change in carrying capacity.

These changes in recruitment in absolute terms are likely associated with changes in *per capita* recruitment, which must in turn be linked to changes in the value of some vital parameter, for example a modified pregnancy rate or age at first parturition[23]. Detection of such changes in sampled animals at the times and in the directions predicted by population model fits to catch-at-age data would add weight to conclusions about overall trends in minke whale abundance based upon the IDCR-SOWER survey data alone.

Priority areas for future research

In terms of baseline methodology, the most important aspect highlighted by these analyses is that the regression method used from the 1995/96 cruise onwards for school size estimation makes larger differences to the abundance estimates from some earlier cruises than might have been anticipated. More attention to the most appropriate method for mean school size estimation is clearly warranted. Furthermore, consideration would be desirable as to whether the algorithm adopted here to determine the level of pooling used for effective search half-width and mean school size estimation could be improved.

The potential to quantify a number of factors that bias abundance estimates (generally downwards) also merits attention. The more important of these raise the following issues:

(1) how best to deal with 'like minke' sightings, particularly since the proportions recorded have changed over time;
(2) how best to evaluate a closing/IO mode calibration factor R for combining abundance estimates from these two survey modes, given possible confounding effects introduced by the 'like minke' classification changes over time, as indicated above; adjustments might also be made for the probable dependence of R on whale density, if the data prove sufficient to allow this to be estimated with adequate precision;
(3) the need to investigate the potential for using duplicate sighting information from IO mode to provide estimates for $g(0)$; and
(4) estimating the proportion of the population not covered by the survey because of animals within the pack-ice and north of 60°S.

Finally, methods are needed to improve upon the simple extrapolation approach that was used here to compare abundance estimates from surveys of the same region with different spatial coverages.

[22] The model requires an increase in minke whale carrying capacity over the middle decades of the 20th century to explain the initial increasing trend in recruitment. This is a plausible consequence of the decrease of populations of other large baleen whales during those middle decades as a result of over-exploitation. A subsequent reduction in this carrying capacity could arise from some combination of the effects of the partial recovery of the larger Antarctic baleen whales under protection, increases in other competing predators (such as crabeater seals), and changes in the physical environment (IWC, 1997a).

[23] There are indications that age at first parturition for minke whales in Area IV declined during the 1950-70 period when the population seems to have been expanding (e.g. Thomson *et al.*, 1999).

ACKNOWLEDGEMENTS

The DESS database is an outstanding source of sightings data on Antarctic cetaceans. Enormous effort and time have been put into collecting the basic data, for which thanks are due to the crew and scientists on board the annual IWC/IDCR and IWC/SOWER cruises. The Japanese and USSR governments and the International Whaling Commission provided funding for these cruises, with the governments of Australia, South Africa and the United States also making contributions for some of the cruises. Further substantial contributions have been made by staff of the IWC Secretariat and RUWPA at the University of St Andrews to the processes of entering and validating these basic data and developing DESS. The efforts of Samantha Strindberg, Marion Hughes, Dave Borchers and especially Louise Burt in fielding the authors' numerous (and sometimes psychotic) questions about DESS and the sightings data are gratefully acknowledged. Peter Best, Paul Ensor and Sharon Hedley provided a wealth of information about conditions on the cruises. Debra Palka, Peter Best and two anonymous reviewers are thanked for their comments on an earlier version of this paper, as is Andre Punt for providing detailed results for the modified Baleen II model fits for Area IV of Butterworth and Punt (1999). Rebecca Rademeyer analysed the influence of excluding possible vs. definite duplicates, extracted the smearing parameters shown in Fig. 5 and unearthed the start and end dates for the surveys. The contributions of many other scientists, too numerous to mention individually, who have contributed to the development of the methods used to analyse these data during extensive discussions in the Scientific Committee of the IWC over the last two decades, also deserve recognition. Funding support for these analyses was provided by the International Whaling Commission and the South African National Research Foundation.

