Inferences on the dynamics of Southern Hemisphere minke whales from ADAPT analyses of catch-at-age information[1]

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ABSTRACT

The dispute over the last two decades in the IWC Scientific Committee as to whether inferences of utility for management purposes can be drawn from catch-at-age information for Southern Hemisphere minke whales is reviewed, particularly in the context of whether or not such data are able to reveal if this population was increasing prior to the start of major commercial harvests in the early 1970s. Butterworth *et al.* (1996) developed an ADAPT VPA estimation procedure to address this last question. This paper extends that procedure to take account of assumed separability of the fishing mortality matrix for the periods of the commercial and of the Japanese scientific take (although only for ages above 15 for the former). A base-case estimator is motivated from the many possible variants of the procedure, and applied to catch-at-age and survey abundance estimates for Areas IV and V, both separately and in combination. The survey estimates used include results from both international and Japanese research programmes. Bootstrap methods are used to estimate precision, and a number of sensitivity tests for the Area IV assessment are performed. Estimates are provided of the extent to which this precision is expected to improve given the further data to be collected before the end of the Japanese scientific programme (JARPA) as currently conceived; this is achieved by using the current Area IV assessment as a basis to develop an operating model of the population for evaluation (by simulation) of the information content of future data. The Area IV base-case assessment shows satisfactory behaviour under retrospective analysis, and is consistent with the separability assumptions made. It provides an estimate of 5.5%yr^{-1} (90% confidence interval [1.4%; 9.1%]) for the historic (increasing) trend in minke whale recruitment over the period 1947-1968 prior to the exploitation of this resource. The positivity of this estimate and the associated interval is robust to a number of sensitivity tests. The point estimate of this trend for Area V is larger, but less precisely estimated. Important implications (both qualitative and quantitative) for management of the resource that follow from these results are discussed. The point estimate of age-independent natural mortality M for Area IV is 0.057yr^{-1}. The root mean square error of this estimate by the end of the JARPA programme is estimated to be about 0.022yr^{-1} (much of this reflecting negative bias related to assumptions concerning the slope of the commercial selectivity-at-age vector for large ages). The point estimates of M for Area V, and for the two Areas combined, are lower. A notable result of the Area IV assessment is a marked drop in recruitment from 1970 to the mid-1980s, for which some possible reasons are advanced. Patterns of inter-annual change in recruitment (as distinct from overall trends) are well estimated from the data, indicating that the availability of catch-at-age data leads to the provision of a much finer probe to detect possible links between minke whale dynamics and environmental factors than would survey estimates of total abundance alone.

KEYWORDS: MINKE WHALE; TRENDS; MODELLING; RECRUITMENT RATE; INDEX OF ABUNDANCE; SOUTHERN HEMISPHERE; SCIENTIFIC PERMITS; DIRECT CAPTURE; SURVEY-VESSEL

INTRODUCTION

The question of whether inferences of utility for management purposes can be drawn from catch-at-age information for Southern Hemisphere minke whales has been in dispute in the Scientific Committee of the International Whaling Commission for the last two decades. Some 20 years ago, predispositions towards an M (natural mortality rate) value of about 0.lyr^{-1}, based on an interspecific relationship between M and maximum male length for cetaceans put forward by Ohsumi (1979a), led to the inference from these data (specifically from the slope of the descending limb of the catch curve -a plot of the log of catch numbers against age - which exceeded the value then used for M by about 0.04yr^{-1}) that this minke whale population had been increasing prior to exploitation (e.g. Ohsumi, 1979b). This, together with other evidence which at that time was considered to point in the same direction (e.g. minke whale earplug transition phase analyses which suggested a decline in the age at maturity prior to exploitation; Masaki, 1979[6]), contributed to the theory that Southern Hemisphere minke whales had increased prior to the start of (substantial) minke whale exploitation off Antarctica in the early 1970s. This inferred increase in numbers (and drop in the age at sexual maturity) was seen as a plausible response to the additional food made available to krill feeders through the earlier large reduction in numbers of other Antarctic whale species -the blue whale in particularby excessive harvests. Indeed, at the end of the 1970s, the IWC Scientific Committee had stated this as an established fact (IWC, 1980, pp.50, 99).

In the early 1980s, inferences from these catch-at-age data were used as a basis to estimate productivity levels and hence recommend sustainable catches for Southern Hemisphere minke whales (e.g. IWC, 1983, p.93). However, in a watershed debate at the Scientific Committee's 1984 meeting (IWC, 1985, pp.41, 77-8), it was agreed that the productivity estimates forthcoming from the two methods in use at that time to analyse the catch-at-age information

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[6]The reality of this decline was subsequently called into question (e.g. Cooke. 1985a) although more recent analyses using a longer time-series of data have strengthened the case that a real decline did occur (e.g. Butterworth *et al.*. 1997).

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should be rejected. These conclusions were reached primarily on the basis of contributions by de la Mare (1985a; b), which showed that the methods could produce unreliable results if minke whale natural mortality was age-dependent, and also argued that the high slope of the minke whale catch curve for large ages was plausibly attributed to an increasing natural mortality with age.

During that same period, Sakuramoto and Tanaka (1985; 1986) developed a multi-cohort model for the analysis of these catch-at-age data, the results from which suggested pre-exploitation annual rates of increase in recruitment of 3-4%. However, Cooke (1985b) countered that the values estimated were entirely dependent on certain assumptions made for the computations, such as the value used for natural mortality *M*. Further reservations raised about the approach (including the confounding of interpretation of the data by possible trends in selectivity-at-age) are recorded in IWC (1986, pp. 41, 68) and IWC (1987, pp.40, 69, 80-1).

In 1987, following the imposition of a moratorium on commercial whaling by the IWC, Japan proposed a feasibility study (see IWC, 1989b) for what came to be called the 'Japanese Whale Research Programme under Special Permit in the Antarctic' or JARPA. The Convention governing the IWC makes allowance for national Governments to issue such permits for catches of whales for scientific research purposes (e.g. see Donovan, 1992). JARPA incorporated both catches and sighting surveys of minke whales, which were to take place each austral summer season in the Antarctic, alternately in Areas IV and V (700E-130oE and 130°E-170°W, respectively, see Donovan, 1991). After two seasons of feasibility studies, JARPA proper commenced in Area IV in the 1989/90 season.

The primary purpose of JARPA was stated to be the estimation of the age-specific natural mortality of minke whales. This was to be achieved by obtaining representative samples of the age structure of the population through random sampling, combined with systematic sighting surveys. The programme was motivated on the argument that the main reason the Scientific Committee had failed to reach agreement in immediately preceding years on catch limit recommendations for Southern Hemisphere minke whales, had been its inability to agree upon the value of natural mortality and its age-specific patterns (IWC, 1988, p.139).

The validity of this argument was contested at the 1987 meeting of the Scientific Committee, as was the ability of the methodology proposed to estimate natural mortality (see IWC, 1988, pp.55-7, 139-49). Key contributions to these opposing views were provided by de la Mare (1989), who showed that simultaneous estimation of a time series of recruitment rates and age-dependent mortality rates was not possible from catch-at-age data alone. Further, de la Mare (1990) argued that even if, in addition, annual abundance estimates with a CV of 0.15 could be achieved, JARPA would not provide estimates of natural mortality sufficiently precise to determine historical recruitment trends or refine sustainable yield prediction, even if continued for 30 years. It may seem surprising to readers familiar with the behaviour of Virtual Population Analyses (VPAs) of catch-at-age data for fish stocks that historic (in contrast to recent) trends in recruitment are not automatically well determined because of the backwards convergence property of VPA. The reason is that such backwards convergence requires that the cumulative fishing mortality over the whole life-span of a cohort is reasonably high, but Southern Hemisphere minke whales have been too lightly exploited for this to be the case.

This dispute as to the utility of catch-at-age information, and particularly the further such information which has become available through JARPA's lethal sampling (without which information on ages cannot be obtained), for drawing inferences about the population dynamics of Southern Hemisphere minke whales, has continued unresolved to the present (see IWC, 1989a, pp.37-8; IWC, 1990, pp.64-6; IWC, 1991, pp.72-4; IWC, 1992a, p.73; IWC, 1992b, pp.263-4; IWC, 1995a, pp.81-2; and further papers referenced therein).

Butterworth and Punt (1990) entered this debate with the demonstration that, at least deterministically, the provision of further catch-at-age data through JARPA could resolve whether or not there had been an historic increasing trend in minke whale recruitment, given temporal invariance of selectivity-at-age (above a certain age) and natural mortality-at-age. Essentially this follows because an increasing recruitment trend cannot continue indefinitely, so that the large slope of the descending limb of the catch curve will decrease in time if there was an historic increase, but will remain unchanged if it reflects only age-specific natural mortality and selectivity effects. Butterworth and Punt (1990) used simulated age-structure data from a generalised operating model to assess the likely precision with which a crude VPA-like approach might be able to estimate such a possible historic increase rate. They concluded that it would be unable to discriminate an annual increase rate of 4% from zero even after 25 years of data. However, improvements to their estimator developed in Bergh *et al.* (1991a; b) gave more promising results, and they suggested moving to estimator tests based on the actual catch-at-age data available (from both JARPA and earlier commercial whaling).

In taking up this last suggestion, Butterworth *et al.* (1996) also introduced an ADAPT (Gavaris, 1988) approach for the joint analysis of catch-at-age and abundance survey data for these minke whales. A key feature of their implementation was to group the catch-at-age data into cells including a number of years and of ages - combinations of three years and three ages were chosen -to handle the problem of small sample sizes and (essentially by transformation of the time variable) to reduce the catch-at-age matrix to a size (in terms of these new 'age' groups) typical of that considered in most age-data-based fishery assessments.

Shortcomings of the Butterworth *et al.* (1996) approach were that it involved external specification of selectivity-at-age values for the most recent year analysed, and also that it assumed an absence of sampling variability in the catch-at-age data for that same year. This led to poor performance of the estimator, as demonstrated by the results of retrospective analysis[7] in Butterworth and Punt (1996), who therefore extended the original approach to estimate the selectivity-at-age vector for the scientific permit catches directly from the data, and to account for sampling variability, by assuming separability of the fishing mortality matrix for the period of the scientific catches. This led to greatly improved results on retrospective analysis.

This paper takes that extension yet further, by admitting separability for the fishing mortality matrix for the commercial catch above a certain age as well. It also takes

[7] Retrospective analysis involves repeating assessments using only the data available up to some earlier year. and checking whether or not estimated trends in, say. recruitment remain similar to those of the current assessment (thus reflecting acceptable performance) rather than evidencing systematic deviations.

Table 1

The catches-at-age matrices for minke whales used for the analyses of this paper. Both commercial and scientific permit catches are included, with the matrices developed in terms of the procedures detailed in the Appendix. Each matrix is expressed in terms of combination years and combination ages (three-year groupings, where the notation is such that the three seasons 1969/70 to 1971/72 are referenced as 1971, and ages 1 to 3 as 2, etc.)

	Age																		
Year	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	53	Total
Area IV																			
1971	121	256	314	310	352	319	284	235	146	95	99	45	30	25	3	7	17	4	2,663
1974	820	1,508	1,773	1,716	1,423	1,261	895	723	470	345	170	110	92	18	15	13	7	0	11,358
1977	80	329	437	633	618	529	283	234	125	79	48	11	25	6	0	2	6	0	3,444
1980	213	493	626	730	776	751	596	469	294	228	138	117	64	47	36	23	18	0	5,617
1983	235	499	606	808	709	886	664	506	346	216	84	47	34	32	7	7	3	0	5,689
1986	68	181	330	478	598	676	598	539	358	234	116	92	51	20	15	6	0	0	4,359
1989	110	91	62	54	48	62	56	30	37	21	9	10	7	5	1	0	0	0	603
1992	48	35	38	28	18	19	20	15	19	14	12	8	4	2	2	2	1	1	288
1995	95	82	83	93	52	37	36	29	43	22	24	25	11	6	3	9	5	5	660
Area V																			
1974	21	62	129	133	131	89	74	48	30	3	10	4	0	0	0	0	0	0	734
1977	38	279	374	488	502	439	320	188	146	98	40	34	9	13	12	0	0	2	2,982
1980	58	179	323	344	395	464	264	246	259	198	84	81	37	23	26	25	0	0	3,006
1983	117	382	479	584	700	678	527	376	285	150	103	60	34	23	11	6	2	1	4,518
1986	61	151	202	307	357	497	426	314	275	164	75	64	15	14	3	4	2	3	2,936
1989	23	33	24	33	38	25	21	16	4	11	5	4	4	0	0	0	0	0	241
1992	33	55	65	70	58	56	57	59	52	35	26	21	16	8	5	2	0	1	619
1995	31	25	44	45	37	29	30	19	22	15	10	14	7	3	0	0	0	0	330

JARPA in addition to IWC/IDCR and SOWER[8] estimates of abundance into account in applying this extended approach to data for Area IV and Area V.

The paper first develops the data to be analysed, and then provides technical details of the estimation process advanced and of associated options which have been encoded. The choice of options for a 'base-case' estimator is motivated, and this is then applied to provide assessments for Areas IV and V both separately and in combination, together with associated bootstrap estimates of precision. A number of sensitivity tests are applied to the Area IV assessment, which is also used as the basis for simulation evaluation of the likely level of precision possible for some key population parameters (e.g. natural mortality, *M*) by the end of the JARPA programme as currently conceived (the 2003/04 season for Area IV).

Note that most of the analyses of this paper are based on the three-year-three-age grouping referenced above. The associated notation convention used refers, for example, to the three seasons 1969/70 to 1971/72 as '1971', and to ages 1 to 3 as age '2'. The words 'year/age' are used in the paper for both 'true' years/ages and 'combination' years/ages, with clarification provided in the text as to which is intended in cases where this is not obvious from the context.

DATA

The catch-at-age matrices used for the analyses of this paper are developed in the same way as for Butterworth *et al.* (1996). Details are given in the Appendix. Table 1 provides the results for both sexes combined for Areas IV and V separately, where these results are in terms of the combinations of three years and of three ages used as the base-case grouping in this paper.

Failure to use an age-length key in scaling the scientific catch age distribution upwards from numbers aged to numbers caught could introduce bias if ear-plug readability depends on animal age, because such scaling implicitly assumes that the animals aged constitute an unbiased sample from the age distribution of the whole catch (a problem which the use of an age-length key could circumvent). Table 2 gives results for readability as a function of length for the scientific catch from Area IV. There is some suggestion that there may be such an effect, with plugs for the smallest/youngest animals somewhat less likely to be readable (an average readability of 79% for animals < 8m, compared to 89% for larger animals) - a matter whose possible consequences for the analyses of this paper are addressed later.

