Draft simulation testing framework to be used during the development of OMP-17

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This document details the framework to be used to simulation test candidate MPs during the development of OMP-17. A summary of assumptions made in this simulation testing framework are listed below. Appendix A provides the full details, with data used listed in the tables at the end of the Appendix. This is a draft, as parts of this framework still need to be finalised, including some relationships (highlighted in yellow) which need to be updated using posterior median values rather than estimates at the joint posterior mode.

There are two main hypotheses for sardine: a single stock hypothesis or a two-mixing component hypothesis (with "west" and "south" sub-stocks). Two different types of candidate MPs have been proposed:

a) Candidate MPs which recommend a single directed >14cm sardine TAC and associated ≤14cm sardine bycatch.
b) Candidate MPs which recommend a separate directed >14cm sardine TAC for west and south-east of Cape Agulhas, and an associated split in the ≤14cm sardine bycatch.

All other sardine bycatches are assumed to be taken from the single or west sub-stock only.

There are therefore four alternative possible combinations of sardine TAC/B by area / stock:

i) A single area sardine TAC/B and a single sardine stock.
ii) A two-area sardine TAC/B and a single sardine stock.
iii) A single area sardine TAC/B and two sardine sub-stocks.
iv) A two-area sardine TAC/B and two sardine sub-stocks.

The following assumptions are made in the implementation simulation of Candidate MPs:

i) All sardine catch/bycatch is from the single stock
ii) The TAC/Bs are added and all catch/bycatch is from the single stock
iii) The TAC/Bs are split by sub-stock in a pre-defined year-specific proportion
iv) The TAC/B for west of Cape Agulhas is assumed taken from the west sardine sub-stock and the TAC/B for east of Cape Agulhas is assumed taken from the south sardine sub-stock.

Summary list of assumptions made in the framework to be used to simulation test OMP-17

1) Half the sardine is caught between 1 November and 30 April and half from 1 May to 31 October.

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2) Half the juvenile anchovy is caught between 1 November and 30 June and half from 1 July to 31 October.
3) Half the adult anchovy is caught between 1 November and 31 March and half from 1 April to 31 October.
4) The assumptions made during the development of the underlying operating models (de Moor 2016b, de Moor and Butterworth 2016a,b), such as maturity ogives and stock-recruitment relationships and differences in these assumptions between alternative operating models (robustness tests), are carried forward during projections.
5) In the underlying operating model which assumes two sardine sub-stocks, the movement of west sub-stock sardine to the south sub-stock in November is assumed either to be i) dependent on a relationship with the ratio of the south to west sub-stock total biomass from the previous November, or ii) random based on movement estimated between 2006 and 2015.
6) The recruit survey is simulated to commence mid-May each year.
7) All directed sardine catch and >14cm sardine bycatch with round herring and anchovy is split into age groups according to the selectivity-at-age estimated by the underlying operating model. The >14cm sardine TAB with round herring and anchovy, assumed to originate from the single or west component, is not always assumed taken; the bycatch is drawn from a distribution based on the historical bycatches with a maximum of $TAB^{S}_{y,big,rh} = 7000t$
8) All TABs for ≤14cm sardine are assumed to consist of 0-year-old sardine.
9) Half of the ≤14cm sardine bycatch with round herring, $TAB^{S}_{y,small,rh} = 1000t$, assumed to originate from the single or west component, is caught by the time of the recruit survey (mid-May). This full TAB is simulated to be caught each year.
10) The maximum amount of ≤14cm sardine bycatch in the directed (>14cm) sardine catch used to set the sardine TAB, ω_j, is not always assumed taken; a proportion is drawn from a distribution based on the historical proportions with a maximum of ω_j.
11) 60% of the ≤14cm sardine bycatch with directed sardine is caught by the time of the recruit survey (mid-May).
12) Half of $TAB^{A} = 500\text{t}$ is taken by the end of June, with the remaining half taken by the end of the normal season.
13) The initial anchovy TAC, $TAC^{1,A}_{y}$, is caught by the end of June, and 76% of this is caught by the end of May with the remaining 24% caught during June.
14) 29% of the total anchovy catch landed by the end of June ($TAC^{1,A}_{y} + \frac{1}{2}TAB^{A}$) are juveniles caught by mid-May.
15) The annual adult anchovy catch is 38% of the anchovy catch landed by the end of June ($TAC^{1,A}_{y} + \frac{1}{2}TAB^{A}$).

16) The juvenile (≤14cm) sardine bycatch with anchovy is assumed to be taken from the single or west sardine component.
17) The juvenile (<14cm) sardine bycatch with anchovy from January to 31 May is 1.327 times that from January to mid-May.
18) Juvenile (<14cm) sardine bycatch with anchovy over the months of June to December is taken to be a proportion of the anchovy catch during these months, with the monthly proportions and variances being estimated from the monthly juvenile sardine to anchovy ratios, based upon historical catch monthly observations and draws from model predicted recruitment.
19) In the implementation of sardine bycatch with anchovy, correlations in the juvenile single stock or west component sardine to anchovy ratios apply between successive months only.
20) In the implementation of sardine bycatch with anchovy, 42% of the July to December anchovy catch is taken in July, 26% in August and 20% in September.
21) For all catches simulated, an upper limit is placed on the industry's efficiency by assuming that no more than 95% of the selectivity-weighted stock abundance may be caught.
22) The ratio of juvenile single stock or west component sardine to anchovy in May (and used in the Harvest Control Rule), r_y , is restricted to a maximum of 1.
23) The ratios of juvenile single stock or west component sardine to anchovy in the months of June, July, August, September and October to December, used in simulating how much juvenile sardine is actually caught, are restricted to a maximum of 2.
24) The ratio of model predicted November juvenile single stock or west component sardine to anchovy used when simulating the future single stock or west component bycatch with anchovy is restricted to a maximum of 1.
25) Implementation simulation does not account for the closure of the anchovy fishery if the initial sardine bycatch with anchovy allowance is reached (see de Moor and Butterworth 2012 for reasons), although the sardine bycatch is limited by this allowance.
26) Implementation simulation accounts for the closure of the anchovy fishery if the sardine bycatch with anchovy allowance is reached, by proportionally decreasing the amount of juvenile anchovy catch simulated to be taken within a year.
27) Future survey observations are generated taking the historical correlation between the single stock or west component sardine and anchovy into account, and the variance is based on a regression between historical survey CV and model predicted abundance.
28) Survey and catch-related observations already known for 2016 have been used instead of model simulated observations. The undercatch of the final anchovy TAC has been taken into account. The recruitment in November 2015, and the corresponding recruitment residual are obtained by combining information from both the stock recruitment relationship and the known June 2016 survey results.