REFERENCES

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. pp. 267-81. *In:* B.N. Petran and F. Csaàki (eds.) *International Symposium on Information Theory*. 2nd. Edn. Akadèemiai Kiadi, Budapest, Hungary. 451pp.

Ashbridge, J., Borchers, D.L. and Burt, M.L. 1998. Estimates of Antarctic minke density from the first six IWC/IDCR independent observer surveys. Paper SC/50/CAWS34 presented to the IWC Scientific Committee, April 1998 (unpublished). [Paper available from the Office of this Journal].

Best, P.B. 1985. External characters of southern minke whales and the existence of a diminutive form. *Sci. Rep. Whales Res. Inst., Tokyo* 36:1-33.

Best, P.B. and Butterworth, D.S. 1980. Report of the Southern Hemisphere minke whale assessment cruise, 1978/79. *Rep. int. Whal. Commn* 30:257-83.

Borchers, D.L. 1993. Preliminary analysis of the 1991/92 IWC minke whale sightings survey in Area V. Paper SC/45/SHBa20 presented to the IWC Scientific Committee, April 1993 (unpublished). 17pp. [Paper available from the Office of this Journal].

Borchers, D.L. 1994. Methods of estimating mean school size from IWC sightings survey data. *Rep. int. Whal. Commn* 44:429-37.

Borchers, D.L. and Burt, M.L. 1996. Analysis of the 1993/4 IWC minke whale sightings survey in Area I. Paper SC/48/SH6 presented to IWC Scientific Committee, June 1996, Aberdeen (unpublished). 13pp. [Paper available from the Office of this Journal].

Borchers, D.L. and Butterworth, D.S. 1990. Report of the sub-committee on stock estimation, Appendix 5. Comparison of Antarctic minke school densities in closing and passing (with IO) mode. *Rep. int. Whal. Commn* 40:142-3.

Borchers, D.L. and Cameron, C. 1995. Analysis of the 1992/93 IWC Minke Whale Sightings Survey in Area III. Paper SC/47/SH16 presented to the IWC Scientific Committee, May 1995 (unpublished). 16pp. [Paper available from the Office of this Journal].

Borchers, D.L., Butterworth, D.S. and Kasamatsu, F. 1990. Southern Hemisphere whale abundance estimates south of 30°S derived from IWC/IDCR survey and Japanese scouting vessel data. Paper SC/42/SHMi18 presented to the IWC Scientific Committee, June 1990 (unpublished). 42pp. [Paper available from the Office of this Journal].

Branch, T.A. and Butterworth, D.S. 2001. Estimates of abundance for frequently sighted cetacean species based on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys. *J. Cetacean Res. Manage*.

Branch, T.A. and Ensor, P. 2001. Report of the Scientific Committee. Annex G. Report of the sub-committee on the Comprehensive Assessment of whale stocks - In-depth Assessments. Appendix 8. Recommended species code changes for minke and blue whale sightings, for analysis of IDCR-SOWER surveys. *J. Cetacean Res. Manage. (Suppl.)* 3:200-3.

Brown, M.R. and Butterworth, D.S. 1999. Estimates of abundance for Southern Hemisphere humpback and blue whales from IWC/IDCR-SOWER survey cruises. Paper SC/51/CAWS35 presented to the IWC Scientific Committee, May 1999, Grenada, WI (unpublished). 15pp. [Paper available from the Office of this Journal].

Buckland, S.T. 1987a. An assessment of the performance of line transect models for fitting IWC/IDCR cruise data, 1978/79 to 1984/85. *Rep. int. Whal. Commn* 37:277-9.

Buckland, S.T. 1987b. Estimation of minke whale numbers from the 1984/85 IWC/IDCR Antarctic sightings data. *Rep. int. Whal. Commn* 37:263-8.

Buckland, S.T. and Anganuzzi, A.A. 1988. Comparison of smearing methods in the analysis of minke sightings data from IWC/IDCR Antarctic cruises. *Rep. int. Whal. Commn* 38:257-63.