Table 2

Readability (%) of minke ear plugs for total age as a function of animal length for JARPA samples from Area IV from 1987/88-1995/96 for males and females combined.

Body length (m)	Total sample	Readability
4.5 - 4.9	7	100
5.0 - 5.4	50	86
5.5 - 5.9	95	83
6.0 - 6.4	48	67
6.5 - 6.9	79	67
7.0 - 7.4	75	83
7.5 - 7.9	126	83
8.0 - 8.4	407	91
8.5 - 8.9	430	88
9.0 - 9.4	188	88
9.5 - 9.9	39	85
10.0 - 10.4	2	100

There are two sources of information for abundance estimates: the IWC surveys, and the survey component of JARPA. The estimates from these surveys used in this analysis, with associated CVs, are listed in Table 3. Because

[8] The International Decade of Cetacean Research (IDCR) commenced in the mid-1970s. The major component of this IWC initiative came to be a set of annual surveys carried out off Antarctica, whose primary aim was the estimation of abundance of the Southern Hemisphere minke whale population. Every year since the 1978/79 austral summer season, from 2-4 vessels have undertaken sighting surveys in a region off Antarctica which has covered from 40-70 degrees of longitude, and generally most of the open ocean area from ice-edge to latitude 60°S, with abundance estimates evaluated from the observations made using line transect methodology. Since 1996/97, these surveys have fallen under the IWC's Southern Ocean Whale and Ecosystem Research Programme (SOWER). For the purpose of this paper, the IDCR and SOWER surveys are collectively termed 'IWC surveys'.

the analysis relies on comparability of such estimates over time, the IWC estimates used are those for 'equivalent northern boundaries' as developed for the 'additional variance' estimation of Punt *et al.* (1997). Although there have been IWC surveys in Areas IV and V subsequent to 1988/89, these have not covered the full extent of an Area in a single season. Pending agreement on how most appropriately to combine such estimates to reflect results pertinent to a complete single Area, they have not been taken into account in the analyses of this paper.

Table 3

Abundance estimates, with CV's in parenthesis, used in analyses in this paper. The sources of the various estimates and other pertinent details are given in the text.

Survey		Combination year to which applied	Estimate (CV)
Area IV			
IWC	1978/79	1980	68,381 (0.155)
IWC	1988/89	1989	58,215 (0.326)
JARPA	1989/90	1989	24,868 (0.168)
JARPA	1991/92	1992	25,951 (0.293)
JARPA	1993/94	1995	26,359 (0.161)
JARPA	1995/96	1995	21,213 (0.180)
Area V			
IWC	1980/81	1980	135,422 (0.216)
IWC	1985/86	1986	160,741 (0.187)
JARPA	1990/91	1992	77,560 (0.201)
JARPA	1992/93	1992	54,970 (0.189)
JARPA	1994/95	1995	84,230 (0.507)
Areas IV + V			
IWC	1978/79 + 1980/81	1980	203,803 (0.153)
IWC	1988/89 + 1985/86	1989	218,956 (0.162)
JARPA	1991/92 + {1990/91, 1992/93}	1992	87,868 (0.131)
JARPA	{1993/94, 1995/96} + 1994/95	1995	107,746 (0.397)

The JARPA estimates of abundance based on SSV[9] data given in table 6 of Nishiwaki *et al.* (1997) have been used for this analysis. These were preferred to those based on the SV data because they provide a longer time series and are generally more precise. Nishiwaki *et al.* (1997) list a number of reasons why the JARPA estimates are not expected to be comparable to those from the IWC surveys (e.g. the former involve a form of closing mode survey, whereas the latter are standardised to passing (IO) mode). In particular, the JARPA protocol whereby survey starts from a pre-fixed position each day, whether or not survey of all the trackline to that point had been completed on the previous day, leads to undersampling of higher densities areas and hence a negative bias in JARPA abundance estimates compared to those from the IWC surveys (see Burt and Borchers, 1997 and IWC, 1998). Accordingly, this analysis treats the JARPA estimates as relative abundance indices, with the relative bias between the IWC and JARPA estimates being estimated in the model fitting process.

For the case where Areas IV and V are analysed together, combined abundance estimates have been developed by adding those for seasons relatively close in time (see Table 3). For the JARPA estimates in this case, combinations have been developed consistent with the combination-years chosen. In a three-year period, there are two JARPA estimates for one Area, and one for the other; the procedure used is to take an inverse-variance-weighted average of the first two, and then to add that result to the third. This procedure does mean, however, that the 1989/90 JARPA survey result for Area IV is not taken into account in this combined analysis.

[9] The JARPA Programme has incorporated both sighting-and-sampling (i.e. whale catching) survey vessels (SSVs), and (at a later stage) vessels dedicated to sighting surveys only (SVs).

ESTIMATION METHODS

The ADAPT estimator considered in this paper involves specifications for the population dynamics, the parameterisation of fishing and natural mortality, and the likelihood. Each of these components is considered in turn. Note that 'year' and 'age' as used below refer to 'combination year' and 'combination age' unless otherwise specified. To assist in giving illustrations to the reader, the specifications have been written for combinations at the three-year and three-ages level for Area IV, but could easily be generalised for other choices for these periods or for other Areas.

Basic population dynamics

The basic population dynamics are taken to be governed by the following equations:

$$N_{y+3,a+3} = (N_{y,a} - C_{y,a})\exp(-M_a) \qquad 2 \le a \le m-3 \qquad (1)$$

$$F_{y,a} = C_{y,a} / N_{y,a} \qquad (2)$$

where: $N_{y,a}$ is the number of minke whales (normally both sexes combined) of age a present at the start of year y;

$C_{y,a}$ is the number of such whales taken during year y;

M_a is the (possibly age-dependent) rate of natural mortality;

$F_{y,a}$ is the actual rate of fishing mortality on animals of age a during year y[10,11];

m is the oldest age considered in the analysis (taken here, as in Butterworth *et al.* (1996), to be $m=29$ - sample sizes for larger ages are very small, and furthermore such ages are less reliably estimated because of the difficulties of counting large numbers of closely spaced layers in ear plugs).

Whale catches in the Antarctic are limited to a shortish period around the end of the calendar year, so that it is customary to model the population dynamics assuming a pulse fishery at the start of the year as in Equation (1). Strictly, this justification no longer holds when time-steps in excess of one year (as here) are considered. However, for the cases investigated here, both M and F are sufficiently small that Equation (1) still represents a reasonable approximation.

[10] Note that although the $F_{y,a}$ and M_a as defined by Equation (2) apply to three-year periods, any numerical values will be quoted will be in units yr^{-1} (i.e. dividing the actual values obtained by 3), as is conventional (and more readily interpretable) practice.

[11] The word 'actual' is used here in the context of the assumptions being made that every animal in the catch is aged without error, so that given the assumptions of Equation (3), the difference between $C_{y,a}$ and $C^E_{y,a}$ is caused by sampling variability only. These assumptions are relaxed later in the paper where, for example, the consequences of possible ageing error are considered in sensitivity tests.

Model parameterisation

The parameters needed to compute the numbers-at-age matrix are the terminal actual fishing mortalities $\{F_{y,m}: y = 71,74..n\}$ and $\{F_{n,a}: a = 2,5,..m-3\}$. Fishing mortality is assumed to be separable (in expectation). Different selectivity patterns are assumed for the years of commercial and scientific catches:

$$F^E_{y,a} = \begin{cases} S^c_a F_y & \text{if } y < 89 \\ S^s_a F_y & \text{otherwise} \end{cases} \qquad (3)$$

where: S^c_a is selectivity-at-age for the period of commercial catches ($S^c_m = 1$);
S^s_a is selectivity-at-age for the period of scientific catches ($S^s_m = 1$);
F_y is the fishing mortality for year y on age m (i.e. the fully-selected fishing mortality in cases where $S^{c/s}_a \leq 1$ for $a \neq m$)[10]; and
$F^E_{y,a}$ is the expected rate of fishing mortality on animals of age a during year y, which differs from the actual rate $F_{y,a}$; the difference arises because the actual catch made ($C_{y,a}$) differs from that expected in terms of Equation (3) ($C^E_{y,a} = F^E_{y,a}N_{y,a}$) because of sampling variability[11].

Natural mortality is assumed to change linearly between ages 2 and 29, to be constant from ages 29 to 41, and to be infinite thereafter[12]:

$$M_a = \begin{cases} M_2 + \tau(a-2) & \text{if } 2 \leq a \leq 29 \\ M_2 + 27\tau & \text{if } 29 < a \leq 41 \\ \infty & \text{if } a \geq 44 \end{cases} \qquad (4)$$

One sensitivity test admits quadratic behaviour between ages 2 to 29. This dependence is specified by the three parameters: M_2, M_{29} and the age at which the parabola has a minimum (biologically a maximum would not seem realistic, as natural mortality would be expected to increase for both the youngest and oldest ages). A further set of sensitivity tests considers the possibility of time-dependence in M by generalising Equation (1):

$$N_{y+3,a+3} = (N_{y,a} - C_{y,a})\exp(-\tilde{M}_y M_a) \qquad 2 \leq a \leq m-3 \qquad (5)$$

where: $\tilde{M}_y$ is a factor related to the 'overall' level of natural mortality during year y, standardised by setting $\tilde{M}_{68} = 1$.

The values for the $\tilde{M}_y$ are pre-specified, rather than estimated.

For the case for which m is chosen to be 29, the total number of possible estimable parameters is therefore 38[13]:

(i) the eighteen terminal fishing mortalities: $\{F_{95,2}, F_{95,5}, \ldots, F_{95,26}\}$; $\{F_{71,29}, F_{74,29}, \ldots, F_{95,29}\}$;
(ii) the nine free selectivities-at-age for the period of commercial catches: $\{S^c_a: a = 2,5,\ldots,26\}$ where $S^c_{29} = 1$;
(iii) the nine free selectivities-at-age for the period of scientific catches: $\{S^s_a: a = 2,5,\ldots,26\}$ where $S^s_{29} = 1$; and
(iv) the two parameters which define the natural mortality schedule: M_2 and τ.

The associated computer code has been written to allow a variety of simplifications of this parameterisation, so as to reduce the number of parameters and hence achieve a sufficiently parsimonious model:

(a) natural mortality is independent of age (i.e. $\tau = 0$);
(b) the commercial catch information for ages 2 to 14 is excluded from the likelihood, so that it is not necessary to estimate $\{S^c_a: a = 2,5,..,14\}$;
(c) selectivity for the commercial catches is flat ($S^c_a = 1$) above age a^c_{flat} (reduces the number of parameters by $(29 - a^c_{flat})/3$);
(d) selectivity for the scientific catches is flat ($S^s_a = 1$) above age a^a_{flat} (reduces the number of parameters by $(29 - a^s_{flat})/3$);
(e) selectivity-at-age for the commercial catches for ages between 17 and a^c_{low} is the same (reduces the number of parameters by $(a^c_{low} - 17)/3$);
(f) selectivity-at-age for the scientific catches for ages between 2 and a^s_{low} is the same (reduces the number of parameters by $(a^s_{low} - 2)/3$);
(g) selectivity-at-age for the commercial/scientific catches changes linearly between age $a^{c/s}_{slop}$ and age 29, i.e.

$$S^{c/s}_a = 1 - \beta^{c/s}(29 - a) \qquad (6)$$

(reduces the number of parameters by $26 - a^{c/s}_{slop})/3$);
(h) for some of the years of commercial catch, the terminal fishing mortalities $F_{y,29}$ can be set by formula rather than treated as estimable parameters - the options possible are first

$$F_{y,29} = F_{y,26} \qquad \text{for } y = 71,\ldots y^* \text{ where } y^* \leq 86 \qquad (7)$$

and secondly

$$F_{y,29} = \alpha F_{y,26} \qquad \text{for } y = 71,\ldots y^* \qquad (8)$$

$$\text{where} \quad \alpha = \sum_{y=y^*+3}^{86} (F_{y,29} / F_{y,26}) / [(86 - y^*)/3]$$

i.e. α is the average F_{29} / F_{26} ratio for the other years of commercial catch.

Note that the choice of $m = 29$ together with an effective absence of catches prior to $y = 71$ means that recruitment ($N_{y,2}$) cannot be estimated further back in time than year $y = 44$ for Area IV. Given $C_{y,29}$ and estimates of $F_{y,29}$, the consequent estimates of $N_{y,29}$ from Equation (2) can be projected forwards as well as backwards along their respective cohorts using Equation (1), thus providing numbers-at-age estimates up to age 44. Note that this formulation therefore assumes the input $C_{y,a}$ values to be exact in terms of the equations for the dynamics, thus ignoring the variance associated with their estimation by scaling upwards, or using an age-length key based upon the lesser number of animals actually aged each year (see Appendix).

The likelihood function

The likelihood function contains contributions from three sources: the estimates of absolute abundance from the IWC surveys in Area IV in 1978/79 and 1988/89 (and, in principle, could include estimates from similar surveys in subsequent years); the estimates of relative abundance from the JARPA surveys; and the catch-at-age data. The

[12] The natural mortality rates for ages 2-44 are also constrained to lie between 0.01 and 0.25yr^{-1} when treated as estimable parameters.
[13] This total omits the F_y parameters, whose explicit estimation is not required for the procedures following.

abundance surveys of the latter research programme are treated as providing relative rather than absolute abundance values for reasons discussed in the preceding section.

The contribution of the absolute (IWC) abundance estimates to the negative of the logarithm of likelihood function (ignoring constants) is given by:

$$\ell nL_1 = \sum_y \frac{1}{2(\sigma_y^N)^2}\left(\ell nN_y^{obs} - \ell n\hat{N}_y\right)^2 \qquad (9)$$

where: N_y^{obs} is the abundance estimate for year y;
σ_y^N is the standard error of the logarithm of N_y^{obs} (approximated by $\sqrt{CV_y^2 + CV_{add}^2}$);
CV_y is the coefficient of variation of N_y^{obs};
CV_{add} is the 'additional standard error'[14]; and
$\hat{N}_y$ is the model-estimate of the 1+ abundance for year y[15]:

$$\hat{N}_y = \sum_{a=2}^{44} \hat{N}_{y,a} \qquad (10)$$

The contribution of the relative (JARPA) abundance data to the negative of the logarithm of the likelihood function (ignoring constants) is given by:

$$\ell nL_2 = \sum_y \frac{1}{2(\sigma_y^R)^2}\left(\ell nR_y^{obs} - \ell n(q\hat{N}_y)\right)^2 \qquad (11)$$

where: R_y^{obs} is the relative abundance index for year y;
σ_y^R is the standard error of the logarithm of R_y^{obs} (approximated by a combination of its CV and an 'additional standard error' as for Equation (9) above); and
q is the relative bias of estimates from JARPA compared to those from IWC surveys.

