A summary history of the application of statistical catch-at-age analysis (SCAA) to Antarctic minke whales

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ABSTRACT

Various forms of SCAA methods have been applied to data for Antarctic minke whales since this method was first presented to the Scientific Committee of the International Whaling Commission by Punt and Polacheck (2005). A brief overview is provided of the historical use of methods which use catch-at-age data to draw inferences regarding trends in abundance for Antarctic minke whales. The original version of the SCAA and how this method has been modified over time to more adequately mimic the available data on length, conditional age-at-length and indices of abundance from IDCR/SOWER and JARPA/JARPAII is described. The paper also lists the specifications for the reference case analyses in each paper presented to the Scientific Committee. The focus is on methodology, with only limited comment on the results from each subsequent analysis.

KEYWORDS: CATCH-AT-AGE; ANTARCTIC MINKE WHALE; POPULATION MODEL; SOUTHERN HEMISPHERE

INTRODUCTION

Several catch-at-age methods have been applied to data for Antarctic minke whales. The range of questions which have motivated the analyses using these methods have increased over time in response to the needs and priorities of the International Whaling Commission (IWC) and its Scientific Committee. This paper reviews the application of catch-at-age methods to data for Antarctic minke whales. The first section provides some of the early history, including how catch curve methods, and subsequently virtual population analysis (VPA)-based approaches, were applied. However, the focus of the paper is on the statistical catch-at-age (SCAA) method which has been presented to the Scientific Committee since 2005. The purpose is to outline how this method has been developed in response to input from the Scientific Committee, and to summarise the current state of the method and the key issues which need to be addressed. Table 1 provides a summary of the main topics which have been discussed by the Scientific Committee in regard to the SCAA for Antarctic minke whales.

THE PRE-SCAA YEARS

Debates over the reliability of inferences that might be drawn from catch-at-age information for Antarctic minke whales have a long history in the IWC Scientific Committee. In the early 1980s, the Committee's recommendations on catch limits for minke whales followed from its acceptance that Antarctic minke whales had been increasing, prior to being exploited to a substantial extent. This increase was postulated to be a response to the substantial exploitation of other baleen whale species and hence to the creation of a 'krill surplus' (IWC, 1980). The evidence that points towards these conclusions (until these came under question in 1983; IWC, 1984a), involves estimates of the slope of the descending limb of minke whale catch curves (Ohsumi, 1979). Catch limit recommendations in that period (e.g. IWC, 1983; 1984b; 1985) were based on estimates of replacement yield (RY), where the catch levels were intended to stabilise the increasing populations[1]. The methods used to estimate RY in turn depended critically on the catch-at-age data and the value of natural mortality, M, and included taking the difference between the catch curve slope (Z) and M, and later the multi-cohort method (Sakuramoto and Tanaka, 1985; 1986). However, reservations (e.g. Chapman, 1983; Cooke, 1985; de la Mare, 1985a; 1985b) that came to be expressed over that period concerning the reliability of the resultant estimates included concerns of confounding, with the possibility that M increased at larger ages and also that an age-independent value for M was not well determined (note the sensitivity of population trend estimates to the value of M as illustrated in Fig. 1). As the justification for these reservations came to be more widely appreciated, by the mid-1980s the Scientific Committee found itself in the position of being unable to reach consensus on catch limit recommendations for Antarctic minke whales.

The Japanese Whale Research Programme under Special Permit in the Antarctic (JARPA) stated that its primary objective was to estimate the age-specific natural mortality coefficient for minke whales in response to this situation (Government of Japan, 1987), although this was later changed to estimation of average (over age) natural mortality (Government of Japan, 1992). This objective was planned to be achieved by obtaining representative samples of the age structure of the population through random sampling, combined with systematic sighting surveys. However, several members of the Scientific Committee (e.g. de la Mare, 1990) argued that JARPA would not provide estimates of natural mortality with sufficient precision to determine the historical recruitment trend and refine sustainable yield predictions even if catch-at-age data in addition to survey estimates of abundance were available with a CV of 0.15 for 30 years. Butterworth and Punt (1990) showed that future catch-at-age data from JARPA could, in principle, resolve

[1]The IWC's 'New Management Procedure' was not designed to address cases where a population was increasing above its unexploited population size, e.g. Allen (1980).

Table 1

Major issues considered during the development of the SCAA and their current status.

Issue	Current status
Model structure	
Stock structure	Stock I (Indian) is found in Areas III–E, IV and V–W; Stock P (Pacific) is found in Areas V–E and VI–W.
Can the model fit the Japanese length-at-age data	• Allowing for time-varying growth and selection addressed most of the bias. • Diagnostics reported by Punt *et al*. (2014) suggest adequate fits. • The time-trajectory of the growth rate parameter κ may be biologically unrealistic.
How does *M* change with age	• Changes piecewise linearly at ages 3, 10, 30, 35. • Sensitivity is explored to a Siler function in Punt *et al*. (2014).
How does carrying capacity change with year	• Changes as an autoregressive function of time.
Vulnerability	(1) JARPA/JARPA II: Logistic function of length. (2) Japan commercial: Dome-shaped function of length, with the length of maximum selectivity time-varying. (3) Soviet Union commercial: As for Japan commercial.
Extent of process error	Results are generally insensitive to the values for the parameters which determine variation in selectivity, recruitment, growth and spatial distribution.
Calves can exceed mature females	Resolved by adding a penalty term and re-parameterizing how recruitment is modelled.
Likelihood function	
Indexes	
IDCR/SOWER indices agreed	Punt *et al*. (2014) used the estimates by Okamura and Kitakado (2012).
Use of JARPA indices	Punt *et al*. (2014) used the estimates in Hakamada *et al*. (2013).
Why are the results insensitive to ignoring the JARPA indices	Still be to be resolved: Punt *et al.* (2014) found the results from the SCAA were sensitive to ignoring the JARPA age and length-composition data, but not the JARPA abundance indices.
Composition data	
How should the composition data be included in the assessment	• The Soviet Union length data have been dropped from the assessment owing to concerns about misreporting. • The Japanese data (both commercial and JARPA data) are included in the assessment as length-frequency data and conditional age-at-length data.
Inclusion of age-reading error matrix	The most recent estimates of age-reading error matrices as developed by Kitakado *et al.* (2013) are included in the latest version of the SCAA.
Data weighting	
Abundance index data	No additional variance assumed; 'process error' accounted for by allowing the proportion of each stock in each area to vary over time.
Compositional data	• Selected using the method of McAllister and Ianelli (1997). • Results are generally insensitive to how the data are weighted (e.g. Punt *et al*., 2014).
Quantification of uncertainty	
Sensitivity analyses	All assessments have reported results in which assumptions have been changed.
Variance estimation	Asymptotic variances are computed for all model outputs; attempts to apply MCMC have not been successful given the complexity of the model (i.e. the time to compute a single evaluation of the likelihood function).
Simulation testing	Limited simulation testing has been undertaken – a full evaluation of the method would require very considerable computing resources.