Buckland, S.T., Anderson, D.R., Burnham, K.P. and Laake, J.L. 1993. *Distance Sampling: Estimating Abundance of Biological Populations*. Chapman and Hall, New York and London. xii+446pp.

Burt, M.L. and Borchers, D.L. 1996. Analysis of the 1994/5 minke whale sightings survey in Area III/IV. Paper SC/48/SH7 presented to IWC Scientific Committee, June 1996, Aberdeen (unpublished). 12pp. [Paper available from the Office of this Journal].

Burt, M.L. and Borchers, D.L. 1997. Minke whale abundance estimation from the 1995-96 IWC survey in Area VI. Paper SC/49/SH8 presented to the IWC Scientific Committee, September 1997, Bournemouth (unpublished). 14pp. [Paper available from the Office of this Journal].

Burt, M.L. and Borchers, D.L. 1999. Minke whale abundance estimation from the 1996/97 IWC-SOWER survey in Area II. Paper SC/51/CAWS17 presented to the IWC Scientific Committee, May 1999, Grenada, WI (unpublished). 13pp. [Paper available from the Office of this Journal].

Burt, M.L. and Stahl, D. 2000. Minke whale abundance estimation from the 1997-98 IWC-SOWER Antarctic Cruise in Area II. Paper SC/52/IA13 presented to the IWC Scientific Committee, June 2000, in Adelaide, Australia. [Paper available from the Office of this Journal].

Butterworth, D.S. 1986. Further results from the 1984/85 IWC/IDCR Antarctic minke whale assessment cruise. Paper SC/38/Mi11 presented to the IWC Scientific Committee, May 1986 (unpublished). 20pp. [Paper available from the Office of this Journal].

Butterworth, D.S. 1988. Report of the sub-committee on Southern Hemisphere minke whales, Appendix 4. An alternative method of incorporating school size information into Antarctic minke sighting abundance estimates. *Rep. int. Whal. Commn* 38:84.

Butterworth, D.S. 1991. Report of the sub-committee on Southern Hemisphere minke whales, Appendix 4. The use of $g(0) = 1$ for Southern Hemisphere minke whale sighting surveys. *Rep. int. Whal. Commn* 41:126.

Butterworth, D.S. and Best, P.B. 1982. Report of the Southern Hemisphere minke whale assessment cruise, 1980/81. *Rep. int. Whal. Commn* 32:835-74.

Butterworth, D.S. and Borchers, D.L. 1988. Estimates of g(0) for minke schools from the results of the independent observer experiment on the 1985/86 and 1986/87 IWC/IDCR Antarctic assessment cruises. *Rep. int. Whal. Commn* 38:301-13.

Butterworth, D.S. and McQuaid, L.H. 1985. Preliminary analysis of certain sighting experiments carried out in the 1984/85 IWC/IDCR Antarctic minke whale assessment cruise. Paper SC/J85/S6 presented to the IWC Workshop on Minke Whale Sightings, June 1985 (unpublished). 51pp. [Paper available from the Office of this Journal].

Butterworth, D.S. and Punt, A.E. 1999. An initial examination of possible inferences concerning MSYR for Southern Hemisphere minke whales from recruitment trends estimated in catch-at-age analyses. *J. Cetacean Res. Manage.* 1(1):33-9.

Butterworth, D.S. and Silberbauer, M.J. 1987. A sighting estimate of the Antarctic Area V minke whale population based upon the 1985/86 IWC/IDCR assessment cruise. Paper presented to the IWC Scientific Committee, June 1987 (unpublished). 16pp. [Paper available from the Office of this Journal].

Butterworth, D.S., Best, P.B. and Basson, M. 1982. Results of analysis of sighting experiments carried out during the 1980/81 Southern Hemisphere minke whale assessment cruise. *Rep. int. Whal. Commn* 32:819-34.