If some 'prior' information is available about q, and this can be expressed in the form of a lognormal LN(q^{obs};σ_q^2) distribution, then an extra term can be added to the negative of the logarithm of the likelihood function:

$$\ell nL_2^* = \frac{1}{2\sigma_q^2}(\ell nq^{obs} - \ell nq)^2 \qquad (12)$$

The maximum likelihood estimate of q can be obtained analytically using the formula[16]:

$$\ell n\hat{q} = \left(\ell nq^{obs}/\sigma_q^2 + \sum_y \ell n(R_y^{obs}/\hat{N}_y)/(\sigma_y^R)^2\right) \Big/ \left(1/\sigma_q^2 + \sum_y 1/(\sigma_y^R)^2\right) \qquad (13)$$

For case (b) above where a fixed selectivity pattern is assumed to apply to the commercial catch for ages 17 and above only, then assuming a multinomial distribution of the catch-at-age for each year, the contributions of the commercial and scientific catches to the log-likelihood (ignoring constants) are given by:

$$\ell nL_3^c = \sum_{y=71}^{86} \lambda_y \sum_{a=17}^{m} C_{y,a}^* \ell n\hat{p}_{y,a} \qquad (14a)$$

$$\ell nL_3^s = \sum_{y=89}^{95} \lambda_y \sum_{a=2}^{m} C_{y,a}^* \ell n\hat{p}_{y,a} \qquad (14b)$$

where: $C_{y,a}^*$ is the effective[17] number of animals of age a caught during year y, computed as $C_{y,a}C_y^*/C_y$[18];
C_y is the total catch in numbers during year y;
C_y^* is the number of animals actually aged, with ages which are included in the likelihood for year y (for the scientific catches, this is the total number of animals whose actual (as distinct from combination) ages were assessed to lie between 1 and 30, while for the commercial catches it is the total number of animals whose actual ages were assessed to lie between 16 and 30);
λ_y is a factor to account for over-dispersion (assuming that the catch-at-age distributions are not under-dispersed implies that $0 < \lambda_y \leq 1$); and
$\hat{p}_{y,a}$ is the model-estimate of the expected proportion of the catch during year y which consists of animals of age a (these formulae follow from the assumptions of Equation (3) for the expected rate of fishing mortality):

$$\hat{p}_{y,a} = \begin{cases} S_a^c N_{y,a} \Big/ \sum_{a'=17}^{29} S_{a'}^c N_{y,a'} & \text{if } y < 89 \\ S_a^s N_{y,a} \Big/ \sum_{a'=2}^{29} S_{a'}^s N_{y,a'} & \text{otherwise.} \end{cases} \qquad (15)$$

For simplicity, it is assumed that λ_y is constant (λ^c) for all of the years of commercial catches and also (a potentially different) constant (λ^s) for all of the years of scientific permit catches. For the analyses in which $\lambda^{c/s}$ is not taken to be equal to 1, the estimation involves an iterative reweighting approach. First, the values for the parameters of the model are obtained by maximising a likelihood function in which

[14] This additional variance arises from the fact that the variance estimates provided by surveys relate only to the sampling variability of those surveys. What is relevant for fitting population models to abundance data is the total variability of survey estimates about the underlying true abundance trend. This is affected not only by survey sampling variability, but also by other factors such as inter-annual changes in the proportion of the population in the area surveyed at the time of the survey. For further details, see IWC (1997).

[15] Numbers-at-age are not computed for ages 41 and 44 for 1979 because, as indicated above, the available data do not permit estimation of recruitment for the associated cohorts. A (small) correction factor obtained by regressing on $(\hat{N}_{y,41} + \hat{N}_{y,44}/\hat{N}_y)$ year is therefore applied to the estimate for 1979, which is computed using Equation (10) with the summation extending only to $a = 38$.

[16] If the 'prior' information about q is ignored, the terms involving σ_q are dropped from Equation (13).

[17] The multinomial distributions assumed by the likelihood formulations of Equations (14) require specification of the number of samples for each year and age which can be considered as effectively independent.

[18] Strictly for the scientific catch, $C_{y,a}^*$ should be the actual number of whales caught in year y and assigned to be age a; however, this formula will provide virtually identical results and has the convenience of being reasonably applicable for both the scientific and commercial catches.

$\lambda^{c/s}$ is taken to be equal to 1 for all years. The following formula (see McAllister and Ianelli, 1997, appendix 2) is then applied to provide updated estimates for the λ's:

$$\lambda^{c/s} = \sum_y 1 \Bigg/ \sum_y \left\{ \frac{C_y^* \sum_a (\rho_{y,a} - \hat{\rho}_{y,a})^2}{\sum_a \hat{\rho}_{y,a}(1-\hat{\rho}_{y,a})} \right\} \qquad (16)$$

where $\rho_{y,a}$ is the observed proportion of the catch during year y which consists of animals of age a:

$$\rho_{y,a} = \begin{cases} C^*_{y,a} \Big/ \sum_{a'=17}^{29} C^*_{y,a'} & \text{if } y < 89 \\ C^*_{y,a} \Big/ \sum_{a'=2}^{29} C^*_{y,a'} & \text{otherwise} \end{cases} \qquad (17)$$

The summations over year and age in Equation (16) depend on the period considered. For example, to estimate a value for λ^c for the years of commercial catches, the summations over year cover the years 1971 to 1986 and summations over age cover ages 17 to m. The estimation is then repeated replacing λ^c by the updated estimates unless the estimate of λ^c exceeds 1 (corresponding to under-dispersion) in which case it is set equal to 1. This process is repeated until convergence takes place.

Bootstrap estimation of precision

Bootstrap estimates of precision are calculated using an extension of the approach described in Butterworth *et al.* (1996). The procedure involves generating a large number of artificial datasets (typically 100) and fitting the model to each. Each artificial dataset contains a pseudo catch-at-age matrix, and pseudo absolute and relative abundance indices.

The pseudo vector of catches-at-age for year y is obtained by generating a sample from the multinomial distribution with probabilities defined from the actual catch-at-age for year y (Table 1) and then scaling the resultant age-frequency upwards to the total catch for year y. The sample size for year y used when generating the age-frequency is set equal to the actual number of animals aged during that year[19]. This procedure does not reflect the actual practice for the commercial catches (which involves the use of an age-length key - see Appendix) exactly. However, it will constitute an adequate approximation provided the shape of the length distribution of the subsample of all the whales aged does not differ markedly from that for all whales caught, i.e. provided certain length ranges in the catch are not highly disproportionately under- or over-sampled in the ageing exercise.

Two of the sensitivity tests concerned with the estimation of precision consider the impact of ageing error. This is implemented by adding such error to the multinomial sample generated from the actual catch-at-age data (i.e. before scaling upwards to the total catch) using the equation:

$$a' = a(1+\varepsilon) \qquad \varepsilon \sim N(0;\sigma_e^2) \qquad (18)$$

[19] If the catch-at-age data appear to be over-dispersed, account of this is taken in the bootstrap generation process by reducing the actual sample size by multiplying by the over-dispersion factor (λ).

where: a' is the observed age of an animal of actual age a, and
σ_e reflects the extent of ageing error.

Ageing error is added independently to each age and a' is bounded to lie between 1 and 53 (generated ages outside this range are set equal to 1 and 53 respectively). Two choices for σ_e, in addition to the base-case choice of 0, are considered. The choice $\sigma_e = 0.066$ corresponds to the extent of the error estimated for age readings by Kato (Tanaka and Fujise, 1997) while the choice $\sigma_e = 0.132$ is double this size.

The pseudo absolute abundance estimates are drawn from lognormal distributions defined by the point estimates and CVs in Table 3. The pseudo relative abundance indices are generated similarly. If a 'prior' for the relative bias factor q for the relative abundance indices is used, each bootstrap dataset contains a pseudo relative bias factor generated from a lognormal distribution with a median given by q^{obs} and a CV of σ_q.

The specification of the base-case estimator

The preceding section indicates that a large number of variants of the ADAPT estimator developed could be applied to the available data. To facilitate interpretation of results, a preferred base-case estimator has been developed. Sensitivity tests are detailed later, which systematically explore the consequences of alternative choices for many aspects of this base-case estimator.

As in Butterworth *et al.* (1996), the base-case-estimator operates on a three-age-three-year grouping basis, with a maximum age $m = 29$ in the VPA. As there is no independent information on the JARPA-IWC survey relative bias factor q, σ_q is set to ∞ (i.e. effectively, L_2^* - see Equation (12) - is omitted from the likelihood). All but the first terminal fishing mortality for the maximum age m considered are treated as estimable parameters. Thus, for $y = 71$ for Area IV, $F_{y,29}$ is fixed by use of Equation (7). This choice was made as otherwise essentially only one datum ($C_{71,29}$) is available upon which to base an estimate of $F_{71,29}$.

Natural mortality M

The base-case estimator assumes M to be an estimable parameter, independent of age a (i.e. $\tau = 0$ in Equation (4)). The reason for this is not that this is thought to be the situation in reality, but rather that preceding studies (e.g. Butterworth *et al.* (1996)) have suggested that such an estimator performs better than one which attempts estimation also of a linear trend of M with age a. This was because the lesser bias of this latter estimator tends to be more than offset by the additional variance arising from estimation of a further parameter from the data.

Selectivities-at-age: S_a^c and S_a^s

For the commercial catches, a consistent selectivity-at-age pattern is assumed to apply from age $a = 17$ and above only (see Equation (14a)). This assumption was made because Sakuramoto and Tanaka (1985) present arguments that the commercial selectivity pattern for ages below 15 varied between seasons. The commercial selectivity slope parameter β (which is taken to apply to the age range $a = 23$ to 29, i.e. $a^c_{slop} = 23$ in Equation (6)) was set to zero, so that, for example, $S^c_{26} = 1$ where $S^c_{29} = 1$ by definition. There are two reasons for this choice. First, although the commercial whalers would clearly have wished to select for larger (and hence older) animals, minke whale growth is (on average) very limited at older ages, with less than 0.5m growth to be expected after an animal reaches an age of 10 years. Best (1984) presents results indicating that shipboard estimates of minke whale length had a root mean square error (RMSE) of some 0.8m. Thus, the whalers would clearly have been unable to preferentially select older animals amongst those of age, say, 20 and above on the basis of apparent size[20].

The commercial whaling fleet did not catch at random throughout an Area (as the scientific take intends), but rather concentrated in regions of higher minke whale density near to the ice-edge. Thus non-uniform commercial selectivity-at-age could result if there is age-specific segregation of the animals. Table 4 presents results for the average age of the whales sampled in JARPA between 80° and 130° E over the January-March period (covering the peak of commercial whaling operations) as a function of latitude. This section of Area IV was chosen as the continental edge and ice-edge run roughly east-west for this longitude range, so that latitude is a good proxy for distance from the ice-edge. From 61°S southward, there is a clear tendency for average age to increase, suggesting that older animals are more likely to be found closer to the ice-edge. This in turn suggests that the slope parameter β cannot be negative, i.e. that S^c_{26} is not greater than 1. The base-case estimator sets $\beta^c = 0$ ($S^c_{26} = 1$), with the implications for bias should β^c in fact be positive that are discussed below[20]. [Table 4 also indicates high average ages in latitudes 59°-61°S; this may be an artefact of small sample sizes, but does merit further investigation.]

Table 4

Average age by latitude of minke whales (both male and female) sampled in JARPA surveys between longitudes 80°-130°E over the January-March period from 1987/88 to 1995/96.

Latitude range (°S)	Sample size	Average age (yrs)
59-60	6	16.3
60-61	47	17.4
61-62	63	10.5
62-63	58	10.3
63-64	138	14.9
64-65	190	13.4
65-66	280	15.5
66+	7	16.9

Given that the scientific take intends a random sample, the scientific selectivity-at-age function (S^s_a) is taken to be flat for large ages a. The evidence for non-uniform selectivity-at-age at younger ages for both the commercial (age 17 and above) and scientific (age 2 and above) catches was examined for Area IV by the use of likelihood ratio tests. Starting with a uniform function (all $S^{c/s}_a = 1$), these parameters were successively freed and treated as estimable, starting with the parameter for the youngest age under consideration. This exercise suggested that the first two selectivities in each set (S^c_{17} and S^c_{20}; S^s_2 and S^s_5) were less than 1. Furthermore, however, over a wide range of age-independent values for M (0.02 to 0.14yr^{-1}), no difference significant at the 5% level between S^c_{17} and S^c_{20}, and between S^s_2 and S^s_5 was detected. Thus the base-case estimator allowed two estimable selectivity-at-age parameters: $S^c_{17} = S^c_{20} \leq S^c_{23} = 1$ and $S^s_2 = S^s_5 \leq S^s_8 = 1$, with likelihood ratio tests indicating these distinctions (from values of 1) to be justified at the 5% level. Some difference between the selectivities at these and at higher ages seems possible for the commercial catch given the distributional patterns of both animals and whaling operations as discussed above. For the scientific take, similar differences might also be expected, with some of the smaller (younger) minke whales remaining to the north of the JARPA survey area (as indicated by long-established evidence from high 'proportion takeable' estimates from IWC surveys - see, for example, estimates listed in Chapman, 1985). The formulation of the base-case estimator for the selectivity-at-age of the scientific take is consistent with the results of Cooke *et al.* (1997), whose multiple regression analysis found no evidence for heterogeneity with respect to Area, time within a season, latitude or school size in the scientific take for animals over 9 years of age.

[20] P. Best (pers. comm.) and T. Polacheck (pers. comm.) point out that this argument holds only for selection of whales from different schools. Within a school, likely ability to make comparisons on relative size suggests that whalers would have been able to select the larger animals more successfully than we infer from the results of Best (1984). This suggests β^c greater than rather than equal to zero, the implications of which are discussed later in the paper.

Additional variance (CV_{add})

Repetition of the analysis of Punt *et al.* (1997) at the Area level yields a point estimate $CV_{add} = 0$, with an approximate 95% confidence interval of [0; 0.31]. Hence, noting this point estimate, the base-case estimator uses the CV estimates of Table 3 *without* any additional variance added (see Equation (9) and following).

In summary

Note that the base-case estimator for Area IV thus has 21 estimable parameters:

(i) seventeen terminal fishing mortalities, $\{F_{95,2}, F_{95,5}, \ldots, F_{95,26}\}$; $\{F_{74,29}, \ldots, F_{95,29}\}$;
(ii) one selectivity-at-age for the period of commercial catches, $\{S^c_{17} = S^c_{20} \leq 1\}$;
(iii) one selectivity-at-age for the period of scientific catches, $\{S^s_2 = S^s_5 \leq 1\}$;
(iv) the relative bias of the JARPA survey estimates of abundance, q; and
(v) the age-independent natural mortality, M.