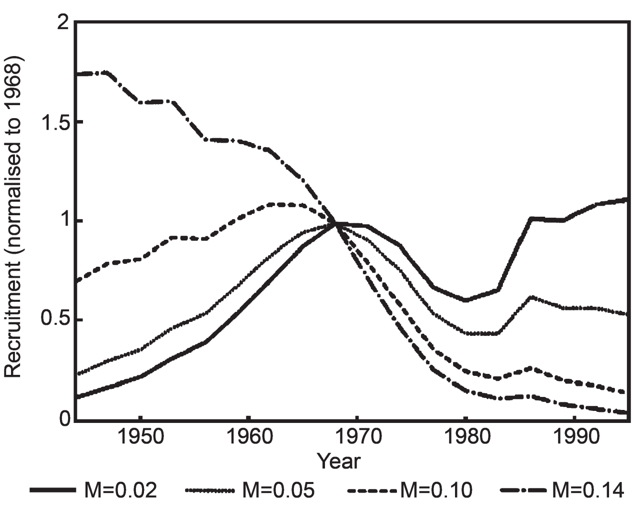

Fig. 1. Estimates from ADAPT-VPA of time-trajectories of age-2 abundance for minke whales in Antarctic Area IV for fixed values for age-independent natural mortality, *M* = 0.0,5 0.05, 0.10, and 0.14yr^{-1}. Each series is normalised to its 1968 level (reproduced from Butterworth *et al*., 1999).

whether or not abundance was increasing historically given temporal invariance of selectivity-at-age above a certain age and knowledge of natural mortality-at-age. However, they also showed that a simple VPA-like method was unable to discriminate an annual rate of increase of 4% from zero even after 25 years of data. Bergh *et al.* (1991a; 1991b) refined the VPA method, which improved the precision of the estimates of the rate of increase.

Butterworth *et al.* (1996) introduced the use of ADAPT-VPA (Gavaris, 1988) to the Scientific Committee. This method, in common with other VPA-like procedures, assumes that the catches-at-age are measured with negligible error compared to other model inputs such as survey estimates of abundance. Unlike most fishery assessments, the ADAPT-VPA developed by Butterworth *et al.* (1996) was based on grouping and analysing the catch-at-age data on a 3-age-3-year basis to overcome small sample size problems for the statistical distribution underlying the estimator used at that stage. This variant of ADAPT-VPA, however, performed poorly in terms of retrospective analyses (Butterworth and

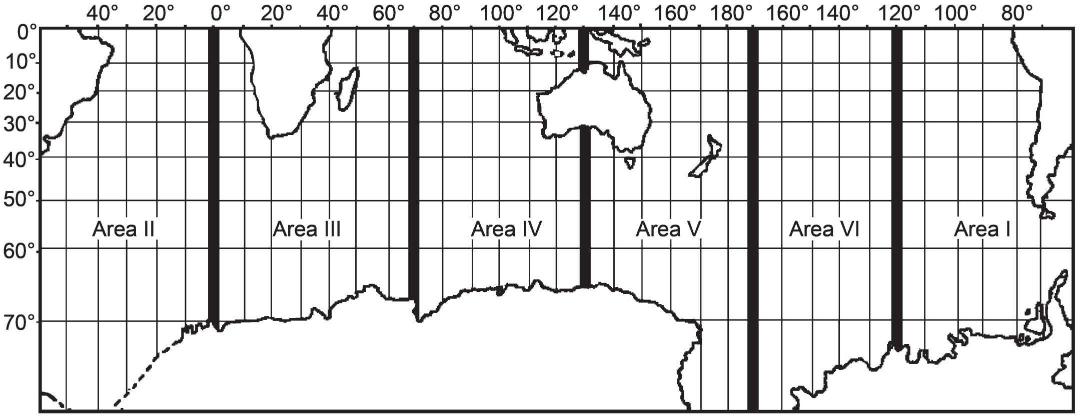

Fig. 2. Map of the Southern Hemisphere showing the locations of the areas referred to in this paper.

Punt, 1996). Butterworth *et al.* (1999) extended the ADAPT-VPA framework by making the separability assumption for the commercial (catches of Antarctic minke whales were taken by Japan and the USSR in the Antarctic and by Brazil and South Africa to the north, prior to the ban on commercial whaling that came into force in 1986) as well as JARPA catches and by taking JARPA as well as IDCR/SOWER estimates of abundance into account for parameter estimation purposes. Butterworth *et al.* (1999) estimated the precision of the results from the ADAPT-VPA using a bootstrap procedure and evaluated the performance of the method using simulations with a focus upon IWC Management Areas IV and V (see Donovan, 1991 and Fig. 2). They estimated a historical rate of increase for Area IV (Fig. 2) of $0.055yr^{-1}$ (90% CI 0.014–0.091) over the period 1947–68 (Fig. 3). The estimate of the rate of increase for Area V was positive, but less precise. Age-independent natural mortality for Area IV was estimated to be $0.057y^{-1}$. A notable feature of the Area IV assessment in Butterworth *et al.* (1999), which was confirmed by further analyses by Butterworth *et al.* (2002) and all subsequent analyses, was the marked drop in recruitment from 1970 to the mid-1980s (Fig. 3)[2].