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Appendix A: The framework used to simulation test a joint MP for South African sardine and anchovy: OMP-17

In this appendix, the framework used to simulation test OMP-17 is detailed. The framework consists of a population dynamics model for future simulation of the effects of alternative MPs on the sardine and anchovy populations, an implementation model which generates future catches-at-age given annual TAC/Bs, and an observation model which generates the necessary data (in this case, catch and survey data) to be input into the Harvest Control Rules. Catches-at-age are given in numbers of fish (billions), whereas the TACs and TABs are given in biomass (in thousands of tons). All parameters are listed in Table A1.

Population dynamics model

Given the numbers-at-age at the beginning of the projection period (i.e., November 2015), values for future catches output from the implementation model, $C^{i}_{j,y,a}$, $i = S, A$ (see below), the population dynamics model projects numbers-at-age and spawning biomass at the beginning of November for $2016 \le y \le 2036$ as follows. The sardine adult catch is assumed to be taken half way between 1st November and 31st October each year[1]. The anchovy juvenile catch is assumed to be taken as a pulse at 1st July and the adult catch is assumed to be taken as a pulse at 1st April. All notation allows for multiple components of both species, though only a single stock for anchovy is considered in all Operating Models (OMs).

Sardine:

$$\begin{aligned}
N^{S,pred}_{j,y,1} &= \left(N^{S,pred}_{j,y-1,0}e^{-M^S_{ju}/2} - C^{S,pred}_{j,y,0}\right)e^{-M^S_{ju}/2} \\
N^{S,pred}_{j,y,a} &= \left(N^{S,pred}_{j,y-1,a-1}e^{-M^S_{ad}/2} - C^{S,pred}_{j,y,a-1}\right)e^{-M^S_{ad}/2},\ 2 \le a \le 4 \\
N^{S,pred}_{j,y,5^+} &= \left(N^{S,pred}_{j,y-1,4}e^{-M^S_{ad}/2} - C^{S,pred}_{j,y,4}\right)e^{-M^S_{ad}/2}\left(N^{S,pred}_{j,y-1,5^+}e^{-M^S_{ad}/2} - C^{S,pred}_{j,y,5^+}\right)e^{-M^S_{ad}/2} \\
B^{S,pred}_{j,y} &= \textstyle\sum_{a=0}^{5+} N^{S,pred}_{j,y,a}\overline{w}^S_{j,a} \\
SSB^{S,pred}_{j,y} &= \textstyle\sum_{a=0}^{5+} f^S_{j,a}N^{S,pred}_{j,y,a}\overline{w}^S_{j,a}
\end{aligned} \qquad \text{(A.1)}$$

Anchovy:

$$\begin{aligned}
N^{A,pred}_{j,y,1} &= \left(N^{A,pred}_{j,y-1,0}e^{-8M^A_{ju}/12} - C^{A,pred}_{j,y,0}\right)e^{-4M^A_{ju}/12} \\
N^{A,pred}_{j,y,2} &= \left(N^{A,pred}_{j,y-1,1}e^{-5M^A_{ad}/12} - C^{A,pred}_{j,y,1}\right)e^{-7M^A_{ad}/12} \\
N^{A,pred}_{j,y,3} &= N^{A,pred}_{j,y-1,2}e^{-M^A_{ad}} \\
N^{A,pred}_{j,y,4^+} &= N^{A,pred}_{j,y-1,3}e^{-M^A_{ad}} + N^{A,pred}_{j,y-1,4^+}e^{-M^A_{ad}} \\
B^{A,pred}_{j,y} &= \textstyle\sum_{a=0}^{4+} N^{A,pred}_{j,y,a}\overline{w}^A_{j,a} \\
SSB^{A,pred}_{j,y} &= \textstyle\sum_{a=0}^{4+} f^A_{j,a}N^{A,pred}_{j,y,a}\overline{w}^A_{j,a}
\end{aligned} \qquad \text{(A.2)}$$

[1] The sardine stock assessment was fit to quarterly commercial proportion at length data and thus catch was modelled to be taken quarterly (de Moor and Butterworth 2016a,b). The catch tonnage between 1984 and 2015, however, is almost equally split from 1 November to 30 April and 1 May to 31 October.

In the two component OM of sardine, movement of west component ($j = 1$) sardine to the south component ($j = 2$) at the beginning of November, is modelled in one of two ways:

MoveR: Age-1 movement, $move_{y,1}$, for $y_1 \leq y \leq y_n$ is drawn randomly from $move_{y,1}$ for $2006 \leq y \leq 2015$.