Butterworth, D.S., Best, P.B. and Hembree, D. 1984a. Analysis of experiments carried out during the 1981/82 IWC/IDCR Antarctic minke whale assessment cruise in Area II. *Rep. int. Whal. Commn* 34:365-92.

Butterworth, D.S., Rickett, L.H. and Best, P.B. 1984b. Preliminary analysis of results from the 1983/84 IWC/IDCR minke whale assessment cruise in Antarctic Area VI. Paper SC/36/Mi13 presented to the IWC Scientific Committee, May 1984 (unpublished). 26pp. [Paper available from the Office of this Journal].

Butterworth, D.S., Buckland, S.T., Kishino, H. and Silberbauer, M.J. 1987. Revised sightings estimates of Antarctic minke whale abundance for the 1978/79 to 1984/85 IWC/IDCR assessment cruises. Paper SC/39/Mi18 presented to the IWC Scientific Committee, June 1987 (unpublished). 37pp.

Butterworth, D.S., Borchers, D.L., Chalis, S., De Decker, J.B. and Kasamatsu, F. 1994. Estimates of abundance for Southern Hemisphere blue, fin, sei, humpback, sperm, killer and pilot whales from the 1978/79 to 1990/91 IWC/IDCR sighting survey cruises, with extrapolations to the area south of 30°S for the first five species based on Japanese scouting vessel data. Paper SC/46/SH24 presented to the IWC Scientific Committee, May 1994 (unpublished). 129pp. [Paper available from the Office of this Journal].

Butterworth, D.S., Punt, A.E., Geromont, H.F., Kato, H. and Fujise, Y. 1999. Inferences on the dynamics of Southern Hemisphere minke whales from ADAPT analyses of catch-at-age information. *J. Cetacean Res. Manage.* 1(1):11-32.

Cooke, J.G. 1987. Estimation of the population of minke whales in Antarctic Area IV W in 1984/85. *Rep. int. Whal. Commn* 37:273-6.

Donovan, G.P. 1991. A review of IWC stock boundaries. *Rep. int. Whal. Commn* (special issue) 13:39-68.

Ensor, P., Shimada, H., Brown, M., Cawthorn, M., Findlay, K., Gomi, K., Hara, T. and Kawasaki, M. 1995. 1994-95 IWC/IDCR Southern Hemisphere Minke Whale Assessment Cruise. Paper SC/47/SH2 presented to the IWC Scientific Committee, May 1995 (unpublished). 45pp. [Paper available from the Office of this Journal].

Ensor, P., Pastene, L.A., Cawthorn, M., Findlay, K., Hedley, S., Iwakami, H., Kleivane, L., Pitman, R., Tsurui, T. and Sakai, K. 1998. 1997-98 IWC Southern Ocean Whale and Ecosystem Research (IWC-SOWER) Antarctic Cruise, Area II. :45. Paper SC/50/Rep1 presented to the IWC Scientific Committee, April 1998 (unpublished). [Paper available from the Office of this Journal].

Free, C.A. 1983. Report of the sub-committee on minke whales, Appendix 5. Southern Hemisphere minke whales multiplicative regression analysis of Japanese CSW data. *Rep. int. Whal. Commn* 33:111-3. [Paper available from the Office of this Journal].

Haw, M.D. 1991a. Estimation of minke whale abundance from the 1989/90 IWC/IDCR Antarctic assessment cruise in Area I. Paper SC/43/Mi1 presented to the IWC Scientific Committee, May 1991 (unpublished). 18pp. [Paper available from the Office of this Journal].

Haw, M.D. 1991b. An investigation into the differences in minke whale school density estimates from passing mode and closing mode survey in IDCR Antarctic assessment cruises. *Rep. int. Whal. Commn* 41:313-30.

Haw, M.D. 1993a. Estimation of minke whale abundance from the 1990/91 IWC/IDCR Antarctic assessment cruise in Area VI. Paper SC/45/SHBa1 presented to the Scientific Committee, April 1993 (unpublished). 33pp. [Paper available from the Office of this Journal].