Butterworth *et al.* (1999) identified several hypotheses for the decline in recruitment including 'super-compensation', increased competition from other krill predators, poor environmental conditions and bias in the estimation method. IWC (2002; 2003) identified further hypotheses which could address the reasons for the decline, expressing these in terms of the change in abundance estimates from CPII and CPIII, along with sources of information and analysis methods. IWC (2005) noted that population modelling could provide a way to address the plausibility of the hypothesis that decline in recruitment is related to competition and other population dynamic-related factors. It considered that a SCAA modelling approach would provide the most appropriate way to address the population dynamics-related issues because a SCAA could allow *inter alia* for errors in catch-at-age data, more than a single stock, environmental covariates, fleet-specific vulnerabilities (IWC, 2005)[3] and changes over time in vulnerabilities to be addressed and explored within a single model framework. IWC (2005) noted that there were also other tasks which needed completion to address the issues:

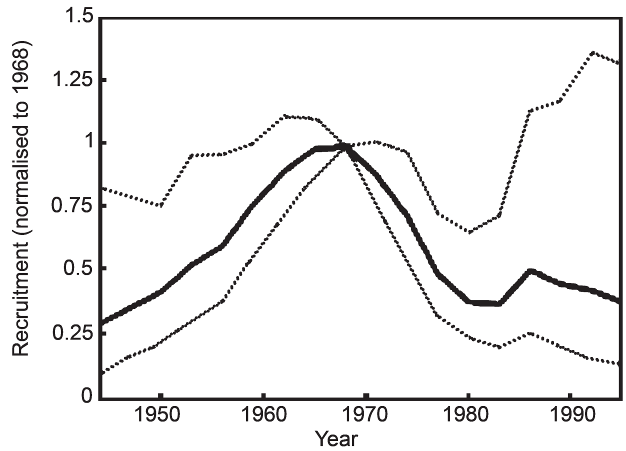

Fig. 3. Bootstrap estimates of medians (solid lines), and 5%- and 95%-iles (dotted lines), for recruitment at age-2 (relative to its estimated 1968 level) for Area IV for the ADAPT-VPA base-case estimator (reproduced from Butterworth *et al.*, 1999).

(1) development of a set of stock structure hypotheses for the animals found in Areas IV and V;

(2) compilation of time series of abundance estimates to use, including both from IDCR/SOWER and JARPA cruises, as well as estimates of variances and co-variances; and

(3) compilation of a set of relevant environmental covariates.

ENTER THE SCAA

Punt and Polacheck (2005) noted that there were several potential concerns with the ADAPT-VPA approach as implemented at that time that could be addressed within the context of SCAA as described below.

(1) The catch age-composition data are assumed to be known exactly when constructing the numbers-at-age matrix. This assumption may be invalid due to the impact of ageing error, sampling error associated with construction of age-length-keys, and because age-length keys[4] are available only for the Japanese fleets and need

[2]The wide confidence intervals in Fig. 3 are due in no small part of uncertainty in the estimate of M.

[3]Often also referred to as 'selectivities' by the Scientific Committee. Vulnerability combines the effect of age (or length) – specific selectivity by the whalers with the relative probability of whalers encountering a whale of a given age or length given the spatial and temporal distribution of the whaling effort.

[4]Also referred to as conditional age-at-length data.

to be applied to construct the age-composition of the Soviet catches.

(2) It is not possible to estimate the numbers-at-age for some of the oldest ages in the earliest years for which commercial age-composition data are available directly using back-projection. Butterworth *et al.* (1999) provided only an *ad hoc* means to specify these.

(3) One of the key objectives of these past assessments of minke whales in Areas IV and V was to estimate the Maximum Sustainable Yield Rate (*MSYR*), whether carrying capacity has changed (and in what way) and whether inter-annual variation in recruitment can be partly explained by environmental covariates. Butterworth and Punt (1999) addressed this issue by fitting the Baleen II model (de la Mare, 1989; Punt, 1999) to the estimates of recruitment from the ADAPT-VPA. While this approach was sufficient to enable estimates of *MSYR*, changes in carrying capacity, etc. to be obtained, Punt and Polacheck (2005) argued that this approach was questionable as it involved fitting a model to the output from another model rather than to raw (or appropriately summarised) data.

SCAA (Fournier and Archibald, 1982) involves developing a population dynamics model and fitting it by maximising an objective function (which under some circumstances can be interpreted as a likelihood function). Two key differences between the original ADAPT-VPA approach (for example, Butterworth *et al.*, 1999) and SCAA analysis are that the latter does not assume that the age-composition data are known exactly (although it often makes fairly strong assumptions regarding age- or length-specific vulnerability and how it changes over time) and can calculate numbers-at-age for years for which catch age-composition data are not available. Punt and Polacheck (2005) noted that this shows that it is possible to estimate numbers-at-age and *MSYR*/carrying capacity simultaneously[5].

The original SCAA method of Punt and Polacheck (2005) allowed for errors in the catch-at-age data, more than a single stock, environmental covariates on recruitment, fleet-specific vulnerabilities, age-specific natural mortality and changes over time in vulnerability. This method included two ways to include the catch-at-age data in the objective function minimised: (a) including the commercial age-composition data (by fleet: Japan/Soviet Union) as information on the age-structure of the commercial catches; and (b) including the age-length keys (available for the catches by Japan only) and the length-frequency information (available for both Japan and the Soviet Union) separately. The latter was preferred by Punt and Polacheck (2005) because it reflects the way the data were collected[6]. The catch data were assumed to be log-normally distributed, but with a CV small enough (0.05) that the model closely mimicked the observed data almost perfectly. The JARPA and IDCR/SOWER estimates of abundance were also assumed to be log-normally distributed. Two types of error associated with the catch-at-age data were considered: age-reading error (readings assumed to be correct on average, but with non-zero random ageing error) and sampling error. The extent of sampling error was related to the number of animals aged (adjusted by an overdispersion factor), but the parameters determining the age-reading error matrix were guesses in the absence of information to parameterise an age-reading error matrix for Antarctic minke whales. The lack of information on age-reading error was addressed following an age-reading experiment conducted under the auspices of the Scientific Committee in 2010 (see below).

The SCAA method of Punt and Polacheck (2005) allowed natural mortality to change in a piecewise linear manner with age and carrying capacity to change in a piecewise linear manner with the year. Vulnerability was allowed to be uniform over all ages (for JARPA)[7], logistic or dome-shaped. Time-dependence in vulnerability was modelled by allowing the length-at-50%-vulnerability to change from one year to the next when vulnerability was assumed to be governed by a logistic curve, i.e. the shape of the vulnerability curve was the same each year, but the length at which vulnerability reached 50% changed over time[8]. Growth was assumed to be governed by a time-invariant von Bertalanffy growth curve.