Sensitivity tests for the base-case assessment

Base-case assessments are provided by application of the base-case estimator developed above to the catch-at-age and abundance data in Tables 1 and 3. A number of sensitivity tests for the resultant Area IV assessment are also pursued.

(i) Age-dependence of M - the estimation of linear and quadratic dependence on age a is examined.
(ii) Commercial selectivity slope (β^c) - alternative fixed values (to 1) for S^c_{26} are examined, and this is also treated as an estimable parameter. This test is conducted for the cases both of M independent of age a and M linear in a. Given the choice $a^c_{slop} = 23$, fixing S^c_{26} specifies S^c_{23}. This sensitivity test then assumes that $S^c_{17} = S^c_{20} \leq S^c_{23}$, rather than ≤ 1 as for the base-case.
(iii) Some older animals 'hidden' in the pack-ice - Table 4 indicates a trend towards older animals closer to the edge of the pack-ice, and it is known that minke whales are present within the pack-ice region (e.g. Ensor, 1989), where they can be neither surveyed (nor sampled) by IWC, JARPA or commercial whalers. This suggests that the probability that a minke whale is 'hidden' in this way may increase with age, which

would correspond to a decreasing slope in selectivity-at-age for both the commercial and scientific catches (since both would be equally affected by such a possibility). This is investigated by setting (see Equation 6) $\beta^c = \beta^s$ to values differing from 1, with $a^c_{slop} = 23$ and $a^s_{slop} = 11$. As for the base-case, S^s_8 was equated to S^s_{11} with $S^s_2 = S^s_5$ estimated for these sensitivity tests, while for the commercial selectivities, $S^c_{17} = S^c_{20}$ was estimated, though no longer subject to the constraint that it did not exceed S^c_{23}[21].

(iv) Retrospective analysis - this standard VPA diagnostic procedure (comparing trends with those for analyses carried out with only those data available at some earlier times) is followed for analyses up to combination-years $y = 92$ and $y = 89$.

(v) Absolute abundance estimates - although the IWC estimates are used as absolute in the analysis, they may be biased for various reasons (e.g. animals to the north of the common boundary line used for the IWC estimates listed in Table 3); thus the consequences both of doubling and of halving the IWC estimates is explored.

(vi) Lesser readability of earplugs from younger animals (Kato *et al.*, 1991) in the scientific take - as noted above, this may lead to an underestimate of the scientific catch-at-age of younger animals - as a simple way of examining the consequences of this, the contributions of ages $a = 2$ and 5 are omitted from the pertinent contribution to the likelihood (L^s_3 - see Equation (14b)).

(vii) Greater inter-annual consistency in the commercial selectivity-at-age - age $a = 14$ is included in the pertinent contribution to the likelihood (L^c_3 - see Equation (14a)), with S^c_{14} treated as an additional estimable parameter subject to $S^c_{14} \leq S^c_{17} = S^c_{20} \leq 1$.

(viii) Separate assessments for males and females - this is problematic because although the catch-at-age matrices are readily disaggregated by sex, the same is not the case for the sighting survey estimates of abundance; as a crude first attempt, sex-disaggregated assessments have been conducted for Area IV by halving the abundance estimates in Table 3, and multiplying their CVs by $\sqrt{2}$.

(ix) Technical modifications - the consequences of the alternative choices of $m = 26$ and $m = 32$ for the oldest age considered in the VPA ($m = 29$ for base-case) are examined, as well as those of choosing a four-age-four-year instead of a three-age-three-year grouping.

(x) Alternative treatment of the JARPA abundance estimates - as a result of biases introduced by the survey protocol applied (Burt and Borchers, 1997), these estimates may also give biased indications of trends in relative abundance (IWC, 1998). Two sensitivity tests examine imposing an annual 2% increasing/decreasing trend on the abundance estimates, while another examines the consequences of assuming that the JARPA estimates are proportional to the square root of $\hat{N}$ rather than $\hat{N}$ itself.

(xi) Time trends in M – allowance is made for the possibility that M (assumed in this test to be independent of age) is time dependent by changing M linearly with time from 1944 to 1968 and then linearly (but with a change of slope) from 1968 to 1995 (see Equation 5).

[21] This is a simple initial investigation of the consequences of this possibility, which ignores the fact that if some animals are 'hidden' in this manner, the total population numbers to which survey estimates are fitted – see Equations (10) and (11) – should be summations of true numbers-at-age downweighted in an age-dependent manner to allow for the fact that older animals are preferentially unavailable to the surveys. Given, however, that key results of interest (see Table 8) show little sensitivity to changes in absolute estimates of abundance (sensitivity test (v)), failure to take this downweighting into account seems unlikely to have much impact on those results.

ASSESSMENT RESULTS AND DISCUSSION

Area IV

For this Area, preliminary analyses estimated λ to be greater than 1 for the periods of both the commercial and the scientific permit catches. Since the possibility of under-dispersion is excluded (this hardly seems likely, and would overweight data if incorrectly assumed), λ has been taken to be equal to 1 for all of the analyses for Area IV. Fig. 1 (see also Table 6) shows estimated recruitment ($N_{y,a}$) trends for the base-case estimator computed for various alternative age-independent values of M ranging from 0.02 to 0.14yr^{-1}. This range captures a wide set of possible historic (1947-68) recruitment trends - from rapidly increasing to continuously declining. The plots are normalised to the corresponding estimates of recruitment in 1968 for ease of trend comparison, as absolute recruitment levels differ greatly for the different values of M.

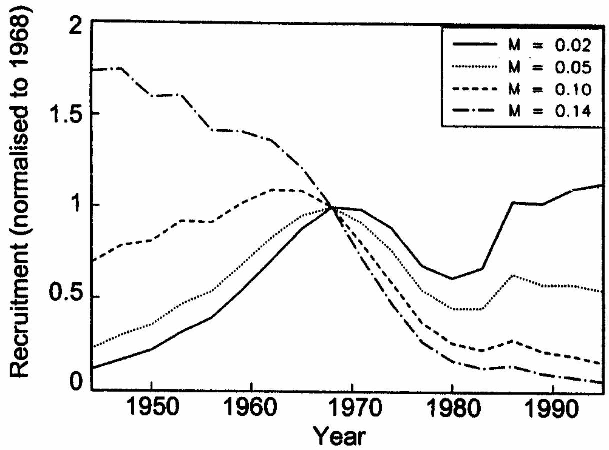

Fig. 1. Estimates of recruitment ($N_{y,2}$) for Area IV plotted against year for fixed values of age-independent natural mortality M = 0.02, 0.05, 0.10 and 0.14yr^{-1}. Each series is normalised to its 1968 level.

The recruitment trend for the base-case estimator itself, which estimates the value of an age-independent value of M from the data (obtaining an estimate 0.057yr^{-1}) is shown overleaf in Fig. 2. Fig. 3 illustrates how the estimator is able to distinguish amongst alternative values of M based upon the survey abundance estimates. Fig. 3a shows the trends in total population size from 1980 to 1995 (here corresponding to estimated numbers-at-age $N_{y,a}$ summed from $a = 2$ to $a = 44$, using the procedure of footnote 15 to extrapolate where necessary) for different values of age-independent M, with this trend changing from positive to negative as M is increased. The total abundance estimates fitted are shown in Fig. 3b, together with the corresponding base-case estimate of the total abundance trend (note that the JARPA estimates as shown in this plot are adjusted by the estimate of the relative bias factor q). The trend of these estimates is slightly downward, essentially allowing the base-case estimator to 'choose' from amongst the possibilities shown in Fig. 3a.

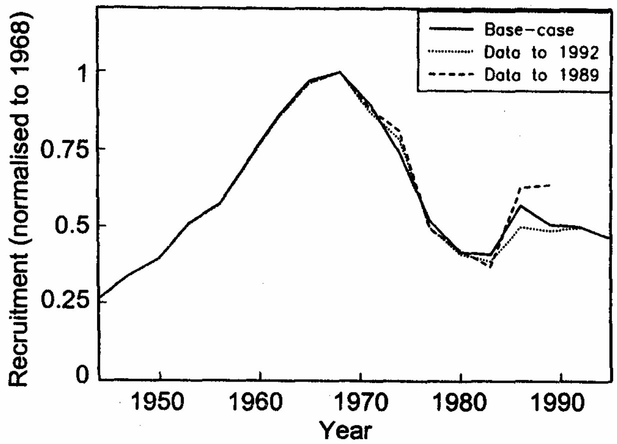

Fig. 2. Estimates of recruitment ($N_{y,2}$) for Area IV plotted against year as in Fig. 1 for the base-case estimator, for which M is assumed to be independent of age with a value estimated by fitting the data (and yielding $M = 0.057\text{yr}^{-1}$), are shown by the full line. The other lines show retrospective analyses, which involve applying the base-case estimator to the data available up to 1992, and up to 1989 only - in both cases fixing $M = 0.057\text{yr}^{-1}$.

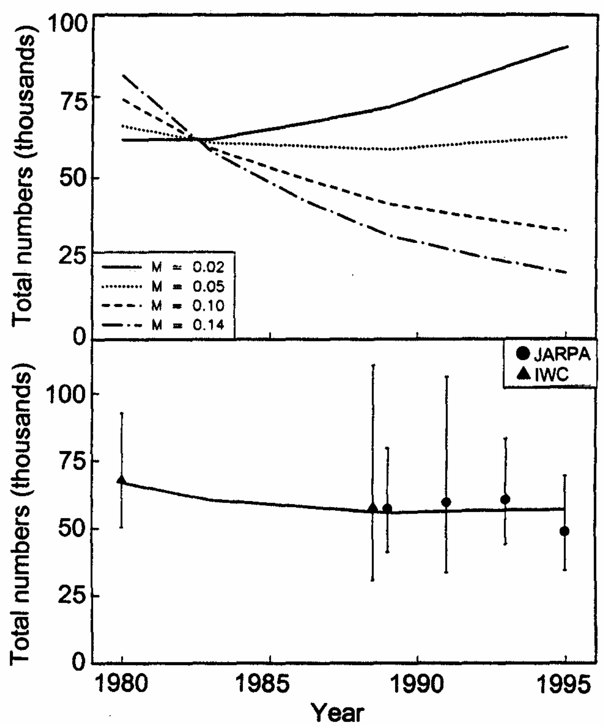

Fig. 3. Plots of estimated total population size ($\sum_{a=2}^{44} N_{y,a}$) against year for Area IV for fixed values of age-independent natural mortality $M = 0.02, 0.05, 0.10$ and 0.14yr^{-1} are shown in the upper panel. The plot for the base-case estimator, which estimates $M = 0.057\text{yr}^{-1}$ is shown in the lower panel, together with the abundance estimates input to this estimation procedure. The JARPA abundance estimates have been scaled to be comparable to the IWC estimates by use of the base-case estimate of the relative bias factor $q = 0.431$. The error bars show 90% CI's for these abundance estimates under the assumption of distribution lognormality.

Fig. 2 also includes the results of a retrospective analysis, showing recruitment trend estimates based on data available up to 1992 only and to 1989 only. There are no indications of a systematic trend in the estimates of year-to-year changes in recruitment as more data became available, consistent with an absence of model mis-specification. [The retrospective analysis is run for the same value of $M = 0.057\text{yr}^{-1}$ as estimated by the base-case estimator for data through to 1995. If M is treated as an estimable parameter in these retrospective fits, different values to 0.057 result, essentially 'rotating' the plots in Fig. 2 somewhat. This is to be expected, as M is not that precisely estimated, even given data up to 1995 - see Table 9. But the objective of the retrospective analysis is rather to address the issue of consistency over time in estimates of inter-annual changes (within this overall 'rotational' degree of freedom), and these changes do seem well estimated by the available data.] The numbers-at-age ($N_{y,a}$) matrix for Area IV estimated by the base-case estimator is given in Table 5a, with estimates of the commercial and scientific selectivity-at-age vectors (S_a^c and S_a^s respectively), together with the estimate of the relative bias factor q for the JARPA/IWC abundance estimates, given in Table 5b. Table 5c gives values for the 'apparent' selectivity-at-age $S_{y,a}^*$. This statistic is developed by first calculating a 'fully-selected' fishing mortality F_y^* for each year; this was taken to be the average fishing mortality over ages $a = 23$ to 29 for the years of commercial catch, and $a = 8$ to 29 for those of the scientific take. The 'apparent' selectivity for age a in year y is then given by:

$$S_{y,a}^* = F_{y,a} / F_y^* \tag{19}$$

If the model used for the base-case estimator was mis-specified, one would expect to see systematic patterns in $S_{y,a}^*$ in Table 5c over age ranges for which the underlying selectivity ($S_a^{c/s}$) was constant. There is no obvious indication of such patterns in this Table.

Another assumption to be tested is that of independence of the age samples, as tacitly assumed by the forms of Equations (14a) and (14b) with λ taken to be 1. If there was positive correlation in these samples, these equations would give undue weight to these data, leading to negatively biased estimates of variance for quantities of interest whose values are estimated in the assessment. This test was effected by considering, as an approximate measure[22] of goodness of fit, a χ^2 statistic for the catch-at-age data:

$$\chi^2 = \sum_{y=71}^{86} \sum_{a=17}^{m} \frac{(C_{y,a}^* - C_y^* \hat{\rho}_{y,a})^2}{C_y^* \hat{\rho}_{y,a}} + \sum_{y=89}^{95} \sum_{a=2}^{m} \frac{(C_{y,a}^* - C_y^* \hat{\rho}_{y,a})^2}{C_y^* \hat{\rho}_{y,a}} \tag{20}$$

For the base-case assessment, the value of χ^2 is 31.41 (df = 40). The null hypothesis that the catches included in the analysis are multinomially distributed about the model predictions therefore cannot be rejected ($P > 0.75$), so that there is no statistically significant evidence of non-independence in the age samples in this instance. Repeating the assessment including commercial catch-at-age data for all ages gives a significant result under this test, consistent with the assumption that the commercial selectivity varied from year to year for the younger ages.

[22] This statistic is described as approximate because the resultant inferences fail to take into account that absolute abundance estimates and relative abundance indices are also fitted in the estimation process.

Table 5

Results for the application of the base-case estimator to the data for Area IV. The symbols used are defined in the text.

(a) Numbers-at-age matrix $N_{y,a}$ ($\hat{M}$ = 0.057).