Haw, M.D. 1993b. Report of the sub-committee on Southern Hemisphere baleen whales, Appendix 6. Corrections to estimates of abundance of Southern Hemisphere minke whales obtained from IWC/IDCR data. *Rep. int. Whal. Commn* 43:114.

International Whaling Commission. 1983. Report of the sub-committee on minke whales. *Rep. int. Whal. Commn* 33:91-122.

International Whaling Commission. 1984. Report of the sub-committee on Southern Hemisphere minke whales. *Rep. int. Whal. Commn* 34:77-101.

International Whaling Commission. 1987. Report of the sub-committee on Southern Hemisphere minke whales. *Rep. int. Whal. Commn* 37:68-88.

International Whaling Commission. 1988. Report of the sub-committee on Southern Hemisphere minke whales. *Rep. int. Whal. Commn* 38:76-87.

International Whaling Commission. 1989. Report of the sub-committee on Southern Hemisphere minke whales. *Rep. int. Whal. Commn* 39:71-93.

International Whaling Commission. 1991. Report of the sub-committee on Southern Hemisphere minke whales. *Rep. int. Whal. Commn* 41:113-31.

International Whaling Commission. 1993. Report of the Scientific Committee, Annex E. Report of the sub-committee on Southern Hemisphere baleen whales. *Rep. int. Whal. Commn* 43:104-14.

International Whaling Commission. 1994a. Report of the Scientific Committee, Annex E. Report of the sub-committee on Southern Hemisphere baleen whales. *Rep. int. Whal. Commn* 44:93-107.

International Whaling Commission. 1994b. Report of the Scientific Committee, Annex H. The Revised Management Procedure (RMP) for Baleen Whales. *Rep. int. Whal. Commn* 44:145-52.

International Whaling Commission. 1994c. Report of the Scientific Committee, Annex Q. Report of the *ad hoc* Working Group on the 1993/94 IWC/IDCR Southern Hemisphere minke whale assessment cruise. *Rep. int. Whal. Commn* 44:195-9.

International Whaling Commission. 1997a. Report of the IWC Workshop on Climate Change and Cetaceans. *Rep. int. Whal. Commn* 47:293-319.

International Whaling Commission. 1997b. Report of the Scientific Committee. Annex E. Report of the sub-committee on Southern Hemisphere baleen whales. *Rep. int. Whal. Commn* 47:128-52.

International Whaling Commission. 1998. Report of the Scientific Committee. Annex E. Report of the Sub-Committee on Abundance Estimation. *Rep. int. Whal. Commn* 48:144-59.

International Whaling Commission. 2000. Report of the SOWER 2000 Workshop. *J. Cetacean Res. Manage. (Suppl.)* 2:319-46.

International Whaling Commission. 2001. Report of the Scientific Committee. Annex G. Report of the Sub-Committee on the Comprehensive Assessment of Whale Stocks - In-depth Assessments. *J. Cetacean Res. Manage. (Suppl.)* 3:177-208.

Joyce, G.G., Kasamatsu, F., Rowlett, R. and Tsunoda, L. 1988. The IWC/IDCR Southern Hemisphere minke whale assessment cruises: the first ten years. Paper SC/40/O 16 presented to the IWC Scientific Committee, May 1988 (unpublished). 98pp. [Paper available from the Office of this Journal].

Kasamatsu, F., Joyce, G.G., Ensor, P. and Mermoz, J. 1996. Current occurrence of baleen whales in Antarctic waters. *Rep. int. Whal. Commn* 46:293-304.

Kato, H. and Fujise, Y. 2000. Dwarf minke whales: morphology, growth and life history with some analyses on morphometric variation among the different forms and regions. Paper SC/52/OS3 presented to the IWC Scientifc Committee, June 2000, in Adelaide, Australia.