MoveB: Age-1 movement is a function of the ratio of south to west component November biomass in the previous year (de Moor et al. 2016), i.e.

$$move^*_{y,1} = 0.5835\left(1 - exp\left\{-0.9425\frac{B^{S,pred}_{2,y-1}}{B^{S,pred}_{1,y-1}}\right\}\right) \quad \text{(A.3a)}$$

In order to allow error about this relationship and satisfy $0 \leq move_{y,1} \leq 1$, the logit scale is used. Thus:

$$move_{y,1} = \frac{exp\left\{ln\left(\frac{move^*_{y,1}}{1-move^*_{y,1}}\right)+\xi_y\right\}}{1+exp\left\{ln\left(\frac{move^*_{y,1}}{1-move^*_{y,1}}\right)+\xi_y\right\}}, \text{ where } \xi_y \sim N(0, 0.261^2), \quad \text{(A.3b)}$$

with the standard deviation obtained from the model of de Moor and Butterworth (2016), corrected for bias.

Then the proportion of age 2+ sardine moving is given by $move_{y,2} = \phi \times move_{y,1}$, and

$$N^{S,pred}_{1,y,a} = (1 - move_{y,a})N^{S^*}_{1,y,a}$$

$$N^{S,pred}_{2,y,a} = N^{S^*}_{2,y,a} + move_{y,a}N^{S^*}_{1,y,a} \qquad y_1 \leq y \leq y_n \quad \text{(A.4)}$$

where $N^{S^*}_{j,y,a}$ is simply the numbers-at-age a given by equation (A.1) prior to movement.

Letting $f\left(SSB^{i,pred}_{j,y}\right)$ denote the stock recruitment curve of the chosen model, with parameters a^i_j and b^i_j, then future recruitment $N^{i,pred}_{j,y,0}$ is assumed to be log-normally distributed about a stock recruitment relationship as follows:

$$N^{i,pred}_{j,y,0} = f\left(SSB^{i,pred}_{j,y}\right)e^{\varepsilon^i_{j,y}\sigma^i_{j,r}} \quad \text{(A.5)}$$

where

$$\varepsilon^i_{j,y} = s^i_{j,cor}\varepsilon^i_{j,y-1} + \omega^i_{j,y}\sqrt{1 - \left(s^i_{j,cor}\right)^2}, \text{ where } \omega^i_{j,y} \sim N(0,1) \quad \text{(A.6)}$$

In the two component OM of sardine, some recruits originating from the south component ($j = 2$) are assumed to contribute to west component ($j = 1$) recruitment at the beginning of November:

$$N^{S,pred}_{1,y,0} = N^{S^*,pred}_{1,y,0} + pN^{S^*,pred}_{2,y,0}$$

$$N^{S,pred}_{2,y,0} = (1 - p)N^{S^*,pred}_{2,y,0} \qquad y_1 \leq y \leq y_n \quad \text{(A.7)}$$

where $N^{S^*,pred}_{j,y,0}$ is simply the recruits given by equation (A.5) prior to movement.

Implementation model

The candidate MPs outputs the following TAC/Bs:

1) An annual directed >14cm sardine TAC, TAC_y^S, which may be split by area ($TAC_y^{S,w}$ and $TAC_y^{S,s}$) in a candidate MP which allocates sardine TAC west and south of Cape Agulhas. In years of low biomass, a precautionary initial TAC may be given followed by a final TAC after the recruit survey.
2) An initial and final anchovy TAC ($TAC_y^{1,A}$ and $TAC_y^{2,A}$).
3) An annual time-invariant anchovy TAB for sardine only right holders, TAB^A.
4) An annual time-invariant >14cm sardine TAB with directed round herring and anchovy fishing, TAB_{big}^S.
5) An annual time-invariant ≤14cm sardine bycatch with round herring, and to a lesser extent with anchovy, $TAB_{small,rh}^S$.
6) For each sardine TAC in 1) there is a corresponding ≤14cm sardine TAB with directed (>14cm) sardine, $TAB_{y,small}^S$, which may be split by area ($TAB_{y,small}^{S,w}$ and $TAB_{y,small}^{S,s}$) in a candidate MP which allocates sardine TAC west and south of Cape Agulhas.
7) For each anchovy TAC in 2) there is a corresponding ≤14cm sardine TAB with anchovy, $TAB_{y,anch}^{1,S}$ and $TAB_{y,anch}^{2,S}$.

Given these TAC / TABs output from the MP (in thousands of tons), the implementation model simulates the implementation of these catch limits by the industry to yield future catches-at-age (in billions).

There are four alternative possible combinations of sardine TAC/B by area / component:

i) A single area sardine TAC/B and a single sardine stock.
ii) A two-area sardine TAC/B and a single sardine stock.
iii) A single area sardine TAC/B and two sardine components.
iv) A two-area sardine TAC/B and two sardine components.

Defining $TAC_{j,y}^S$ to be the directed >14cm sardine TAC assumed taken from component j, the following separation of TAC by component is effected:

i) $TAC_{1,y}^S = TAC_y^S$ and $TAB_{1,y,small}^S = TAB_{y,small}^S$, with only a single sardine stock
ii) $TAC_{1,y}^S = TAC_y^{S,w} + TAC_y^{S,s}$ and $TAB_{1,y,small}^S = TAB_{y,small}^{S,w} + TAB_{y,small}^{S,s}$ with only a single sardine stock
iii) $TAC_{1,y}^S = \tau TAC_y^S$ and $TAC_{2,y}^S = (1-\tau)TAC_y^S$, and $TAB_{1,y,small}^S = \tau TAB_{y,small}^S$ and $TAB_{2,y,small}^S = (1-\tau)TAB_{y,small}^S$
iv) $TAC_{1,y}^S = TAC_y^{S,w}$ and $TAC_{2,y}^S = TAC_y^{S,s}$, and $TAB_{1,y,small}^S = TAB_{y,small}^{S,w}$ and $TAB_{2,y,small}^S = TAB_{y,small}^{S,s}$.