Punt and Polacheck (2005) noted that there were substantial differences between growth curves estimated within the assessment and those estimated externally to the assessment, which led them to conclude that 'there is clearly some inconsistency between the JARPA length-at-age data and the remaining data sources'. During discussion of this issue at the 2005 meeting of the Scientific Committee, Hatanaka commented that growth rate may have changed over time, as suggested by analyses by Kato (1987). Hatanaka also noted that the commercial catches were closer to the ice edge, which may have influenced relative vulnerability. Polacheck and Punt (2006) extended the SCAA to allow for time-varying growth and found that a large part of the apparent inconsistency between the lengths-at-age for the commercial and JARPA catches could be explained by changes over time in vulnerability and growth. However, Polacheck and Punt (2006) noted that the time-changes in growth and vulnerability may be artefacts because: (a) the model generally estimates that smaller animals were either similarly or more vulnerable during the period of the commercial catches than during JARPA; (b) a large change in growth rates is estimated to have occurred coincidentally with the change from commercial harvesting to JARPA; and (c) residual systematic lack of fit still existed.

The original version of the SCAA (in common with the original ADAPT-VPA analyses) was applied to data for Areas IV and V, treating the populations in those areas as separate

[5]Subsequent development of the ADAPT-VPA approach (e.g. Mori *et al*., 2007) estimated the stock-recruitment relationship, allowed for age-reading errors, allowed for time-varying proportions of the assessed stock in multiple areas, and considered the possibility of changes over time in the age-at-sexual-maturity.

[6]This is also a preferred way to include age-length key and length-frequency data in many fisheries assessments, particularly when the length-frequency includes sizes for which age data are not available.

[7]This assessment assumed that vulnerability was uniform across all ages; subsequent assessments estimated a specific vulnerability parameter for age 1 owing to poor fits to the abundance of age-1 animals in the JARPA samples when vulnerability was assumed to uniform. Sensitivity was also explored to assuming that the vulnerability for JARPA was logistic or dome-shaped.

[8]The length at maximum vulnerability was assumed to change over time when vulnerability was assumed to be dome-shaped.

stocks. Punt and Polacheck (2005) outlined how multiple stocks which mix could be modelled within the context of a SCAA. Punt and Polacheck (2006) developed a number of scenarios for the minke whales in Antarctic Areas III–E to VI–W in terms of number of stocks (one or two) and whether Area V–W was an area of mixing. Punt and Polacheck (2006) also extended the SCAA to include time-varying proportions of stocks in each spatial stratum considered in the analysis. This allowed the model to mimic the abundance estimates without the need to estimate an 'additional variance' parameter. Estimating an additional variance parameter postulates that the sampling CVs for the abundance estimates are too small so discrepancies between model predictions and data are due to additional error whose cause is not necessarily identified. In contrast, modelling time-varying proportions of the stocks spatially assumes that the sampling CVs are approximately correct, but that the proportion of each stock in each area changes over time. IWC (2007) noted that the SCAA method of Punt and Polacheck (2006) could lead to the number of calves produced approaching or exceeding the available number of sexually mature females. In response to this, later analyses included a penalty term to avoid this behaviour.

Punt and Polacheck (2007) further modified their reference case analysis by fitting the length-frequency and conditional age-at-length data for JARPA separately; previous analyses had fitted to the age-composition data for JARPA, obtained by multiplying the length-frequencies by the age-length keys. The change was made so that it was possible to estimate the extent to which the growth rate had changed over time. They provided the first SCAA-based estimates of $MSYR_{1+}$[9]. However, in common with subsequent attempts to estimate $MSYR_{1+}$, the estimates were sensitive to the assumptions on which the analysis was based, with some estimates of 0% (although those cases often corresponded to poor fits to the data and/or model runs in which it was not possible to obtain a positive definite Hessian matrix).

Some of the results in Punt and Polacheck (2007), such as the estimated rates of natural mortality for age-0 animals, were biologically unrealistic. IWC (2008) therefore recommended that consideration be given to estimating common values for some parameters for the W (Areas III–E, IV, and V–W) and E (Areas V–E and VI–W) stocks[10,11]. This is because by pooling the data across stocks, the estimates of some of these parameters would be less noisy and hence the model fitting process would be less likely to 'chase noise in the data'. Punt and Polacheck (2008) therefore conducted analyses in which some of the parameters of the model (those related to carrying capacity, resilience, growth and natural mortality) were assumed to be the same for the I- and P- stocks. This pooling was clearly supported by model selection methods, and subsequent analyses assumed that the age-specific pattern of natural mortality is the same for the I- and P-stocks, but that the average value for natural mortality differs between stocks. They found the results from the SCAA were sensitive to large (random) age-reading errors. They also tried to evaluate the precision of the estimates from the SCAA by applying a Markov chain Monte Carlo (MCMC) method to sample parameter vectors from the posterior distribution, but this algorithm failed to converge. In addition, they conducted some preliminary simulation tests.

IWC (2009) noted that the SCAA indicated that the JARPA abundance estimates were uninformative, particularly with respect to the variance associated with mortality rate estimates. It was suggested that the general lack of sensitivity to ignoring the JARPA abundance estimates may be due to some structural constraints of the model (i.e. the stock-recruitment relationship and/or the vulnerability functions). As such, within the then-current model structure, the JARPA abundance estimates might provide little additional information. IWC (2009) recommended that this be explored further. Punt (2009a) conducted additional sensitivity tests using the same reference model as Punt and Polacheck (2008). It was found that while the results were insensitive to ignoring the JARPA indices, the results were sensitive to ignoring the JARPA length-frequency and conditional age-at-length data. The issue of which data sources are informative regarding which model outputs remains a topic for analysis (see below).

IWC (2009) agreed that resolution of questions concerning ageing of Antarctic minke whales was the highest priority task for the catch-at-age modelling work at that time and proposed a workplan to address the issue. Punt (2009b) used simulations to assess the implications of different levels of ageing bias on the performance of the SCAA method of Punt and Polacheck (2008). Simulations based on deterministic data suggested that a 20% under-estimate of age in 1970 which changes linearly to zero in 1986 would lead to estimated time trajectories of historical increases in carrying capacity which match those from actual applications of the SCAA method when the true carrying capacity is time-invariant. Allowing for observation error made the results more variable. IWC (2010) noted that these results highlighted the need for 'appropriate' error models for use in the modelling.