	Age															
Year	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	Total
1944	5,494	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5,494
1947	7,100	4,633	-	-	-	-	-	-	-	-	-	-	-	-	-	11,734
1950	8,327	5,988	3,907	-	-	-	-	-	-	-	-	-	-	-	-	18,222
1953	10,722	7,022	5,050	3,295	-	-	-	-	-	-	-	-	-	-	-	26,090
1956	12,041	9,042	5,922	4,259	2,779	-	-	-	-	-	-	-	-	-	-	34,043
1959	15,098	10,154	7,626	4,994	3,592	2,344	-	-	-	-	-	-	-	-	-	43,808
1962	18,083	12,733	8,563	6,431	4,212	3,029	1,977	-	-	-	-	-	-	-	-	55,028
1965	20,322	15,250	10,738	7,222	5,424	3,552	2,554	1,667	-	-	-	-	-	-	-	66,729
1968	20,913	17,138	12,861	9,056	6,090	4,574	2,996	2,154	1,406	-	-	-	-	-	-	77,188
1971	18,825	17,637	14,453	10,846	7,637	5,136	3,857	2,526	1,817	1,186	-	-	-	-	-	83,920
1974	15,468	15,773	14,657	11,924	8,886	6,144	4,063	3,014	1,933	1,409	919	-	-	-	-	84,190
1977	10,904	12,354	12,031	10,866	8,609	6,294	4,118	2,671	1,932	1,233	897	632	-	-	-	72,540
1980	8,756	9,128	10,141	9,777	8,630	6,739	4,862	3,234	2,056	1,524	974	716	523	-	-	67,061
1983	8,592	7,205	7,283	8,025	7,630	6,624	5,050	3,598	2,331	1,486	1,094	705	505	387	-	60,513
1986	11,942	7,048	5,655	5,630	6,086	5,837	4,839	3,699	2,607	1,674	1,071	851	555	397	299	58,192
1989	10,640	10,014	5,791	4,491	4,346	4,629	4,352	3,576	2,665	1,897	1,215	806	641	425	318	55,804
1992	10,486	8,880	8,368	4,832	3,742	3,624	3,851	3,623	2,991	2,216	1,582	1,017	671	534	354	56,772
1995	9,721	8,803	7,459	7,025	4,052	3,141	3,041	3,231	3,043	2,506	1,857	1,324	851	563	449	57,063

(b) Selectivity and relative bias.

	Age									
	2	5	8	11	14	17	20	23	26	29
Selectivity - commercial S_a^c	-	-	-	-	-	0.865	0.865	1	1	1
- scientific S_a^s	0.823	0.823	1	1	1	1	1	1	1	1
Relative bias q (JARPA = q.IWC)	0.431									

(c) 'Apparent' selectivity $S^*_{y,a}$

	Age									
Year	2	5	8	11	14	17	20	23	26	29
1971	0.08	0.17	0.26	0.34	0.55	0.74	0.87	1.10	0.95	0.95
1974	0.22	0.39	0.50	0.59	0.66	0.85	0.91	0.99	1.00	1.01
1977	0.10	0.37	0.51	0.81	1.00	1.17	0.96	1.22	0.90	0.89
1980	0.17	0.37	0.42	0.51	0.62	0.76	0.84	1.00	0.98	1.02
1983	0.19	0.48	0.58	0.70	0.64	0.92	0.91	0.97	1.03	1.00
1986	0.04	0.18	0.41	0.60	0.70	0.82	0.88	1.04	0.98	0.99
1989	0.89	0.78	0.91	1.02	0.94	1.15	1.10	0.72	1.20	0.96
1992	0.86	0.73	0.86	1.07	0.90	0.99	0.99	0.80	1.19	1.21
1995	0.83	0.80	0.95	1.14	1.09	1.01	1.08	0.78	1.21	0.74

Sensitivity tests

Given the large number of statistics generated by an assessment, a key sub-set of five was chosen to characterise results in order to facilitate comparisons in sensitivity tests. These are:

(i) the historic recruitment trend, as given by the slope of a linear regression of $\ell n\, N_{y,2}$ against year y for y = 1947 to 1968, and expressed in (true yr)$^{-1}$;

(ii) $N_{83,2}$ / $N_{68,2}$ - usually reflecting the lowest value to which recruitment drops after the 1968 peak, expressed as a fraction of that peak value;

(iii) $N_{95,2}$ / $N_{68,2}$ - current recruitment as a fraction of the 1968 peak value;

(iv) age-averaged natural mortality, $\overline{M}$ - for cases of age-dependent M, this is calculated as:

$$\overline{M} = (M_2 + M_5 + M_8 + ... + M_{29}) / 10; \text{ and} \qquad (21)$$

(v) the recent trend in total population size, as reflected by the slope of a linear regression of $\ell n \left[\sum_{a=2}^{38} N_{y,a} \right]$ against year y for y = 1980 to 1995, and expressed in (true yr)$^{-1}$.

Table 6 (overleaf) shows results for these statistics for a variety of options for the specification of M and its age dependence. While changing the (age-independent) value of M makes key qualitative changes to the results (as also evident from Fig. 1), minimal differences result when attempts are made to estimate linear or quadratic dependence of M on age a. There is a weak indication of a generally increasing trend of M with age, but likelihood ratio tests do not provide statistical justification for estimation of the additional parameter(s) involved (maximal ℓnL increases of 0.13 and 0.52 for introduction of linear and quadratic dependence respectively).

Table 6

Sensitivity of the base-case assessment for Area IV to alternative specifications for natural mortality M and its age-dependence. The statistics reported are defined in detail in the text. Units, where pertinent, are yr^{-1} (i.e. true years, not combination years).

	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95	M_2	M_{17}	M_{29}	$-\ell n\ L$
Constant with a									
$M = 0.02$	0.088	0.672	1.134	0.020	+0.025	0.020	0.020	0.020	17.46
$M = 0.05$	0.061	0.451	0.549	0.050	-0.004	0.050	0.050	0.050	16.51
$M = 0.057$ (base-case)	0.055	0.411	0.465	0.057	-0.011	0.057	0.057	0.057	16.48
$M = 0.10$	0.015	0.226	0.161	0.100	-0.054	0.100	0.100	0.100	17.86
$M = 0.14$	-0.023	0.129	0.059	0.140	-0.094	0.140	0.140	0.140	21.64
Linear in a	0.049	0.407	0.471	0.058	-0.013	0.045	0.060	0.071	16.35
Quadratic in a									
Minimum at a = 2	0.047	0.412	0.477	0.060	-0.013	0.047	0.058	0.084	16.13
Minimum at a = 17	0.054	0.409	0.421	0.066	-0.012	0.095	0.050	0.079	15.96
Minimum at a = 29	0.055	0.411	0.465	0.057	-0.011	0.057	0.057	0.057	16.48

Table 7

Sensitivity of the base-case assessment for Area IV to alternative specifications for the selectivity-at-age functions. In (a), only the commercial selectivity slope parameter β^c (see Equation 6) is considered, where this slope applies to the age range a=23 to 29, i.e. sensitivity test (ii) as detailed in the text. For ease of understanding, rather than β itself, the value of S^c_{26} is given (note: S^c_{29} = 1 by definition). In (b), all results are for the case where M_a is independent of a. The first set of results show the consequences of successively freeing additional S^c_a parameters for constraint-free estimation. The second set is for sensitivity test (iii), which allows for the possibility that some of the older animals are 'hidden' in the pack-ice, with consequent negative slopes for both commercial and scientific selectivities-at-age.

(a)

Estimator variant	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95	M_2	M_{29}	$-\ell n\ L$
M_a indep. of a								
S^c_{26} = 0.80	0.102	0.475	0.621	0.046	+0.005	0.046	0.046	26.15
S^c_{26} = 1.00 (base-case)	0.055	0.411	0.465	0.057	-0.011	0.057	0.057	16.48
S^c_{26} = 1.20	0.030	0.420	0.490	0.053	-0.014	0.053	0.053	18.06
S^c_{26} = 1.05 (estimated)	0.049	0.420	0.482	0.055	-0.011	0.055	0.055	16.22
M_a linear in a								
S^c_{26} = 0.80	0.086	0.447	0.613	0.052	-0.002	0.010	0.094	24.99
S^c_{26} = 1.00	0.049	0.407	0.471	0.058	-0.013	0.045	0.071	16.35
S^c_{26} = 1.20	0.038	0.419	0.465	0.052	-0.013	0.071	0.033	17.74
S^c_{26} = 1.04 (estimated)	0.049	0.422	0.491	0.055	-0.011	0.049	0.060	16.20

(b)

Estimator variant	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95	S^c_{17}	S^c_{20}	S^c_{23}	S^c_{26}	$-\ell n\ L$
Selectivity parameters estimated										
$S^c_{17} = S^c_{20}$ (base-case)	0.055	0.411	0.465	0.057	-0.011	0.865	0.865	1	1	16.48
$S^c_{17} = S^c_{20}$, S^c_{26}	0.049	0.420	0.482	0.055	-0.011	0.978	0.978	1.099	1.049	16.22
$S^c_{17} = S^c_{20}$, S^c_{23}, S^c_{26}	0.050	0.426	0.493	0.054	-0.011	0.962	0.962	1.087	1.024	16.17
S^c_{17}, S^c_{20}, S^c_{23}, S^c_{26}	0.056	0.401	0.445	0.059	-0.012	0.813	0.884	0.990	0.976	15.87
Some older animals 'hidden' in the pack-ice										
$S^c_{26} = S^s_{26}$ = 0.9	0.044	0.456	0.535	0.088	-0.004	0.634	0.634	0.800	0.900	20.51
$S^c_{26} = S^s_{26}$ = 1 (base-case)	0.055	0.411	0.465	0.057	-0.011	0.865	0.865	1	1	16.48
$S^c_{26} = S^s_{26}$ = 1.05	0.053	0.386	0.427	0.050	-0.014	0.989	0.989	1.100	1.050	15.98
$S^c_{26} = S^s_{26}$ (estimated)	0.053	0.385	0.427	0.048	-0.014	1.017	1.017	1.122	1.061	15.95
$S^c_{26} = S^s_{26}$ = 1.1	0.053	0.381	0.427	0.042	-0.014	1.115	1.115	1.200	1.100	16.07
$S^c_{26} = S^s_{26}$ = 1.2	0.049	0.362	0.407	0.031	-0.016	1.385	1.385	1.400	1.200	17.58

Table 7a shows similar results when the possibility of a commercial selectivity slope that is not flat (i.e. β^c of Equation (6) is not zero) at older ages is admitted. This Table gives results for the cases both where M is independent of age a and where it is linear in a, while Fig. 4 shows the former set of results graphically. The key feature of these results is that the estimate of the historic recruitment trend is quite sensitive to the value assumed for β^c (or equivalently S^c_{26}), becoming larger or smaller as S^c_{26} is less than or greater than 1 (recall earlier arguments based on whale and whaling distributions that S^c_{26} is likely not in excess of 1). When S^c_{26} is treated as an estimable parameter, the resultant estimates are slightly above 1, but likelihood ratio tests do not provide statistical justification for the additional estimable parameter (increases in ℓnL of 0.26 and 0.15 for the M_a constant with a and the M_a linear in a cases considered, respectively). When linear dependence of M_a on a is allowed, the estimate of this linear selectivity trend changes from positive to negative over the range of S^c_{26} considered. However, the negative trends occur only for S^c_{26} values in excess of 1, a situation considered unlikely for reasons discussed above.

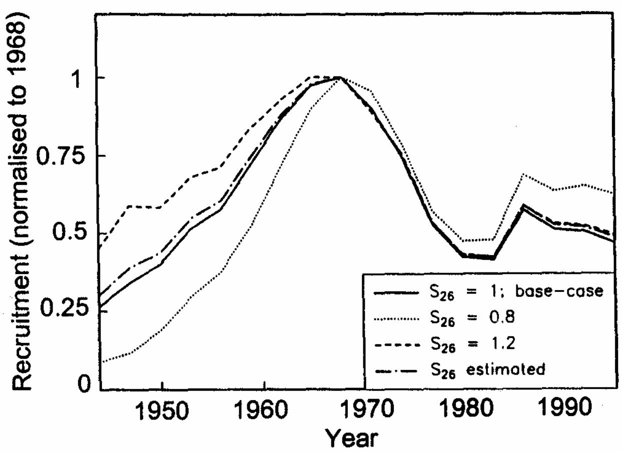

Fig. 4. Sensitivity of the base-case estimates of recruitment ($N_{y,2}$) for Area IV to the commercial selectivity slope parameter (see Equation 6). Results are shown for S^c_{26} = 0.8, 1.0 (the base-case), 1.2 and for the best estimate from fitting to the data of S^c_{26} = 1.05. Each series is normalised to its 1968 level.

During the 1998 meeting of the IWC Scientific Committee, considerable debate took place concerning the results shown in Table 7a (IWC, 1999). Particular concern was expressed that those results had been conditioned on the constraint $S^c_{17} = S^c_{20} \leq S^c_{23}$, thus precluding the possibility of any dome in the commercial selectivity-at-age having its maximum at an age below 23. This is because a decreasing slope in the commercial selectivity, particularly if it commenced at ages less than 23, would lead to estimates of lesser rates of increase in the historic recruitment trend. To investigate this, the base-case calculations (with M_a constant with a) have been repeated while successively freeing additional commercial selectivity-at-age (S^c_a) parameters for constraint-free estimation. The results shown in Table 7b confirm that there is no justification in likelihood-ratio terms for attempting to estimate these additional parameters given the available data, but nevertheless also indicate that the associated point estimates provide a virtually unchanged estimate of the historic recruitment trend and no indication of a maximum in the commercial selectivity-at-age at an age below $a = 23$.

Sensitivity test (iii) relating to the possibility of some older animals 'hidden' in the pack-ice also addresses this question, as it offers a mechanism which would result in the commercial (but then also the scientific) selectivity-at-age decreasing for greater ages. The results of this test are also shown in Table 7b, and again indicate very little sensitivity of the estimate of the historic recruitment trend to this factor, with likelihood maximisation again favouring an estimate of $S^c_{26} = S^s_{26}$ slightly greater than 1, i.e. only a small drop in selectivity with age[23]. The reason for this perhaps surprising result is that the existence of such 'hidden' animals changes the estimate of M, not that of the historic recruitment trend. This is as would be expected from the analyses of Butterworth and Punt (1990), which showed (see particularly equation 10 of that paper) that given temporal invariance of selectivity-at-age (above a certain age) and natural mortality-at-age, the collection of future catch-at-age data could, in principle, allow the estimation of the historic recruitment trend for Southern Hemisphere minke whales. Essentially, the contradiction of the inference of an increasing historic recruitment trend for minke whales on the basis of trends in selectivity-at-age requires that any decrease in this selectivity at larger ages is notably greater for the commercial than for the scientific catch - a scenario for which no obvious potential mechanism immediately suggests itself.