Koopman, B.O. 1956. The theory of search I. Kinematic Bases. *Ops. Res.* 4:324-46.

Loeb, V., Siegal, V., Holm-Hansen, O., Hewitt, R., Fraser, W., Trivelpiece, W. and Trivelpiece, S. 1997. Effects of sea ice extent and krill or salpa dominance on the Antarctic food web. *Nature, Lond.* 387:897-900.

Naito, Y. 1982. Sightings records of minke whales in the pack ice and adjacent waters off the coast of Enderby Land. *Rep. int. Whal. Commn* 32:929-33.

Punt, A.E., Cooke, J.G., Borchers, D.L. and Strindberg, S. 1997. Estimating the extent of additional variance for Southern Hemisphere minke whales from the results of the IWC/IDCR cruises. *Rep. int. Whal. Commn* 47:431-4.

SC-CAMLR. 2000. Report of the Nineteenth Meeting of the Scientific Committee (SC-CAMLR-XIX). CCAMLR, Hobart, Australia.

Strindberg, S. and Burt, M.L. 2000. *IWC Database-Estimation System Software (DESS) User Manual, May 2000*. Research Unit for Wildlife Population Assessment, Mathematical Institute, University of St Andrews, St Andrews. 300pp. [Paper available from the Office of this Journal].

Thomson, R.B., Butterworth, D.S. and Kato, H. 1999. Has the age at transition of Southern Hemisphere minke whales declined over recent decades? *Mar. Mammal Sci.* 15(3):661-82.

Ward, A.J. 1988. Accounting for the effect of pod size in the estimation of blow rates: analysis of data from the 1984/85, 85/86 and 86/87 IDCR minke whale assessment cruises. *Rep. int. Whal. Commn* 38:265-8.

Appendix 1

SUMMARY OF HISTORICAL CHANGES TO THE ‘STANDARD METHODOLOGY’

Effective search half-widths for schools (w_s)

1979: Negative exponential model, but over time adjustments for truncation and smearing were introduced.

1986: Radial distances used to calculate perpendicular distance from the trackline based upon observer estimates of these distances at first sighting, in place of a vessel speed multiplied by closure time basis (Butterworth, 1986).

1987: Hazard rate model with truncation at a perpendicular distance of 1.5 n.miles and smearing as per method II of Buckland and Anganuzzi (1988) (adopted: IWC, 1988, p.77).

Mean school size estimation ($\bar{s}$)

1979: Weighted linear regression of $\bar{s}$ against perpendicular distance y out to $y = 1.0$ n.miles (Best and Butterworth, 1980), to obtain an estimate of the intercept at $y = 0$; if the regression slope was negative, the actual average school size out to $y = 1.0$ n.miles was used.

1987: Estimated by the ratio of whale density estimates to school density estimates, where the former were computed by fitting the $f(y)$ model to school sightings, with each sighting replicated by the estimated number of whales in the school (Butterworth, 1988) (adopted: IWC, 1988, p.77).

1997: Regression of $\bar{s}$ against estimated f(y), provided statistically significant at the 15% level, otherwise actual average school size out to y = 1.5 n.miles (Burt and Borchers, 1997) (re *de facto* adoption see IWC, 1994a, p.105; IWC, 1997b, p.130; IWC, 1998, p.144 and evaluation by Borchers, 1994).

Stratification considerations

1979: Contouring of daily density estimates to obtain abundance estimates (e.g. Best and Butterworth, 1980).

1983: Stratum densities estimated from effort-weighted averages of sighting rates from transects treated as independent (1984, pp.80, 92-3).

1983/84: Cruise track design modified to facilitate stratum-based abundance estimation (see Fig. 1).

1987: Definitions of strata finalised (IWC, 1988, pp.77-8).

1992: Stratification and related options for abundance estimation for RMP adopted (IWC, 1993, p.106).

1992/93: Cruise track design modified to link with RMP *Small Area* specifications (see footnote 7).