An experiment to evaluate age-reading error was conducted during 2010 (Lockyer, 2010). This involved an experienced age-reader (Lockyer) reading 250 earplugs which were collected between 1974/75 and 2005/06 and using the resulting age-estimates to obtain estimates of ageing bias and random age-reading error for three of the readers who read earplugs during the period of commercial whaling as well as during JARPA[12]. This experiment essentially confirmed that the commercial ageing data were reliable (IWC, 2011). Kitakado and Punt (2010) applied the methods of Punt *et al.* (2008) to results from the experiment to develop age-reading error matrices for use in the SCAA. Punt (2010) included the new ageing error matrices in the SCAA, but there was evidence for non-convergence of the minimisation algorithm.

After exploring the reasons for the lack of convergence in Punt (2010), the SCAA was modified (Punt, 2011) by changing the mathematical form of the penalty that prevents

[9]The ratio of MSY to the number of animals aged 1+ and over when exploitation is uniform over ages 1 and older.

[10]See IWC (2007) for the rationale for this option for stocks.

[11]Thereafter referred to as the 'I' (Indian) and 'P' (Pacific) stocks.

[12]The analyses have subsequently been updated to include a fourth age-reader (Kitakado *et al.*, 2013).

the number of calves exceeding the number of mature animals and by assuming that the age-specific pattern of natural mortality is independent of stock (but the average value for natural mortality differs between stocks). The attempt to fit the length-composition data was dropped for the Soviet Union catches, given the information on possible misreporting of catch length distributions by the fleet (IWC, 2011). Rather than estimate vulnerability patterns for the Soviet Union fleet, the vulnerability patterns for the Soviet Union were assumed to be the same as those for Japan. Punt (2011) also explored whether the SCAA, along with its estimated vulnerability patterns, could account satisfactorily for the different length-at-age distributions for younger animals using diagnostics statistics from the r4ss package (Taylor *et al.*, 2014), and found the fits to be adequate.

Punt *et al.* (2013) provided revised SCAA results based on the recommendations from the 2012 Committee meeting (IWC, 2013). This version differs from the 2012 (and 2011) versions of the SCAA in terms of the assumed extent of over-dispersion, as well as the value of the assumed variance of the parameters that defines the proportion of stock, by area and year. It also used revised age-reading error matrices developed by Kitakado *et al.* (2013).

Punt (2014) provides the most recent version of the SCAA based on the recommendations from the 2013 Scientific Committee meeting (IWC, 2014). This assessment is based on the data in Table 2. Rather than forcing the changes in carrying capacity to follow a piecewise linear function, Punt (2014) modelled changes in carrying capacity as an autoregressive function of time and changed the ages at which natural mortality changes using the results of an analysis in which natural mortality was allowed to be an autoregressive function of age. Punt (2014) also revised the approach used to weight data sources by basing the weights for the length-frequency and conditional age-at-length data on the method of Francis (2011) rather than that of McAllister and Ianelli (1997) which will overweigh composition data when the residuals are not independent of year and age. The plus and minus groups for length and age were revised in Punt (2014).

REFERENCE ANALYSES AND SENSITIVITY TESTS

Table 3 lists the specifications for the reference case analyses and Table 4 lists the specifications of all of the sensitivity tests conducted since 2005. It is noteworthy that the early analyses included more sensitivity tests related to the shape of the vulnerability functions. However, recent assessments have not considered many sensitivity tests along these lines, perhaps because the assessment now includes a fairly complicated model for vulnerability, and the length data for the Soviet Union have been removed from the assessment (Table 1). Thus, the current reference case analysis includes many of the options considered as more complex variants of the earlier reference cases (such as that the JARPA selectivity function is a logistic function of length) as part of the reference case analysis.

SUMMARY AND GENERAL CONCLUSIONS

A variety of diagnostic statistics and plots have been developed to evaluate model fit. In general, the model has been able to mimic the estimates of absolute and relative abundance given the estimated changes in abundance, as well as inter-annual variation in the proportion of each stock in each area (for example, figs 5 and 6 of Punt, 2014). The confidence intervals for the abundance estimates have generally intersected the population trajectory, indicating that the extent of process error in the proportion of each stock in each area is sufficient to capture additional variance. The model has also been able to fit the length-frequency and conditional age-at-length data adequately (Punt *et al.*, 2013). One key reason for being able to fit the conditional age-at-length data is time-varying growth. The reasonableness of the inferred changes in growth rate was, however, questioned during the 2013 Annual Meeting of the Scientific Committee (IWC, 2014).

Virtually all of the applications of the SCAA have indicated that recruitment increased substantially between 1930 and 1960–70 and declined thereafter (Fig. 4). The estimated changes in recruitment mimic those inferred from carrying capacity, which is robustly estimated to have increased from 1930 and then declined (Fig. 4). However, the extent of increase and decline in carrying capacity is sensitive to the assumptions of the analysis (see Table 5 for a recent summary of the conclusions from the SCAA).

Natural mortality is estimated to increase with age after about age 30 (Fig. 4). The most recent applications of the SCAA have inferred that natural mortality for younger animals is higher than for older animals, but this has not always been an outcome of the SCAA (e.g. Punt and Polacheck, 2005).

The assumption that vulnerability was constant during the period of commercial harvesting is rejected based on the quality of the fit to the data. Similarly, the earlier SCAA

Table 2

Summary of the data used in the most recent applications of SCAA to data for Southern Hemisphere minke whales in Antarctic Areas III–E, IV, V–W, V–E and VI–W. The range of years denotes the years over which the data concerned are available. In general, the data types concerned are not available for all years in the range.

	Region				
	Area III–E	Area IV	Area V–W	Area V–E	Area VI–W
Catches	1953/54–2009/10	1955/56–2009/90	1955/56–2011/12	1955/56–2011/12	1953/54–2011/12
Length-frequency	1971/72–2009/10	1971/72–2009/10	1974/75–2011/12	1977/78–2011/12	1973/74–2011/12
Age-length keys	1971/72–2009/10	1971/72–2009/10	1974/75–2011/12	1977/78–2011/12	1973/74–2011/12
IDCR estimates	1987/88–1994/95	1988/89–1998/99	1985/86–2001/02	1985/86–2003/04	1990/91–1995/96
JARPA/JARPA II indices	1995/96–2007/08	1989/90–2007/08	1990/91–2008/09	1990/91–2008/09	1996/97–2008/09

Table 3

Summary of the specifications of the reference case SCAAs.