Results for the remaining sensitivity tests are shown in Table 8. Changing the values of the IWC abundance estimates does make a considerable difference to recent recruitment estimates compared to those for the 1968 peak. Increasing the abundance estimates (the more likely direction, given the need to allow both for animals north of the survey area and for the possibility that not all animals on the trackline are sighted) suggests that recent recruitment levels are not as far below the 1968 peak as for the base-case estimator. Other sensitivity test results of some note in Table 8 are that omission of ages $a = 2$ and 5 from L^s_3 (the surrogate test for possible bias in the number of young animals in the scientific take as a result of possible lower readability of earplugs from younger animals) leads to a slight increase in the estimated historic recruitment increase rate, and decrease in the estimated natural mortality rate, while the first of these estimated rates drops under a four- rather than a three-year grouping.

The results are sensitive to imposing a trend with time on the JARPA estimates of relative abundance. However, they are rather less sensitive to variation of the assumption of a linear relationship between these estimates and abundance (primarily because the existing JARPA estimates for Area IV are essentially without trend over time). Estimates of recruitment trends for recent years are not particularly sensitive to time trends in natural mortality. However, the estimate of the increase rate in $N_{y,2}$ from 1947 to 1968 is sensitive to such trends, becoming larger if M has increased over time. Indeed, it is possible to virtually eliminate the positive trend in $N_{y,2}$ from 1947 to 1968 by assuming that natural mortality decreased steadily from 0.143yr^{-1} in 1944 to 0.057yr^{-1} in 1968. Thus, if complete freedom is allowed in trends in natural mortality M over time, it becomes impossible to draw any inference about past recruitment trends. However, hypotheses about systematic changes in M would not seem to merit much credibility unless linked to independent supporting evidence or rationale. Only one such

[23] Naturally, only values of $S^c_{26} = S^s_{26} > 1$ are consistent with the hypothesis of some older animals 'hidden' in the pack-ice; results for a value lower than this are shown purely for the purposes of illustrating the behaviour of the log-likelihood.

Table 8

Further sensitivity tests of the base-case assessment for Area IV.

Variant	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95
Base-case	0.055	0.411	0.465	0.057	-0.011
Retrospective to 92	0.055	0.389	-	0.057[1]	-0.018[2]
Retrospective to 89	0.055	0.371	-	0.057[1]	-0.015[3]
Halve abundance estimates	0.049	0.265	0.272	0.057[1]	-0.038
Double abundance estimates	0.059	0.525	0.615	0.057[1]	0.000
Omit a=2,5 from L_3^s	0.068	0.499	-[4]	0.042	-0.005[3,4]
Include a=14 in L_3^c (i.e. estimate S_{14}^c)	0.057	0.425	0.492	0.054	-0.009
Males only	0.047	0.451	0.444	0.059	-0.012
Females only	0.049	0.324	0.398	0.067	-0.019
m = 26	0.057	0.401	0.434	0.056	-0.012[5]
m = 32	0.068	0.424	0.493	0.053	-0.007
4-year grouping	0.032[6]	0.591[7]	0.381[8]	0.054	-0.016[9]
$R_y^{obs} \rightarrow R_y^{obs} e^{0.02y}$	0.063	0.463	0.588	0.048	-0.002
$R_y^{obs} \rightarrow R_y^{obs} e^{-0.02y}$	0.046	0.362	0.363	0.066	-0.021
$R_y^{obs} \propto \sqrt{\hat{N}_y}$	0.060	0.445	0.545	0.051	-0.005
$\widetilde{M}_{44} = 0.8; \widetilde{M}_{95} = 1.2$ [10]	0.066	0.435	0.485	0.051	-0.012
$\widetilde{M}_{44} = 1.2; \widetilde{M}_{95} = 0.8$	0.040	0.376	0.428	0.065	-0.011
$\widetilde{M}_{44} = 2.5; \widetilde{M}_{95} = 1$	0.007	0.399	0.452	0.057	-0.011

[1] M fixed at same value as for base-case (0.057 yr^{-1}). [2] To 92 only. [3] To 89 only. [4] Statistics for y=95 not reliable as data exclusion essentially precludes recent recruitment estimation. [5] N_y to age 35 only. [6] 47/48-50/51 to 63/64-66/67. [7] 79/80-82/83 compared to 67/68-70/71. [8] 91/92-94/95 compared to 67/68-70/71. [9] 79/80-82/83 to 91/92-94/95 with N_y involving summation to combination age 37-40. [10] $\widetilde{M}_{68} = 1$ - see Equation (5).

Table 9

Bootstrap estimates of precision for the base-case estimator and certain variants thereof applied to data for Area IV. Figures given are medians, with 90% confidence intervals in parenthesis.

Estimator	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95	M_2	M_{29}	S_{26}^c
Base-case	0.054 [0.014;0.091]	0.380 [0.214; 0.729]	0.393 [0.147; 1.334]	0.059 [0.018; 0.101]	-0.016 [-0.056;0.032]	-	-	-
CV_{add}= 0.1	0.054 [0.015; 0.098]	0.389 [0.205; 0.785]	0.405 [0.133; 1.586]	0.060 [0.010; 0.105]	-0.016 [-0.060;0.038]	-	-	-
Omit a=2,5 from L_3^s	0.066 [0.007; 0.100]	0.446 [0.187; 0.882]	-[1]	0.048 [0.010; 0.112]	-[1]	-	-	-
Estimate S_{26}^c	0.045 [0.005; 0.092]	0.424 [0.225; 0.741]	0.429 [0.158; 1.393]	0.057 [0.015; 0.101]	-0.015 [-0.053;0.030]	-	-	1.028 [0.965; 1.172]
M_a linear in a	0.045 [0.002; 0.092]	0.369 [0.213; 0.730]	0.380 [0.146; 1.214]	0.065 [0.019; 0.105]	-0.021 [-0.065;0.029]	0.046 [0.010; 0.113]	0.075 [0.010; 0.135]	-
M_a linear in a; estimate $S_{26}^c \leq 1$	0.045 [0.002; 0.092]	0.363 [0.212; 0.722]	0.380 [0.148; 1.230]	0.065 [0.019; 0.105]	-0.021 [-0.065;0.028]	0.045 [0.010; 0.113]	0.076 [0.010; 0.140]	1 [0.947; 1.000]
M_a linear in a; estimate S_{26}^c	0.041 [0.000; 0.091]	0.373 [0.214; 0.703]	0.405 [0.149; 1.260]	0.060 [0.018; 0.104]	-0.018 [-0.065;0.027]	0.053 [0.010; 0.117]	0.066 [0.010; 0.137]	1.027 [0.944; 1.163]
Ageing error; σ_e=0.066	0.051 [0.012; 0.088]	0.386 [0.226; 0.721]	0.415 [0.145; 1.290]	0.060 [0.021; 0.106]	-0.017 [-0.054;0.029]	-	-	-
Ageing error; σ_e=0.132	0.047 [0.000; 0.083]	0.413 [0.236; 0.799]	0.421 [0.151; 1.158]	0.060 [0.018; 0.102]	-0.019 [-0.057;0.026]	-	-	-

[1] Statistics for y=95 not reliable as data exclusion essentially precludes recent recruitment estimation.

associated mechanism immediately suggests itself: M is density dependent, increasing as the population size grows. As noted above then, this suggests an even faster historic rate of increase in recruitment than estimated when assuming M to be time-independent, rather than that there was no such increase.

Precision

Bootstrap estimates of precision have been calculated based on 100 replicates. The resultant 90% confidence intervals for the five key statistics identified above for the base-case Area IV assessment are shown in Table 9, with the associated recruitment trend plot with confidence intervals in Fig. 5. A likelihood profile indicates a 90% confidence interval for M of [0.013; 0.100] compared to the [0.018; 0.101] from the bootstrap procedure; their similarity suggests that the bootstrap computations are reasonably reliable.

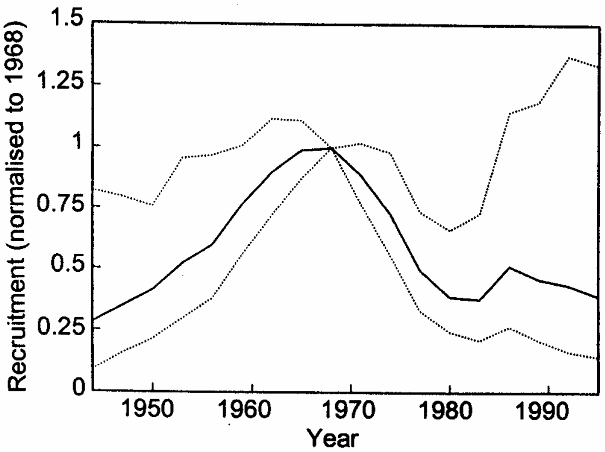

Fig. 5. Bootstrap estimates of medians (solid line), and 5%- and 95%-iles (dotted lines), for recruitment $N_{y,2}$ (relative to its estimated 1968 level for the corresponding bootstrap replicate) for Area IV for the base-case estimator.

Estimates of precision for a number of variants of the base-case estimator are also shown in Table 9. These include variants which attempt to estimate a linear dependence of natural mortality with age and the slope of the commercial selectivity at large age a, as well as those which allow for 'additional variation' in the abundance estimates and consider the impact of ageing error. Results of note are that, almost without exception, confidence intervals for the historic (1947-68) recruitment trend exclude the possibility of a decline. When the commercial selectivity slope is estimated, the confidence limits on S^c_{26} remain reasonably close to 1. Confidence interval estimates were not attempted for the variant of the base-case shown in Table 7b that estimates all four commercial selectivity parameters (S^c_{17}, S^c_{20}, S^c_{23} and S^c_{26}) without constraint, as numerical aspects of the bootstrap procedure used may be unreliable in this situation because these extra parameters constitute a subspace in which the likelihood is rather flat. However, for the case indicated as 'Estimate S^c_{26}' in the Table (corresponding to sensitivity test (ii)), the constraint boundary $S^c_{17} = S^c_{20} \leq S^c_{23}$was not hit for any of the 100 bootstraps. Hence, further to the Table 7b results which indicate no evidence for a commercial selectivity maximum below age $a = 23$ in point estimate terms, this suggests that this conclusion is supported at a high level of statistical significance.

Table 9 also shows that if additional variance at the level $CV_{add} = 0.1$[24] is introduced into the calculations, confidence intervals increase slightly but not substantially. Attempts to estimate age-dependence in M generally result in lower confidence bounds hitting the constraint boundary 0.01yr^{-1}. The impact of ageing error is minimal.

Extension to Area V

Results for the application of the base-case estimator to the data for Area V are given in Table 10. The estimator sets the age-independent estimate of M on the constraint boundary of 0.01yr^{-1}. The resultant estimated recruitment trend, together with those for some other fixed values of M, is shown in Fig. 6. The very low estimate of $N_{y,47}$ is an artefact of the small sample size for the catch-at-age at high ages - specifically $a = 29$ - for year $y = 74$ (see Table 1b), coupled with the application of Equation (7), and hence is not shown in the figure.

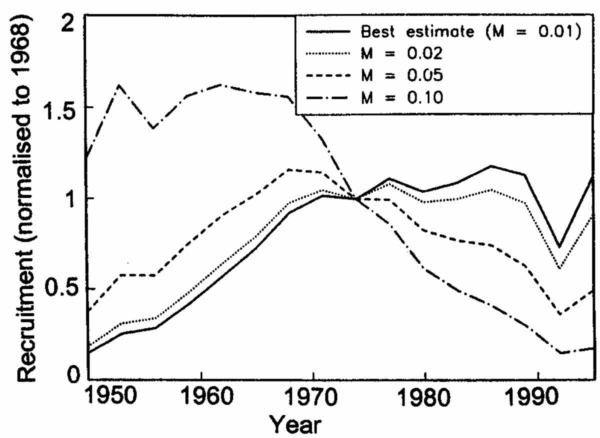

Fig. 6. Estimates of recruitment ($N_{y,2}$) for Area V plotted against year for fixed values of age-independent natural mortality $M = 0.02$, 0.05 and 0.10yr^{-1}. The full line shows the result for the base-case estimator, which sets M on the constraint boundary value of 0.01yr^{-1}. Each series is normalised to its 1968 level.

For this Area, the estimate of λ^c for the period of commercial catches is less than 1 (point estimate 0.688), so that account needs to be taken of over-dispersion in the bootstrap procedure. Bootstrap confidence interval estimates reported in Table 11 show that the precision of estimates is not as good as for Area IV, and do not exclude the possibility of a downward trend in historic recruitment over the 1947-68 period.

When the data for Areas IV and V are combined, the catch-at-age data are again over-dispersed. However, in contrast to the situation for Area V alone, both the commercial (λ^c = 0.742) and scientific take (λ^s = 0.702) data are now estimated to be over-dispersed. One possible reason for this is that even if the scientific catches-at-age reflect random samples within the Areas in which they were collected, bias (and possibly also apparent over-dispersion) can be introduced on combining data from the two Areas, as the sampling proportions differ because of the different sizes of the populations in these Areas. The base-case estimator chooses an age-independent M value of 0.030yr^{-1}, although the associated lower confidence bound hits the constraint boundary of 0.01yr^{-1} (see Table 11). The associated recruitment trend estimate, together with those for some other fixed age-independent values of M, is shown in Fig. 7. For this case, the confidence limits do exclude the possibility of a downward trend in historic recruitment.

The base-case estimator's formulation of two estimable selectivity-at-age parameters ($S^c_{17} = S^c_{20}$ and $S^s_2 = S^s_5$), which was based on analysis of results for Area IV data alone, could have been re-evaluated for the assessments above. However, it was decided to maintain the same format here in the interests of comparability.

[24] Although the point estimate of CV_{add} at the Area level provided by the procedure of Punt *et al.* (1997) is 0, a coarse Bayesian analysis based on a U[0,1] prior provides a posterior median of about 0.08, so that 0.1 seems a reasonable value to examine for sensitivity purposes.