The annual proportion of sardine catch taken west of Cape Agulhas was found to have a relationship with the ratio of the TAC in a particular year to the west component total biomass in November of the previous year (de Moor *et al*. 2016). Thus we have

$$\tau = 0.8971\left(1 - exp\left\{-0.7226\, TAC_y^S / B_{1,y-1}^S\right\}\right). \quad \text{(A.8a)}$$

In order to allow error about this relationship and satisfy $0 \leq \tau \leq 1$, the logit scale is used. Thus:

$$\tau = \frac{exp\left\{ln\left(\frac{\tau^*}{1-\tau^*}\right)+\xi_y\right\}}{1+exp\left\{ln\left(\frac{\tau^*}{1-\tau^*}\right)+\xi_y\right\}}, \text{ where } \xi_y \sim N(0, 1.13^2), \quad \text{(A.8b)}$$

with the standard deviation obtained from the model of de Moor *et al.* (2016), corrected for bias.

Sardine adult catch

The adult sardine catch is simulated using selectivity-at-age estimated by the OM:

$$C_{j,y,a}^{S,pred} = N_{j,y-1,a}^{S,pred} e^{-M_{ad}^S/2} S_{j,a}^S F_{j,y}, \;\; 1 \leq a \leq 5^+ \quad \text{(A.9)}$$

where $$F_{j,y} = \frac{TAC_{j,y}^S + \acute{\tau}_J TAB_{big}^{S,draw}}{N_{j,y-1,0}^{S,pred} e^{-M_{ju}^S/2} S_{j,0}^S \bar{w}_{j,0c}^S + \sum_{a=1}^{5+} N_{j,y-1,a}^{S,pred} e^{-M_{ad}^S/2} S_{j,a}^S \bar{w}_{j,ac}^S}, \quad \text{(A.10)}$$

Anchovy 1-year-old catch

Between 2006 and 2015, the total (annual) 1^+-year-old catch in tons constituted, on average, 38%[2] of the anchovy catch biomass between January and June (the period to which $TAC_y^{1,A}$ and half of TAB^A is taken to apply). Almost all of this catch consisted of 1-year-olds (de Moor 2016b). The anchovy 1-year-old catch is thus taken to be:

$$C_{1,y,1}^{A,pred} = 0.38 \times \frac{TAC_y^{1,A} + 0.5 TAB^A}{\bar{w}_{1c}^A}. \quad \text{(A.11)}$$

Anchovy 0-year-old catch

Between 2006 and 2015 the anchovy juvenile catch in tons from 1st January to 30th April, together with half the May juvenile catch in tons was 29%[3] of the total anchovy catch biomass from January to June. Using the above assumption that $TAC_y^{1,A}$ and half of TAB^A is caught by the end of June, the anchovy 0-year-old catch taken prior to the recruit survey is:

$$C_{1,y,Obs}^{A,pred} = 0.29 \times \frac{TAC_y^{1,A} + 0.5 TAB^A}{\bar{w}_{0c}^A}. \quad \text{(A.12)}$$

and for the whole year:

$$C_{1,y,O}^{A,pred} = \frac{1}{\bar{w}_{0c}^A}\left(TAC_y^{2,A} + TAB^A - \bar{w}_{1c}^A C_{1,y,1}^{A,pred}\right) \quad \text{(A.13)}$$

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[2] 37% for 1984 to 2015

[3] 27% for 1984 to 2015

Sardine 0-year-old catch prior to the recruit survey

The 0-year-old sardine catch prior to the recruit survey is based on the January to mid-May bycatch occurring with i) round herring, ii) >14cm sardine in the directed fishery, and iii) targeted juvenile anchovy, in addition to some larger 0-year-old sardine being landed as directed sardine. It is assumed that half the ≤14cm sardine bycatch with round herring occurs before the recruit survey, and the other half after the recruit survey. It is further assumed that 60% of the ≤14cm sardine in the directed sardine catch is caught by the time of the survey. It is assumed that all 0-year-old sardine landed in the directed >14cm fishery occur after the recruit survey:

$$C^{S,pred}_{1,y,0bs} = 0.5\frac{\acute{\tau}_1 TAB^S_{small,rh}}{\bar{w}^S_{1,0c}} + 0.6\frac{\omega^{draw}_{1,y} TAC^S_{1,y}}{\bar{w}^S_{1,0c}} + k_{janmay}\frac{N^{S,pred}_{1,y-1,0}}{N^{A,pred}_{1,y-1,0}} e^{\sigma_{janmay}\eta_{y,janmay}} \times 0.26\frac{TAC^{1,A}_y}{\bar{w}^S_{1,0c}},$$

$$C^{S,pred}_{2,y,0bs} = 0.5\frac{\acute{\tau}_2 TAB^S_{small,rh}}{\bar{w}^S_{2,0c}} + 0.6\frac{\omega^{draw}_{2,y} TAC^S_{2,y}}{\bar{w}^S_{2,0c}}, \qquad \text{where } \eta_{y,janmay} \sim N(0,1) \qquad \text{(A.14)}$$

Sardine 0-year-old catch (in billions)

In modelling the total sardine juvenile bycatch, the following approach is used. If the full TAB with anchovy were caught, the total juvenile sardine catch by mass would be

$$C^{S,pred}_{1,y,0} = \frac{1}{\bar{w}^S_{1,0c}}\left(\left(\lambda_y TAC^{1,A}_y + r_y\left(TAC^{2,A}_y - TAC^{1,A}_y\right)\right) + \acute{\tau}_1 TAB^S_{small,rh} + \omega^{draw}_y TAC^S_{1,y}\right) +$$
$$N^{S,pred}_{1,y-1,0} e^{-M^S_{ju}/2} S^S_{1,0} F_{1,y}$$

$$C^{S,pred}_{2,y,0} = \frac{1}{\bar{w}^S_{2,0c}}\left(\acute{\tau}_2 TAB^S_{small,rh} + \omega^{draw}_{j,y} TAC^S_{2,y}\right) + N^{S,pred}_{2,y-1,0} e^{-M^S_{ju}/2} S^S_{2,0} F_{2,y} \qquad \text{(A.15)}$$

where

$$\lambda_y = max\{\gamma_y, r_y\}, \qquad \text{(A.16)}$$

$$r_y = \frac{1}{2}\left(r_{y,sur} + r_{y,com}\right), \text{ and} \qquad \text{(A.17)}$$

$$r_{y,sur} = \frac{N^{S,obs}_{1,y,r}}{N^{A,obs}_{1,y,r}}. \qquad \text{(A.18)}$$