Feature	Assessment year 2005 Punt and Polacheck (2005)	2006 Punt and Polacheck (2006)	2007 Punt and Polacheck (2007)	2008/09 Punt and Polacheck (2008); Punt (2009)	2011/12 Punt *et al.* (2012)	2013 Punt *et al.* (2013)	2014 Punt *et al.* (2011)
Population dynamics assumptions							
Spatial strata	IV, V	III–E – VI–W	III–E – VI–W	III–E – VI–W	III–E – VI–W	III–E – VI–W	III–E – VI–W
Ages natural mortality changes	3, 10, 30, 35	3, 10, 30, 35	3, 10, 30, 35	3, 10, 30, 35	3, 10, 30, 35	3, 10, 30, 35	3, 10, 20, 40
Years carrying capacity changes	1960, 1980	1960, 1980	1960, 1980	1960, 1980	1960, 1980	1960, 1980	Autoregressive (σ_K=0.05)
Vulnerability							
JARPA	Uniform	Uniform	Uniform	Logistic	Logistic	Logistic	Logistic
Japan commercial catches	Logistic-length	Logistic-length	Logistic-length	Domed-length[1]	Domed-length[1]	Domed-length[1]	Domed-length[1]
Soviet commercial catches	Logistic-length	Logistic-length	Logistic-length	Domed-length[1]	As for Japan	As for Japan	As for Japan
Age-1 selectivity estimates	No	Yes	Yes	Yes	Yes	Yes	Yes
Likelihood function assumptions							
Plus-group for age data	45	45	45	45	45	45	45
Commercial length data minus and plus lengths	22ft, 32ft (F) 22ft, 31ft (M)	22ft, 32ft (F) 22ft, 31ft (M)	22ft, 32ft (F) 22ft, 31ft (M)	22ft, 32ft (F) 22ft, 31ft (M)	22ft, 32ft (F) 22ft, 31ft (M)	22ft, 32ft (F) 22ft, 31ft (M)	25ft, 32ft (F) 22ft, 31ft (M)
JARPA length data minus and plus lengths	N/A	N/A	17ft, 32ft (F) 17ft, 31ft (M)	17ft, 32ft (F) 17ft, 31ft (M)	17ft, 32ft (F) 17ft, 31ft (M)	17ft, 32ft (F) 17ft, 31ft (M)	25ft, 32ft (F) 17ft, 31ft (M)
Survey abundance indices							
IDCR/SOWER bias	None	None	None	None	None	None	None
JARPA bias	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimate
Additional variance	No	No	No	No	No	No	No
Age-reading error							
Bias	0	0	0	0	From	From	From
Standard error	0.1	0.1	0.1	0.1	Kitakado and Punt (2010)	Kitakado *et al.* (2013)	Kitakado *et al.* (2013)
Overdispersion parameters							
JARPA age data	0.5	0.65	N/A	N/A	N/A	N/A	N/A
Length data[2]	0.65	0.8	0.65	0.65	0.65	0.7	1 commercial 0.15 JARPA
Conditional age-at-length data	0.75	0.75	0.8	0.8	0.8	0.8	0.5 commercial 1 JARPA
Extent of variation in births, σ_c	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Extent of variation in vulnerability, σ_s	10	10	10	10	10	10	10
Extent of variation in the proportion of the population by area, σ_P	N/A	0.2	0.2	0.2	0.2	0.3	0.3
Extent of variation in growth rate, σ_k	N/A	0	0.1	0.1	0.1	0.1	0.02

[1]The length at which vulnerability is 50% is time-varying for logistic selectivity. [2]Commercial only before 2008; commercial and JARPA thereafter.

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Table 4a

Summary of the sensitivity tests conducted. 'RC' indicates that the factor concerned was part of the reference case analysis. The symbols used relate to those used in the actual assessments. For example '2,8,27,28' on the line 'Logistic for JARPA/JARPA II' means that sensitivity tests 2, 8, 27 and 28 in Punt and Polacheck (2005) made the assumption that selectivity for JARPA/JARPA II was logistic.

	Assessment year					
Factor	2005 Punt and Polacheck (2005)	2006 Punt and Polacheck (2006)	2007 Punt and Polacheck (2007)	2009 Punt (2009)	2013 Punt *et al.* (2009)	2014 Punt *et al.* (2011)
(a) Sensitivity tests related to the population dynamics model						
Length-specific vulnerability	–	–	–	–	–	–
Uniform for JARPA/JARPA II	RC	RC	RC	–	S3, S4	B1, B2
Logistic for JARPA/JARPA II	2,8, 27, 28	4	B[1]	RC	RC	RC
Dome-shaped for JARPA/JARPA II	3, 21, 23	–	C,D[1]	–	–	–
Separate logistic selectivity for JARPA and JARPA II	–	–	–	–	S10	B7
Time-varying logistic for JARPA	–	–	–	Yes	–	–
Logistic for Japan commercial catches	RC	RC	RC	–	–	–
Dome-shaped for Japan commercial catches	27,28	5	D	RC	RC	B8
Logistic for Soviet Union commercial catches	RC	RC	RC	–	–	–
Dome-shaped for Soviet Union commercial catches	27,28	5	D	RC	–	–
Extent to which selectivity is time-varying	17	–	–	–	D3, D4	B6, C1, C2
Time-varying logistic between 1988 and 1999	23	–	–	–	–	–
Age-specific vulnerability						
Uniform for JARPA/JARPA II	13	1	A	–	–	–
Logistic for JARPA/JARPA II	14	–	B[1]	–	S1	–
Dome-shaped for JARPA/JARPA II	25	–	C,D[1]	–	–	–
Logistic for Japan commercial catches	13,14,15.24	1	A	–	–	–
Dome-shaped for Japan commercial catches	25	–	B,C,D	–	S1	–
Logistic for Soviet Union commercial catches	13.14,15,24	1	A	–	–	–
Dome-shaped for Soviet Union commercial catches	25	–	B,C,D	–	–	–
Carrying capacity						
Changes piecewise	RC	–	–	–	–	–
Changes in 1960 and 1980; 1960, 1980 and 2002	29, 30	–	–	–	P7	–
Constant carrying capacity	4,8, 23, 24	–	–	–	P5, S4	A5, B1
Carrying capacity as auto-regressive function of time	5	–	–	–	P6	RC
Extent of variation in changes in carrying capacity		–	–	–	–	C3, C4
Growth curve (estimated within the assessment unless specified otherwise)						
Time-invariant von Bertalanffy with constant variance in LAA	BC	6	–	–	P3	A4
Flat topped time-invariant von Bertalanffy[2]	9	–	–	–	–	–
Growth parameters set based on auxiliary information	16, 21, 28	–	–	–	–	–
Constant CV for LAA	17	–	–	–	–	–
Extent of time-varying growth	–	–	–	–	D9, D10	C7, C8
Other						
Density-dependent natural mortality	–	–	Yes	–	–	–
Alternative density-dependence function	–	–	–	–	P1	–
Siler natural mortality	–	–	–	–	–	A1
Autoregressive natural mortality	–	–	–	–	–	A2
Natural mortality is the same for all stocks	–	–	–	–	P4	–