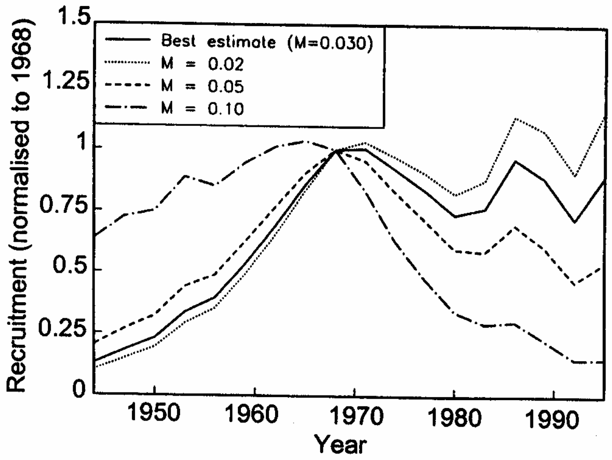

Fig. 7. Estimates of recruitment ($N_{y,2}$) for an assessment of the data for Area IV and Area V combined (see text for details) for fixed values of natural mortality $M = 0.02$, 0.05 and 0.10yr^{-1}. The full line shows the result for the base-case estimator, which estimates $M = 0.030\text{yr}^{-1}$. Each series is normalised to its 1968 level.

THE POTENTIAL IMPROVEMENT IN ESTIMATION PERFORMANCE FOR AREA IV GIVEN FURTHER DATA

Methods

Addressing this issue by means of simulation testing requires the development of an operating model of the actual underlying resource dynamics, from which (pseudo) data can be generated to which estimators are then applied to assess their statistical properties. Sensibly, such a model must be consistent with ('conditioned upon') existing data.

The base-case operating model chosen for this exercise reflects the population parameter sets estimated by a variant of the base-case estimator applied to 100 replicate pseudo datasets generated by the bootstrap procedure described above. The estimator variant used is deliberately chosen to be more complex than the base-case estimator itself, so as to better test this estimator for robustness to reasonable deviations from its assumptions that could apply in practice. Thus, this variant:

(i) assumes M varies linearly with age a to $a = 29$ (and is constant thereafter), in contrast to the base-case estimator's assumption of independence of a;

Table 10

Results for the application of the base-case estimator to the data for Area V.

(a) Numbers-at-age matrix $N_{y,a}$ ($\hat{M} = 0.010$ - constraint boundary).

Year	Age: 2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	Total
1947	295	-	-	-	-	-	-	-	-	-	-	-	-	-	-	295
1950	2,774	287	-	-	-	-	-	-	-	-	-	-	-	-	-	3,060
1953	4,824	2,691	278	-	-	-	-	-	-	-	-	-	-	-	-	7,793
1956	5,425	4,681	2,612	270	-	-	-	-	-	-	-	-	-	-	-	12,987
1959	7,971	5,264	4,542	2,535	262	-	-	-	-	-	-	-	-	-	-	20,573
1962	10,832	7,735	5,108	4,408	2,460	254	-	-	-	-	-	-	-	-	-	30,797
1965	13,789	10,511	7,506	4,957	4,278	2,387	247	-	-	-	-	-	-	-	-	43,674
1968	17,535	13,381	10,200	7,284	4,810	4,151	2,316	239	-	-	-	-	-	-	-	59,917
1971	19,410	17,016	12,985	9,899	7,068	4,668	4,028	2,248	232	-	-	-	-	-	-	77,554
1974	19,035	18,835	16,512	12,601	9,606	6,859	4,530	3,909	2,181	225	-	-	-	-	-	94,294
1977	21,200	18,451	18,217	15,898	12,099	9,195	6,570	4,324	3,746	2,088	216	-	-	-	-	112,005
1980	19,816	20,535	17,635	17,315	14,954	11,254	8,497	6,065	4,014	3,494	1,931	171	-	-	-	125,681
1983	20,742	19,173	19,754	16,799	16,469	14,128	10,471	7,989	5,647	3,644	3,199	1,792	88	-	-	139,894
1986	22,492	20,014	18,235	18,705	15,736	15,302	13,052	9,650	7,387	5,203	3,390	3,004	1,681	52	-	153,903
1989	21,538	21,767	19,276	17,499	17,853	14,923	14,367	12,253	9,059	6,901	4,890	3,217	2,853	1,617	37	168,052
1992	13,894	20,879	21,091	18,682	16,950	17,289	14,457	13,922	11,874	8,787	6,686	4,741	3,118	2,765	1,569	176,703
1995	21,406	13,450	20,208	20,404	18,061	16,391	16,723	13,974	13,453	11,472	8,494	6,463	4,580	3,010	2,676	190,766

(b) Selectivity and relative bias.

	Age: 2	5	8	11	14	17	20	23	26	29
Selectivity - commercial S^c_a	-	-	-	-	-	0.984	0.984	1	1	1
- scientific S^s_a	0.768	0.768	1	1	1	1	1	1	1	1
Relative bias q (JARPA = q.IDCR)	0.370									

(c) 'Apparent' selectivity $S^*_{y,a}$

Year	Age: 2	5	8	11	14	17	20	23	26	29
1974	0.09	0.25	0.60	0.80	1.03	0.99	1.24	0.94	1.03	1.03
1977	0.04	0.35	0.48	0.71	0.97	1.11	1.13	1.01	0.90	1.09
1980	0.06	0.16	0.34	0.37	0.49	0.77	0.58	0.75	1.20	1.05
1983	0.12	0.43	0.52	0.75	0.92	1.04	1.09	1.02	1.09	0.89
1986	0.08	0.22	0.33	0.49	0.67	0.96	0.97	0.96	1.10	0.93
1989	0.72	1.02	0.85	1.27	1.43	1.14	1.01	0.90	0.28	1.12
1992	0.64	0.71	0.82	1.00	0.92	0.86	1.05	1.12	1.18	1.06
1995	0.81	1.05	1.22	1.23	1.14	0.98	1.01	0.78	0.91	0.73

Table 11

Comparative point estimates for application of the base-case estimator to data for Area IV, Area V and the two Areas combined. Figures in parenthesis are bootstrap 90% confidence intervals.

Area	$N_{y,2}$ incr. rate 47-68	$N_{83,2}/N_{68,2}$	$N_{95,2}/N_{68,2}$	$\overline{M}$	N_y incr. rate 80-95
IV	0.055	0.411	0.465	0.057	-0.011
	[0.014; 0.091]	[0.214; 0.729]	[0.147; 1.334]	[0.018; 0.101]	[-0.056; +0.032]
V	0.139	1.159	1.103	0.010[1]	+0.025
	[-0.016; 0.108]	[0.192; 1.330]	[0.052; 1.797]	[0.010[1]; 0.133]	[-0.104; +0.032]
IV + V	0.083	0.764	0.894	0.030	+0.012
	[0.047; 0.110]	[0.449; 1.142]	[0.320; 1.911]	[0.010[1]; 0.073]	[-0.029; +0.037]

[1] Constraint boundary.

Table 12

Results of simulation trials for the base-case estimator for Area IV.

Statistic		Operating model					
		Simple (=Estimator)	Base-case	Double future catches	Continue to 2013	Base-case but estimate linear trend in M	Base-case but estimate selectivity slope
$N_{y,2}$ incr. rate 47-68	Mean true	0.053	0.063	0.063	0.063	0.063	0.063
	Mean est.	0.050	0.049	0.049	0.047	0.046	0.049
	RMSE	0.014	0.024	0.024	0.023	0.025	0.024
$N_{83,2}/N_{68,2}$	Mean true	0.415	0.359	0.359	0.359	0.359	0.359
	Mean est.	0.396	0.388	0.380	0.379	0.386	0.388
	RMSE	0.100	0.095	0.092	0.068	0.093	0.095
$N_{95,2}/N_{68,2}$	Mean true	0.520	0.413	0.413	0.413	0.413	0.413
	Mean est.	0.473	0.452	0.428	0.431	0.450	0.452
	RMSE	0.231	0.188	0.170	0.118	0.186	0.188
$\overline{M}$	Mean true	0.060	0.079	0.079	0.079	0.079	0.079
	Mean est.	0.062	0.063	0.063	0.065	0.063	0.063
	RMSE	0.015	0.022	0.022	0.017	0.022	0.022
N_y incr. rate 80-95	Mean true	-0.015	-0.016	-0.016	-0.016	-0.016	-0.016
	Mean est.	-0.017	-0.016	-0.016	-0.018	-0.017	-0.016
	RMSE	0.016	0.015	0.016	0.009	0.015	0.015

(ii) allows $\hat{S}_2^s \le \hat{S}_5^s \le \hat{S}_8^s \le 1$ and $\hat{S}_{17}^c \le \hat{S}_{20}^c \le \hat{S}_{23}^c \le 1$, compared to the base-case estimator's assumptions that $\hat{S}_2^s = \hat{S}_5^s \le \hat{S}_8^s = 1$ and $\hat{S}_{17}^c = \hat{S}_{20}^c \le \hat{S}_{23}^c = 1$;

(iii) to avoid a large fraction of replicates with $\hat{S}_{23}^c = 1$ forced by the constraint boundary, rejects pseudo datasets for which this occurs and regenerates data to provide 100 sets for which $\hat{S}_{23}^c$ is strictly less than or equal to 1.

The base-case estimator was then applied to the actual catch-at-age and abundance data for Area IV (see Tables 1 and 3), together with future data for each replicate dataset generated in the manner outlined below.

(i) JARPA abundance estimates with expectation given by the true total abundance in the year concerned multiplied by the estimate of q for the bootstrap replicate in question, and lognormal error of CV = 0.2 (the average of the values attained in the previous JARPA SSV surveys in Area IV - see Table 3 - so that as for the base-case estimator, the assumption is made that $CV_{add} = 0$), for the seasons 1997/98, 1999/2000, 2001/02 and 2003/04 (i.e. until the end of the research programme as currently envisaged)[8,25].

(ii) A total of 330 whales are taken in each of these four seasons, of which 86% (the average for the previous scientific take) is aged and provides an age distribution generated from a multinomial distribution whose probabilities are proportional to the true numbers-at-age multiplied by the estimated scientific selectivity-at-age ($\hat{S}_a^s$) pattern for that replicate[26].

Finally, some assumption is needed concerning recruitment to enter the population in the future. Similarly to procedures followed in Butterworth *et al.* (1989; 1992), this is assumed to have expectation and variability as reflected by recent past values, so that for each replicate:

$$N_{y,2}^{true} = \gamma e^{w} \qquad w \text{ from } N(0;\sigma_w^2) \tag{22}$$

where $$\gamma = \left\{\prod_{y=77}^{95} \hat{N}_{y,2}\right\}^{1/7}$$

$$\sigma_w^2 = \frac{1}{6}\sum_{y=77}^{95}[\ell n\, \hat{N}_{y,2} - \ell n\, \gamma]^2$$

In addition to this 'base-case' test, a number of variants are also considered to examine sensitivity. These comprise:

(i) use of the base-case estimator, rather than the more complex variant above, to provide the operating model, so as to examine the estimator's capabilities under 'optimal' conditions;

[25] Given lack of clarity about the Areas to be surveyed in future IWC cruises, results from such have not been taken into account.

[26] Account is not taken in this process for over-dispersion because there is no evidence for over-dispersion for Area IV. The impact of ageing error is also ignored here because the results in Table 9 indicate it to be insubstantial.

(ii) doubling the level of scientific take for the four future seasons in question, to ascertain the extent to which this might improve estimation performance;
(iii) continuing the programme for a further 9 years (i.e. up to a 2013/14 take and survey in Area IV) to ascertain the consequences for estimation precision;
(iv) amending the base-case estimator to one which attempts estimation of a linear trend of M with age a, to ascertain the trade-off between the consequent lesser bias, but likely greater variance from estimation of an additional parameter; and
(v) amending the base-case estimator to one which attempts estimation of a commercial selectivity slope which is non-negative.

Results and discussion

Results of the calculations detailed above are reported in Table 12 for the subset of five key statistics identified earlier. They are shown as the mean of the 100 'true' (operating model) values, the mean of the corresponding 100 estimates provided by the estimator and the root mean square error (RMSE):

$$\sqrt{\frac{1}{100}\sum_{r=1}^{100}\left(x_r^{est}-x_r^{true}\right)^2} \qquad (23)$$

where x_r^{est} and x_r^{true} are respectively the estimated and true values of quantity x for bootstrap replicate r. Furthermore, scatter plots showing (x_r^{true}, x_r^{est}) data pairs for two of the key statistics - the historic recruitment ($N_{y,2}$) rate of increase over the 1947-68 period and the age-averaged natural mortality $\overline{M}$ (see Equation (21)) - are shown in Figs 8 and 9.

It is convenient to commence comment on the results with reference to the 'optimal' case where the operating model corresponds to the base-case estimator (the 'Simple' operating model of Table 12). The scatter plots (Figs 8 and 9) do indicate some tendency towards positive bias at smaller, and negative bias at larger, true values for the two statistics to which these plots correspond. Such behaviour is not surprising because, in the absence of any future data, the estimates are equal to those given by the base-case estimator (dotted lines in Figs 8 and 9) so that the impact of future data is generally to 'move' an estimate from its current value towards the true value (assuming that the estimator is unbiased). The RMSEs for these two statistics (the historic recruitment trend and $\overline{M}$) are 1.4% and 1.5% (yr^{-1}), compared to values now (i.e. without the future four JARPA cruises in Area IV) of 2.3% and 2.5% respectively.

For the base-case operating model, the estimates of the historic recruitment trend and $\overline{M}$ are negatively biased (by 1.4% and 1.6% (yr^{-1}) respectively). The RMSEs for these two statistics are 2.4% and 2.2% (yr^{-1}) respectively. Compared to current values for these RMSEs, these estimates for 2003/4 reflect effectively no improvement for the historic recruitment trend, but an improvement in performance for $\overline{M}$ of 0.2%.

The sensitivity tests reported in Table 12 indicate little improvement in estimation performance for four of the five statistics if catches for the next four JARPA programmes in Area IV are doubled. Attempts to estimate a linear trend of natural mortality M with age a or the slope in selectivity with age for the period of commercial catches bring effectively no benefits in RMSE terms. The reason for this latter result is that the selectivity slope is determined essentially by the historic commercial catch-at-age data, which naturally remain invariant whatever future data are generated for the

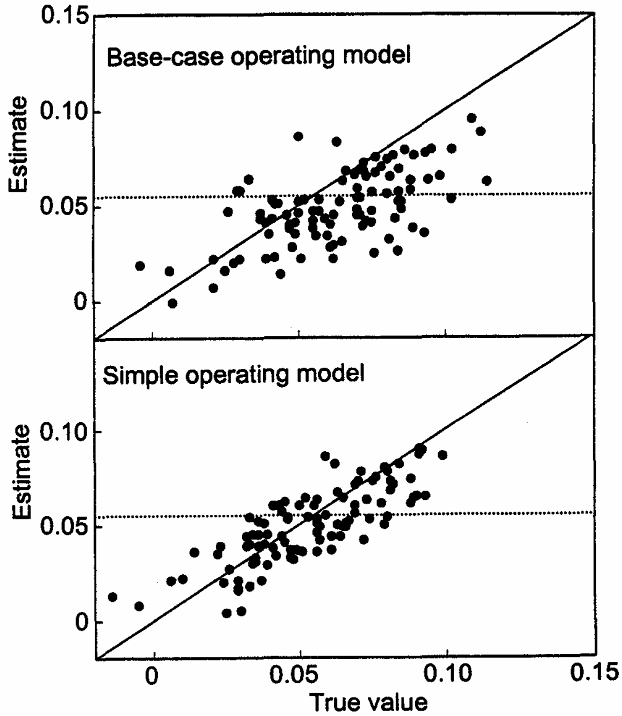

Fig. 8. A scatter plot of estimates of the historic recruitment ($N_{y,2}$) rate of increase over the 1947-68 period for Area IV provided by the base-case estimator against the corresponding true values for data sets generated by an operating model. Results are shown for the base-case operating model in the upper panel, and for the 'simple' operating model (corresponding to the base-case estimator) in the lower panel. The solid line reflects estimate = true, while the dotted lines indicate the estimate in the absence of future catch-at-age data and JARPA abundance estimates.