During simulation[4], the sardine bycatch to anchovy ratio in commercial catches in May, is given by:

$$r_{y,com} = k_{may}\frac{N^{S,pred}_{1,y,r}}{N^{A,pred}_{1,y,r}} e^{\sigma_{may}\varepsilon_{y,may}}. \qquad \text{(A.19)}$$

$$\text{where } \varepsilon_{y,may} = \rho_{may}\eta_{y,janmay} + \sqrt{1-\left(\rho_{may}\right)^2}\,\eta_{y,may}, \qquad \text{(A.20)}$$

with $\eta_{y,may} \sim N(0,1)$ and $\eta_{y,jan:may}$ is given by equation (A.14). As $r_{y,com}$ is based on simulated commercial catches, the model predicted numbers-at-age, $N^{i,pred}_{1,y,r}$, are used rather than those simulated to be survey observations.

[4] During OMP implementation, $r_{y,com}$ will be an *observed* ratio.

Equation (A.15) assumes that the ratio of juvenile sardine to anchovy "in the sea" during May, r_y, will remain a constant for the remainder of the year season. However, there is usually a drop-off in this ratio as the year progresses (Figure A3). This effect is simulated by adjusting equation (A.15) to reflect the actual level of 0-year-old sardine to be expected in the catches with anchovy, given the historical pattern of sardine bycatch to anchovy ratio from May to October-December.

Over the past 10 years (2006-2015), the sardine bycatch with anchovy from January to 31st May has been 1.327 times that from January to mid-May[5]. Adjusting the sardine bycatch prior to the survey to take account of this additional bycatch by the end of May, the catch from the west component or single stock in equation (A.15) is modified as follows:

$$C_{1,y,0}^{S*,pred} = \frac{1}{\bar{w}_{1,0c}^S}\left(\acute{\tau}_1 TAB_{small,rh}^S + \omega_{j,y}^{draw} TAC_{1,y}^S\right) + N_{1,y-1,0}^{S,pred} e^{-M_{ju}^S/2} S_{1,0}^S F_{1,y} + 1.327 \times \left(C_{1,y,0bs}^{S,pred} - 0.5\frac{\acute{\tau}_1 TAB_{small,rh}^S}{\bar{w}_{1,0c}^S} - 0.6\frac{\omega_{1,y}^{draw} TAC_{1,y}^S}{\bar{w}_{1,0c}^S}\right) + \frac{1}{\bar{w}_{1,0c}^S}\left(r_{y,jun} C_{y,jun}^{A,pred} + r_{y,jul} C_{y,jul}^{A,pred} + r_{y,aug} C_{y,aug}^{A,pred} + r_{y,sep} C_{y,sep}^{A,pred} + r_{y,octdec} C_{y,octdec}^{A,pred}\right) \quad \text{(A.21)}$$

The sardine bycatch to anchovy ratios, $r_{y,m}$, are simulated in a similar way to $r_{y,com}$ (equation A.19) as follows:

$$r_{y,m} = k_m \frac{N_{1,y,r}^{S,pred}}{N_{1,y,r}^{A,pred}} e^{\sigma_m \varepsilon_{y,m}}, \quad \text{where } m = jun, jul, aug, sep, octdec \quad \text{(A.22)}$$

And correlation between adjacent months is simulated as follows:

$$\varepsilon_{y,jun} = \rho_{jun}\varepsilon_{y,may} + \sqrt{1-\left(\rho_{jun}\right)^2}\eta_{y,jun}$$

$$\varepsilon_{y,jul} = \rho_{jul}\varepsilon_{y,jun} + \sqrt{1-\left(\rho_{jul}\right)^2}\eta_{y,jul}$$

$$\varepsilon_{y,aug} = \rho_{aug}\varepsilon_{y,jul} + \sqrt{1-\left(\rho_{aug}\right)^2}\eta_{y,aug}$$

$$\varepsilon_{y,sep} = \rho_{sep}\varepsilon_{y,aug} + \sqrt{1-\left(\rho_{sep}\right)^2}\eta_{y,sep}$$

$$\varepsilon_{y,octdec} = \rho_{octdec}\varepsilon_{y,sep} + \sqrt{1-(\rho_{octdec})^2}\eta_{y,octdec}. \quad \text{(A.23)}$$

where $\varepsilon_{y,may}$ is from equation (A.20), and $\eta_{y,m} \sim N(0,1)$, $m = jun, jul, aug, sep, octdec$.

Between 2006 and 2015 the average total anchovy catch from January to May was 76[6]% of that from January to June. Assuming 76% of $TAC_y^{1,A}$ is caught by the end of May, and given the assumption that $TAC_y^{1,A}$ is caught by the end of June, the anchovy catches in equation (A.21), $C_{y,m}^{A,pred}$ ($m = jun, jul, aug, sep, octdec$), are derived as follows (in thousands of tons):

$$C_{y,jun}^{A,pred} = 0.24 \times TAC_y^{1,A} \quad \text{(A.24)}$$

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[5] Bycatch from 1st to 15th May approximated by half the bycatch from the full month of May.