[1]Analyses were conducted with the length/age at modal selection pre-specified instead of being estimated. [2]Length assumed to be constant from age-20. [3]The random deviation about the stock-recruitment relationship is applied to the density-dependent component rather than to the expected number of calves.

analyses consistently found that the vulnerability pattern for the Japanese and Soviet Union commercial fleets were dome-shaped. However, the length data for the Soviet Union are no longer included in the analysis owing to concerns regarding misreporting of catches. The vulnerability pattern for JARPA was initially assumed to be uniform with respect to length or age, but model selection suggested that vulnerability increases with age/length at low values of these quantities, which has led to vulnerability for JARPA (and JARPA II) being assumed to be a logistic function of age/length, consistent with general understanding that the youngest minke whales do not all migrate to the Antarctic in the austral summer.

The results from the SCAA have consistently been found to be insensitive to the weights assigned to the data sources and even when the abundance indices from JARPA/JARPAII are ignored, although why this latter results occurs is the subject of ongoing research because *a priori* the results of the SCAA would be expected to depend on the use of these JARPA/JARPA II data. Punt (2014) found that changing the JAPRA/JARPAII indices so they exhibited a trend changed the results from the SCAA and concluded that the reason that the results of the SCAA are insensitive to ignoring the actual JARPA/JARPAII indices is because these indices are consistent with the other data included in the assessment.

Although the sensitivity of the results from the SCAA to changes to its assumptions has been explored thoroughly (Table 3), the ability to quantify 'estimation error' has remained somewhat elusive. Recent assessments have reported asymptotic variance estimates for key model outputs such as natural mortality as a function of age, as well as for the time-trajectories of 1+ abundance and recruitment (Fig. 4). However, attempts to use MCMC methods or bootstrapping to quantify estimation uncertainty have been

Table 4b

Factor	Assessment year 2005 Punt and Polacheck (2005)	2006 Punt and Polacheck (2006)	2008 Punt and Polacheck (2008)	2009 Punt (2009)	2011 Punt (2011)	2013 Punt *et al.* (2013)	2014 Punt *et al.* (2011)
(b) Sensitivity tests related to the likelihood function and data weighting							
JARPA/JARPA II abundance indices	–	–	–	–	–	–	–
JARPA/JARPA II indices ignored	12, 30	–	Yes	Yes	–	S7	Fig. 11
JARPA II indices ignored	–	–	–	–	–	D1	Fig. 11
Indices relate to 1+ abundance[1]	–	–	–	–	–	P8	–
JARPA/JARPA II indices are absolute	–	–	–	–	–	–	B3
IDCR/SOWER abundance indices	–	–	–	–	–	–	–
Not unbiased	10,11	–	Yes	–	–	S5, S6	B4, B5
Composition data	–	–	–	–	–	–	–
Robust likelihood for proportions[2]	6	–	–	–	–	–	–
Ignore JARPA age data	–	–	–	Yes	–	–	–
Ignore JARPA length data	–	–	–	Yes	–	–	–
Downweight early commercial LF data	7	–	–	–	–	S2	C17
No ageing error	26	–	–	–	–	D2	A6
Linear trends in bias	–	–	Yes	–	–	–	–
High rate of age-reading error	–	–	Yes	–	–	–	–
Bias and random error in age-reading	–	–	–	–	Yes	–	–
Ignore JARPA II composition data	–	–	–	–	–	D1	Fig. 11
Weight on the length-composition data	–	–	–	–	–	D11, D12	C11, C12, C15
Weight on the conditional age-at-length data	–	–	–	–	–	D13, D14	C13, C14, C15
Change length cut-off	–	–	–	–	–	–	C16
Spatial variation in the population distribution							
None	RC	–	–	–	–	P2	A3
Extent of variation in distribution	–	2, 3	–	–	–	D7, D8	C5, C6
Recruitment	–	–	–	–	–	–	–
Extent of temporal variation in recruitment changed	19,20	–	–	–	–	D5, D6	C9, C10

[1]And vulnerability is flat for ages 1+. [2]See Fournier *et al.* (1990) for details.

unsuccessful. This is partially attributable to the complexity of the model (>1,000 parameters, many of which relate to exploitation rates).

Overall, the SCAA has progressed to the point at which most, but not all, of the key issues have been addressed (Table 1). The application of SCAA to Antarctic minke whales is now as sophisticated (or more sophisticated) than applications of this general modelling framework for fisheries management (e.g. Methot and Wetzell, 2013). IWC (2014) evaluated the status of the SCAA (based on the results in Punt *et al.*, 2013). This evaluation highlighted that several of the outcomes of the SCAA were consistent and robust to changes to the assumptions of the analysis (such as that the populations increased prior to 1970 and declined thereafter). It also highlighted that estimates of MSYR were not robust to such changes. This is likely a result of lack of contrast in population size relative to carrying capacity (Punt, 2014). It is, however, not uncommon that estimation of the shape of the stock-recruitment relationship and hence MSYR is poor even when data on stock and recruitment are available which cover a range of levels of relative stock size (Conn *et al.*, 2010; Lee *et al.*, 2012). In addition, the CVs for the estimates of natural mortality seemed very low and that the estimated growth curves may not be reliable.