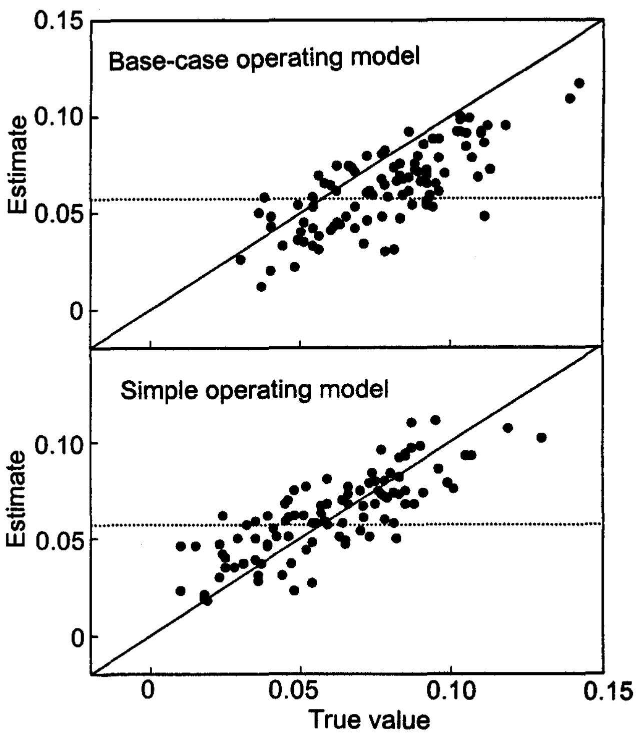

Fig. 9. Scatter plots as in Fig. 8, but here for the age-averaged natural mortality $\overline{M}$.

simulations; results for this option in Table 12 are identical to those for the base-case estimator because the best estimate of the selectivity slope β (subject here to a non-negative constraint) is $\hat{\beta} = 0$ (see Table 7) as assumed for the base-case estimator. Where distinct improvements are to be found is in continuing the programme for a longer period, which yields marked improvements in the RMSE for total population trend and recent relative recruitment level estimates, and also improves M estimation.

The reasons for the differing extents of improvement in the estimates of the historic recruitment trend and $\overline{M}$ relate to the interactions between the influences of historic commercial catch-at-age data, assumptions about the slope (β) of the commercial selectivity-at-age at older ages, and future information on abundance and catch-at-age from the JARPA programme. If the assumption of the base-case estimator that $S^c_{23} = S^c_{26} = 1$ (i.e. that the commercial selectivity-at-age was flat ($\beta = 0$) at older ages) is correct, then future data from JARPA will secure a continuing decrease over time in the RMSE's for both the historic recruitment trend and $\overline{M}$ estimates. However, if the possibility that $S^c_{26} < 1$ is admitted, the only data which have a bearing on the estimate of (the commercial catches-at-age for older ages) have already been collected. Although when S^c_{26} is treated as an estimable parameter subject to the constraint $S^c_{26} \leq 1$, these data provide a best estimate of $S^c_{26} = 1$, alternative possibilities with $S^c_{26} < 1$ are not excluded, and these alternatives cannot be resolved by the future data to be collected in the JARPA programme. These alternative possibilities also introduce negative bias into the estimate of the historic recruitment trend provided by the base-case estimator. The contribution of this bias to the RMSE will not decrease over time because future data do not address it, so that the extent to which this RMSE can drop given future JARPA data is limited. In contrast, the estimate of $\overline{M}$ depends 'equally' on data throughout the period under analysis. Thus although the base-case $\overline{M}$ estimate becomes negatively biased given the possibility that $S^c_{26} < 1$, the size of this bias (as well as the associated estimation variance and hence the RMSE) will continue to decrease over time as more JARPA data become available.

CONCLUDING REMARKS

The introduction referenced the major debate that commenced some 20 years ago concerning interpretation of the catch curve for Southern Hemisphere minke whales: whether the large negative slope at higher ages reflected a population increasing prior to exploitation, or rather simply a large natural mortality (or decreased selectivity) for those ages. The additional data provided by the JARPA programme would appear now to have contributed to resolution of this issue. The base-case estimator for Area IV indicates an upward trend in minke whale recruitment prior to the onset of exploitation (the 1947-68 period) of 5.5% per annum, with a 90% confidence interval of [1.4%; 9.1%]. This estimate is sensitive to assumptions about the slope of the commercial selectivity-at-age for large age and to trends in the natural mortality rate over time. However, arguments based upon the distributional pattern by age of the whales and the operational pattern of the commercial whaling fleet suggest that this slope would not be negative, and hence that the recruitment trend estimate quoted above is negatively biased. Even if this commercial selectivity did decrease as a result of preferentially older animals being unavailable in the pack-ice, the selectivity for the scientific catch would decrease similarly, with the result that the conclusion concerning the historic recruitment trend is unaffected. Furthermore, if this commercial selectivity slope is estimated from the data without the constraint that it cannot be negative, the 90% confidence interval for the recruitment trend estimate remains entirely positive. (This result requires effectively only the weak assumption of separability in expectation of the commercial fishing mortality for ages from 17 to 29.) Similarly, the most likely reason for the natural mortality to change with time - density dependence - would also introduce negative bias into this recruitment trend estimate. Analysis of the Area V data provides a higher point estimate for this recruitment trend, but with poorer precision that does not exclude the possibility of negative values, though combining data for Areas IV and V again produces a statistically significant positive historic trend estimate. Note that not all the available IWC abundance data have been included in these computations - incorporation of such extra data would improve estimation precision.

Resolution of the issue of whether and at what rate Southern Hemisphere minke whales may have increased prior to exploitation is of management importance for two reasons. First, the rate of increase relates to the matter of a range of plausible values for MSY rate (*MSYR*)[27] for minke whales which is a key input to Revised Management Procedure *Implementation Simulation Trials* (IWC, 1993; 1994; 1995b), but one for which there is currently little definitive evidence. Secondly, whether or not the earlier heavy depletion of the large baleen whales (e.g. blue whales) in the Southern Hemisphere by excessive catches may have resulted in a biological interaction response in the form of an increase in the then unexploited minke whales is of importance in interpreting future data and formulating management goals for the Southern Ocean ecosystem overall.

For Area IV, the present estimate of (age independent) M from the assessment is 5.7%yr^{-1}. By the planned end of the current JARPA programme, the RMSE of this estimate should be reduced from 2.5% at present to 2.2% - where both these values are to quite some extent reflective of negative bias arising from possible positive slope in the commercial selectivity-at-age (S^c_a) at older ages which the base-case estimator assumes to be zero. Data for Area V suggest a lower value for M, but the results are less precise than for Area IV. Combining data for the two Areas yields an estimate for M of 3.0%yr^{-1}. Given the data available, there is effectively no advantage for estimating population trend statistics in attempting to estimate trends in M with age, rather than assuming M to be age-invariant (even if it does depend on age in reality).

A notable feature of the base-case assessment results, particularly for Area IV and to a lesser extent for Areas IV and V combined (see Figs 2, 6 and 7), is the marked drop in recruitment indicated over the period from 1970 to the mid-1980s (the higher the value of M, the larger this drop). This drop does not constitute any cause for concern about the population: for example, given the base-case assessment for Area IV, and the current population size of some 57,000 animals, the recruitment ($N_{y,2}$) needed for a stable population is about 9,000, which is similar to the lower recruitment levels experienced since the drop (see Table 5a). The size of this drop in recruitment may also in part reflect the use of negatively biased estimates of absolute abundance from the

[27] *MSYR* is the ratio of *MSY* to *MSYL*, the last being the population size at which *MSY* is achieved.

IWC surveys (see Table 8), but even so some further explanation for this feature needs to be sought. Some possibilities are:

(i) super-compensation (a drop in the absolute recruitment level - see Holt, 1985; Butterworth and Best, 1990) as the population approached its new larger (e.g. following depletion of 'competitors') carrying capacity;

(ii) increased competition from those 'competitors' as they recover following protection from harvesting;

(iii) poorer environmental conditions for reproductive success (in which case, one would seek independent corroborative evidence); and

(iv) violation of certain assumptions underlying the estimator.

Possibilities (i) and (ii) are investigated further in Butterworth and Punt (1999). One possibility in regard to (iv) is that the Areas for which the assessments are conducted may not encompass (as near as makes no odds) closed populations, and further that there have been systematic temporal trends across Areas in the migration of certain age groups over the period analysed. Insofar as this may have happened between Areas IV and V, the difficulty is resolved by assessing the two Areas combined. However, this does introduce a further technical complication, as bias can be introduced on combining random samples of differing age-distributions from two Areas, if the associated sampling proportions differ because of the different sizes of the populations in these Areas. Further investigations might address the matter of adjusting the estimation process to correct for this effect.

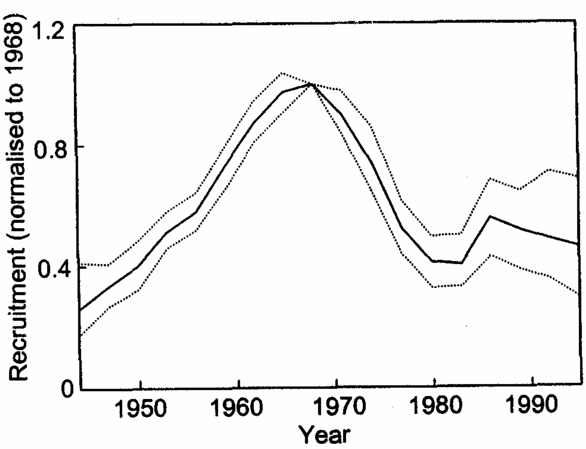

Fig. 10. Bootstrap estimates of medians (solid line), and 5%- and 95%-iles (dotted lines), for recruitment $N_{y,2}$ (relative to its estimated 1968 level for the corresponding bootstrap replicate) for Area IV for the base-case estimator when M is fixed at its corresponding best estimate of $0.057yr^{-1}$. Whereas the confidence intervals in Fig. 5 reflect sampling variability in both survey abundance estimates (and hence particularly uncertainty in the estimate of M) and the catch-at-age data, the intervals for this plot reflect only the latter source of variability.

Even if the low precision of the abundance estimates leads (for the moment) to relatively poor precision in estimates of M, and hence still to relatively large confidence intervals in overall recruitment trend estimation, what is clear from these analyses is that the availability of catch-at-age data allows good estimation of patterns of inter-annual changes in recruitment. This is suggested by Figs 1 and 2, and more clearly demonstrated by Fig. 10. This last Figure shows confidence intervals for relative recruitments for Area IV as estimated by the base-case estimator, but conditional on that estimator's best estimate of an age-independent value of M = 0.057yr-l. Note that these intervals are relatively narrow, and in particular much reduced compared to those in Fig. 5 which also incorporate uncertainty in the estimate of M. The availability of catch-at-age data for this population thus allows for the provision of a much finer probe for the investigation of possible links of environmental factors to minke whale reproductive success (and hence population 'health') than would survey estimates of total abundance alone.

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Appendix

SPECIFICATION OF THE CATCH-AT -AGE MATRICES

The catch-at-age matrix for Area IV used in this paper is obtained by pooling the annual sex-specific catch-at-age matrices and then combining the results into combination ages and combination years.

The catches-at-age by sex are computed differently for the periods of commercial and scientific catches because a much greater fraction (86% compared to 32%, on average) of the scientific catch is aged. The annual catch-at-age vector for each sex for the scientific catch is obtained by scaling the sex-specific age-frequency obtained from aged animals upwards to the total catch by sex, i.e.:

$$C^m_{y,a} = C^m_y \, C^{m*}_{y,a} \Big/ \sum_{a'} C^{m*}_{y,a'}$$
$$C^f_{y,a} = C^f_y \, C^{f*}_{y,a} \Big/ \sum_{a'} C^{f*}_{y,a'} \qquad \text{(A.1)}$$

where: $C^{m/f}_{y,a}$ is the estimated catch of males / females of age a during year y,

where: $C^{m/f*}_{y,a}$ is the number of males / females caught during year y and assigned to be age a, and

where: $C^{m/f}_y$ is the total catch of males / females during year y.

The single animal in the 1989/90 Area IV catch which was not sexed is allocated *pro rata* between males and females. The small sample size for the scientific catch makes the application of more complicated methods such as that used for the commercial catches of little benefit.

The catches-at-age by sex for the period of commercial catch are obtained by applying annual sex-specific age-length keys constructed from the subset of the catches aged by Japanese scientists to the sex-specific length-frequencies for Japan and the (former) USSR:

$$C^m_{y,a} = \sum_l A^{m,l}_{y,a} \, C^{m,l}_y$$
$$C^f_{y,a} = \sum_l A^{f,l}_{y,a} \, C^{f,l}_y \qquad \text{(A.2)}$$

where: $C^{m/f,l}_y$ is the catch during year y of males/females in (1m) length-class l, and

$A^{m/f,l}_{y,a}$ is the probability that a male/female in length-class l caught during year y is of age a (i.e. the relative frequency of males/females of age a in the column of the age-length key for year y for length-class l), as determined by ageing by Japanese scientists.

The age-length keys do not include data for all length-classes. This is generally not a major concern for the analyses of this paper, but there are some instances where animals in those length-classes were caught. To overcome this problem, the age-frequency for the 'nearest' length-class is used when applying Equation (A.2). The 'nearest' length-class is selected by examining whether data are available for any of the adjacent length-classes (starting with greater length) and examining length-classes further from the length-class for which age-frequency information is needed until a length-class for which data are available is found. The seven unsexed animals in the Area IV commercial catch are allocated *pro rata* between males and females.

The same overall approach is applied to provide the catch-at-age matrix used for Area V.