[6] Average from 1984 to 2015 is 72%.

$$C_{y,jul}^{A,pred} = p_{jul}\left(TAC_y^{2,A} - TAC_y^{1,A}\right) \quad \text{(A.25)}$$

$$C_{y,aug}^{A,pred} = p_{aug}\left(TAC_y^{2,A} - TAC_y^{1,A}\right) \quad \text{(A.26)}$$

$$C_{y,sep}^{A,pred} = p_{sep}\left(TAC_y^{2,A} - TAC_y^{1,A}\right) \quad \text{(A.27)}$$

$$C_{y,octdec}^{A,pred} = \left(1 - p_{jul} - p_{aug} - p_{sep}\right)\left(TAC_y^{2,A} - TAC_y^{1,A}\right) \quad \text{(A.28)}$$

where $p_{jul} = 0.42$[7], $p_{aug} = 0.26$[8] and $p_{sep} = 0.20$[9] are taken to be the average 2006 to 2015 proportion of anchovy catch during July to December that is taken in July, August and September, respectively.

Closure of the anchovy fishery

The anchovy catch, $C_{1,y,0}^{A,pred}$, is adjusted if the predicted proportion of $C_{1,y,0}^{S^*,pred}$ which accounts for small sardine bycatch with anchovy exceeds $TAB_{y,anch}^{2,S}$, in order to reflect the closure of the anchovy fishery once the sardine bycatch allowance with anchovy directed fishing is reached. If

$$1.327 \times \left(\bar{w}_{1,0c}^S C_{1,y,0bs}^{S,pred} - \acute{0}.5\tau_1 TAB_{small,rh}^S - 0.6\omega_y^{draw} TAC_{1,y}^S\right) + \left(r_{y,jun} C_{y,jun}^{A,pred} + r_{y,jul} C_{y,jul}^{A,pred} + r_{y,aug} C_{y,aug}^{A,pred} + r_{y,sep} C_{y,sep}^{A,pred} + r_{y,octdec} C_{y,octdec}^{A,pred}\right) > TAB_{y,anch}^{2,S},$$

then the anchovy fishery would be closed once the full bycatch allowance was taken. This is simulated by assuming that the anchovy TAC is taken at the same rate as the sardine bycatch:

$$C_{1,y,0}^{S^{**},pred} = min\left\{C_{1,y,0}^{S^*,pred}; \frac{TAB_{y,anch}^{2,S}}{\bar{w}_{1,0c}^S} + \frac{1}{\bar{w}_{1,0c}^S}\left(\acute{\tau}_1 TAB_{small,rh}^S + \omega_y^{draw} TAC_{1,y}^S\right) + N_{1,y-1,0}^{S,pred} e^{-M_{ju}^S/2} S_{1,0}^S F_{1,y}\right\} \quad \text{(A.29)}$$

$$C_{1,y,0}^{A^*,pred} = min\left\{C_{1,y,0}^{A,pred}; \frac{1}{\bar{w}_{1,0c}^A}\left(TAB^A - \bar{w}_{1c}^A C_{1,y,1}^{A,pred} + \right.\right.$$

$$TAC_y^{2,A}\left[\frac{TAB_{y,anch}^{2,S}}{1.327\times\left(\bar{w}_{1,0c}^S C_{1,y,0bs}^{S,pred} - \acute{0}.5\tau_1 TAB_{small,rh}^S - 0.6\omega_y^{draw} TAC_{1,y}^S\right) + \left(r_{y,jun} C_{y,jun}^{A,pred} + r_{y,jul} C_{y,jul}^{A,pred} + r_{y,aug} C_{y,aug}^{A,pred} + r_{y,sep} C_{y,sep}^{A,pred} + r_{y,octdec} C_{y,oc}^{A,pr}\right.}\right. \quad \text{(A.30)}$$

General

For all catches simulated in the OM, an upper limit is placed on the industry's efficiency by assuming that no more than 95% of the selectivity-weighted abundance may be caught at the time of the pulse.

Observation Model

The survey estimates for total biomass and recruitment are generated by the as follows ($i = A, S$):

$$B_{j,y}^{i,obs} = k_{j,N}^i B_{j,y}^{i,pred} e^{\varepsilon_{j,y,Nov}^i} \quad \text{(A.31)}$$

where $\varepsilon_{j,y,Nov}^S = \eta_{j,y,Nov}^S \tilde{\sigma}_{j,y,Nov}^S$, where $\eta_{j,y,Nov}^S \sim N(0,1)$ (A.32)

[7] Average from 1984 to 2015 is 42%.
[8] Average from 1984 to 2015 is 28%.
[9] Average from 1984 to 2015 is 20%.

and $\varepsilon^A_{1,y,Nov} = \left(\rho_{Nov}\eta^S_{1,y,Nov} + \sqrt{1-\rho^2_{Nov}}\eta^A_{1,y,Nov}\right)\tilde{\sigma}^A_{j,y,Nov}$ [10], where $\eta^A_{1,y,Nov} \sim N(0,1)$ (A.33)

Single stock: $\tilde{\sigma}^S_{1,y,Nov} = \sqrt{min\left(1.1181^2; 0.0486 + \frac{81.0356}{B^{S,pred}_{1,y}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{1,N}\right)^2}$ [11]

West component: $\tilde{\sigma}^S_{1,y,Nov} = \sqrt{min\left(1.1267^2; 0.1496 + \frac{29.4655}{B^{S,pred}_{1,y}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{1,N}\right)^2}$ [12]

South component: $\tilde{\sigma}^S_{2,y,Nov} = \sqrt{min\left(1.2293^2; 0.3749 + \frac{0.1109}{B^{S,pred}_{2,y}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{2,N}\right)^2}$ [12] (A.34)

and $\tilde{\sigma}^A_{1,y,Nov} = \sqrt{min\left(0.4096^2; 0.0215 + \frac{22.2412}{B^{A,pred}_{1,y}}\right) + \left(\lambda^A_{1,N}\right)^2}$ [13] (A.35)

obtained from a regression of the observed CV against the base case OM predicted biomass between 1984 and 2015 at the joint posterior mode (Figure A4).