The amount of data available for Southern Hemisphere minke whales is amongst the most for any marine species. The assessments conducted of this species have been able to estimate trends and absolute population size but it remains impossible to estimate MSYR with much precision. The next steps in this work remain to better understand stock structure for Antarctic minke whales (and hence whether boundaries for the I and W stocks are indeed at the western ends of Areas III–E and IV–W and to allow for mixing of the I and W stocks perhaps using the results from analyses of genetic and non-genetic data (e.g. Kitakado *et al.*, 2014) as priors for the associated mixing parameters.

The assessments developed for Southern Hemisphere minke whales have advanced approaches for conducting stock assessments for marine species in several ways. In particular, the assessments were amongst the first to include multiple stocks within the same model to allow the values of parameters (such as those which determine how natural mortality changes with age) to be shared amongst stocks to improve precision, to include age-composition data in form of conditional age-at-length so that growth can be estimated within the assessment rather than being pre-specified, and to allow for age-reading error to differ among readers. The approaches used to evaluate whether the model is fitting the conditional age-at-length data are now routinely used for fish stock assessment through the most recent versions of r4ss package[13]. All of these features are now being included in assessments of data-rich fish stocks and could be included in assessments of whale stocks for which sufficient data are available.

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[13]See *https://github.com/r4ss/.*

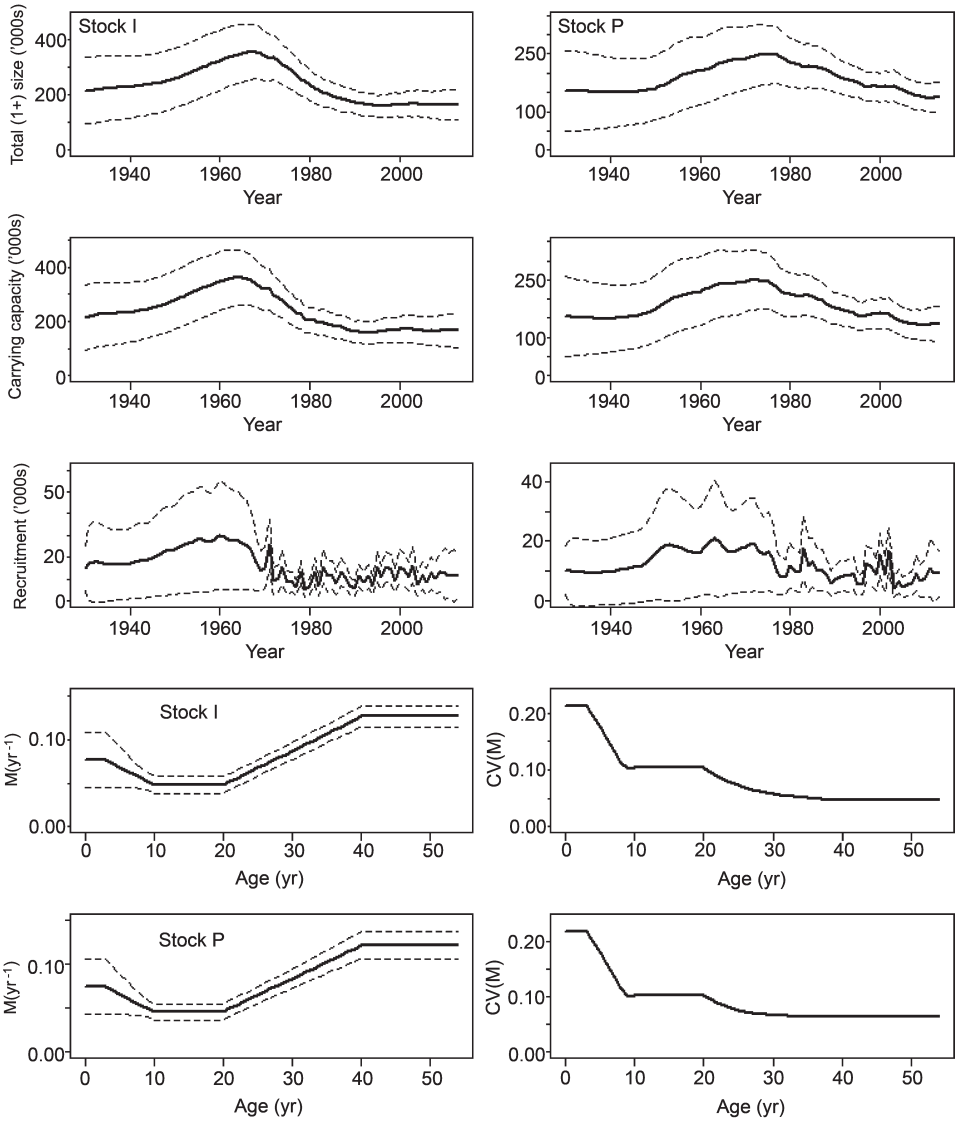

Fig. 4. Time-trajectories of total (1+) population size, carrying capacity, and recruitment (from 1930 and from 1975), and age-specific natural mortality by stock (estimates and CVs) for the reference case analysis of Punt *et al*. (2014). The dotted lines indicate 95% asymptotic confidence interval

Table 5

Reliability of conclusions from the SCAA as recorded in IWC (2014).

Model output	Conclusion
Historical trends in abundance	Relative trends generally consistent – modelled through changes in carrying capacity over about four decades, with abundance peaking in around 1970. The early and peak abundances are not quantitatively reliable. Recent abundance fitted to CPII and CPIII estimates
Extent of change from CPII to CPIII	Trends in abundance over the most recent 20 years are relatively flat. Differences can be explained as variability in distribution.
MSYR	Not robust.
M (natural mortality)	Weakly different by stock. CVs unrealistically low. Further investigation recommended.
Growth curves	Not reliable – a proxy for some unmodelled source of variation.
Stock identity	An input; variable spatial distribution used to account for variability in abundance estimates. Further exploration needed.
Errors in age-determination	Important to take into account.
JARPA/JARPA II abundance estimates	Biased low.
JARPA/JARPA II selectivity	Younger animals under-represented.

this review (even if it was a good thing to do in retrospect). He is, however, thanked for comments on an earlier version of this document as are Doug Butterworth, Greg Donovan, and to Toshihide Kitakado and Daniel Howell for providing reviews.

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