$N^{i,obs}_{j,y,r} = k^i_{j,r} N^{i,pred}_{j,y,r} e^{\varepsilon^i_{j,y,rec}}$, (A.36)

where $\varepsilon^S_{j,y,rec} = \eta^S_{j,y,rec}\tilde{\sigma}^S_{j,y,rec}$, where $\eta^S_{j,y,rec} \sim N(0,1)$ (A.37)

and $\varepsilon^A_{1,y,rec} = \left(\rho_{rec}\eta^S_{1,y,rec} + \sqrt{1-\rho^2_{rec}}\eta^A_{1,y,rec}\right)\tilde{\sigma}^A_{j,y,rec}$ [13], where $\eta^A_{1,y,rec} \sim N(0,1)$. (A.38)

Single stock $\tilde{\sigma}^S_{1,y,rec} = \sqrt{min\left(1.0785^2; 0.1056 + \frac{1.1859}{N^{S,pred}_{1,y,r}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{1,r}\right)^2}$ [11]

West component: $\tilde{\sigma}^S_{1,y,rec} = \sqrt{min\left(1.0785^2; 0.0209 + \frac{2.2298}{N^{S,pred}_{1,y,r}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{1,r}\right)^2}$ [12]

South component: $\tilde{\sigma}^S_{2,y,rec} = \sqrt{min\left(1.0184^2; 0.4690 + \frac{0.0334}{N^{S,pred}_{2,y,r}}\right) + (\varphi^S_{ac})^2 + \left(\lambda^s_{2,r}\right)^2}$ [12] (A.39)

and $\tilde{\sigma}^A_{1,y,rec} = \sqrt{min\left(0.3404^2; 0.0366 + \frac{0.9598}{N^{A,pred}_{1,y,r}}\right) + \left(\lambda^A_{1,r}\right)^2}$ [13] (A.40)

obtained from a regression of the observed CV against the base case OM predicted recruitment between 1985 and 2015 at the joint posterior mode (Figure A4).

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[10] In the two sardine component OM, the assumption is made that anchovy biomass and recruitment is only correlated with the west component.

[11] For the sardine single stock OM, from the base case OM with hockey stick stock recruitment curve (de Moor and Butterworth 2016b)

[12] For the sardine two component OM, from the base case OM with hockey stick stock recruitment curves (de Moor and Butterworth 2016a).

[13] From the anchovy base case OM with a Beverton Holt stock recruitment curve (de Moor 2016b).

Assuming that the recruit survey begins mid-May each year, and that juvenile sardine are caught half-way between 1 November and the start of the survey, while juvenile anchovy caught prior to the survey are taken in a pulse at 1 May, we simulate:

$$N_{j,y,r}^{S,pred} = \left(N_{j,y-1,0}^{S,pred} e^{-3.25M_{ju}^{S}/12} - C_{j,y,0bs}^{S,pred}\right) e^{-3.25M_{ju}^{S}/12}$$

$$N_{j,y,r}^{A,pred} = \left(N_{j,y-1,0}^{A,pred} e^{-0.5M_{ju}^{A}} - C_{j,y,0bs}^{A,pred}\right) e^{-0.5M_{ju}^{A}/12} \quad \text{(A.41)}$$

Assumptions made for 2016

As the stock assessments (de Moor 2016a, de Moor and Butterworth 2016a,b) covered the period to November 2015, the MP testing framework begins from November 2015 and projects to November 2036. A number of parameters that would be simulated in the testing framework for 2016, have however already been observed. Thus the following changes are made to the simulation framework above for 2016:

i) The TAC/TABs (in thousands of tons) for 2016 have already been set using OMP-14, thus $TAC_{2016,init}^{S} = 64.563$, $TAB_{2016,small,init}^{S} = 4.519$, $TAC_{2016}^{S} = 64.928$, $TAB_{2016,small}^{S} = 5.545$, $TAC_{2016}^{1,A} = 254.483$, $TAB_{2016,anch}^{1,S} = 25.866$, $TAC_{2016}^{2,A} = 354.326$, $TAB_{2016,anch}^{2,S} = 31.463$. For candidate MPs which calculate area-specific sardine TAC/Bs, the assumption is made that the TAC was awarded in the same proportion as assumed in a single area/two component scenario (see equation A.8).

ii) As the May 2016 survey observations are available, no error is required, thus equation (A.36) is replaced by $N_{j=1,2016,r}^{obs,S} = 0.811$ billion (CV of 0.425) for either the single stock OM or the west component of the two component OM, $N_{j=2,2016,r}^{obs,S} = 0.850$ billion (CV of 0.887) for the south component of the two component OM, and $N_{j=1,2016,r}^{obs,A} = 118.075$ billion (CV of 0.221) (Coetzee *et al*. 2016a and D. Merkle pers comm.).

iii) The ratio of juvenile sardine to anchovy "in the sea" used in equation (A.13) is $r_{2016} = 0.5 \times (0.0231 + 0.089)$ (de Moor 2016).

iv) The model predicted recruitment in November 2015 is an inverse variance weighted average of the logarithms of two estimates (logarithms are taken as the distributions of the estimates themselves are assumed to be log-normal). The first estimate comes from the recruitment observed in the 2016 recruit survey:

$N_{j,2016,r}^{i,pred} = \frac{1}{k_{j,r}^{i}} N_{j,2016,r}^{i,obs}$ (the best estimate from equation (A.36) for component j of species i)

$$\tilde{N}_{1,2015,0}^{S,pred} = \left(N_{1,2016,r}^{S,pred} e^{0.5(6+t_{2016})M_{ju}^{S}/12} + \acute{C}_{1,2016,0bs}^{S}\right) e^{0.5(6+t_{2016})M_{ju}^{S}/12} - \frac{p}{1-p}\left(N_{2,2016,r}^{S,pred} e^{0.5(6+t_{2016})M_{ju}^{S}/12} + \acute{C}_{2,2016,0bs}^{S}\right) e^{0.5(6+t_{2016})M_{ju}^{S}/12} \quad \text{(equations A.41 and A.7)}$$

$$\tilde{N}_{2,2015,0}^{S,pred} = \frac{1}{1-p}\left(N_{2,2016,r}^{S,pred} e^{0.5(6+t_{2016})M_{ju}^{S}/12} + \acute{C}_{2,2016,0bs}^{S}\right) e^{0.5(6+t_{2016})M_{ju}^{S}/12} \quad \text{(equations A.41 and A.7)}$$

$$\tilde{N}_{j,2015,0}^{A,pred} = \left(N_{j,2016,r}^{A,pred} e^{t_{2016}M_{ju}^{A}/12} + \acute{C}_{j,2016,0bs}^{A}\right) e^{0.5M_{ju}^{A}} \quad \text{(equation (A.41))}$$

where $\acute{C}^{A}_{2016,Obs} = 20.777$ billion, and $\acute{C}^{S}_{j=1,2016,Obs} = 0.673$, and $\acute{C}^{S}_{j=2,2016,Obs} = 0.00$ billion being the juvenile anchovy and sardine catch, respectively from 1 November 2015 to the day before the recruit survey in June 2016, which was 7th June, i.e. $t_{2016} = 1.233$ (de Moor 2016). The standard errors associated with the logarithms of these estimates are:

$$\tilde{\sigma}^{S}_{1,2016,rec} = \sqrt{0.425^2 + (\varphi^{S}_{ac})^2 + \left(\lambda^{S}_{1,r}\right)^2}$$

$$\tilde{\sigma}^{S}_{2,2016,rec} = \sqrt{0.887^2 + (\varphi^{S}_{ac})^2 + \left(\lambda^{S}_{2,r}\right)^2}$$

$$\tilde{\sigma}^{A}_{1,2016,rec} = \sqrt{0.221^2 + \left(\lambda^{A}_{1,r}\right)^2}$$

v) The second estimate comes from the stock recruitment curve, but needs to take account of the serial correlation in residuals about this curve, and so depends on the residual estimated about this curve for November 2014. Thus:

$$\breve{N}^{i,pred}_{j,2015,0} = f\left(SSB^{i,pred}_{j,2015}\right)e^{s^{i}_{j,cor}\varepsilon^{i}_{j,2014}\sigma^{i}_{j,r}}$$

with a standard error of the logarithm of this estimate being given by:

$$\breve{\sigma}^{i}_{j,2015} = \sqrt{1-\left(s^{i}_{j,cor}\right)^2}\,\sigma^{i}_{j,r}$$

vi) The inverse variance weighted average of the logarithms of these two estimates is then given by:

$$ln\left(N^{i,pred}_{j,2015,0}\right) = \frac{\frac{ln\left(\tilde{N}^{i,pred}_{j,2015,0}\right)}{\left(\tilde{\sigma}^{i}_{j,2016,rec}\right)^2}+\frac{ln\left(\breve{N}^{i,pred}_{j,2015,0}\right)}{\left(\breve{\sigma}^{i}_{j,2015}\right)^2}}{\frac{1}{\left(\tilde{\sigma}^{i}_{j,2016,rec}\right)^2}+\frac{1}{\left(\breve{\sigma}^{i}_{j,2015}\right)^2}}$$

This process is essentially shrinking the estimate provided by the survey towards the mean provided by the stock recruitment relationship (adjusted for serial correlation).

vii) The recruitment residual in November 2015, required in the calculation of the recruitment residual in November 2016 (equation A.6), is obtained from equation (A.5) as follows:

$$\varepsilon^{i}_{j,2015} = ln\left(\frac{N^{i,pred}_{j,2015,0}}{f\left(SSB^{i,pred}_{j,2015}\right)}\right)\Big/\sigma^{i}_{j,r}$$

viii) As the November 2016 survey observations are available, no error is required, thus equation (A.31) is replaced by $B^{A,obs}_{j=1,2016} = 1733.040$ thousand tons, $B^{S,obs}_{j=1,2016} = 258.5746$ thousand tons for single area HCRs, and $B^{S,obs}_{j=1,2016} = 183.3558$ and $B^{S,obs}_{j=2,2016} = 75.2188$ thousand tons for two area HCRs (Coetzee *et al*. 2016b).

External inputs into the MP testing framework

Some of the parameters required in the observation model were sampled from the posterior distributions of the underlying OMs (de Moor 2016c,d). In addition, historical catches were used in the calculation of single stock or west component sardine bycatch to anchovy ratios used in the implementation model. These parameters are detailed in this section.

Correlation in survey residuals

The single stock or west component sardine and anchovy November survey residuals are given by ($i = S, A$):

$$\varepsilon^i_{y,Nov} = ln\left(B^{i,obs}_{1,y}\right) - ln\left(k^i_{1,N}\hat{B}^i_{1,y}\right), \qquad 1984 \leq y \leq 2015 \qquad \text{(A.42)}$$

The standard deviations of the residuals are given by:

$$\sigma^i_{Nov} = \sqrt{\frac{\sum_{y=1984}^{2015}\left(\varepsilon^i_{y,Nov}\right)^2}{\sum_{y=1984}^{2015} 1}}, \qquad \text{(A.43)}$$

and

$$\rho_{Nov} = \frac{\sum_{y=1984}^{2015} \varepsilon^S_{y,Nov}\varepsilon^A_{y,Nov}}{\left(\sum_{y=1984}^{2015} 1\right)\sigma^S_{Nov}\sigma^A_{Nov}}. \qquad \text{(A.44)}$$

Similarly, the single stock or west component sardine and anchovy May recruit survey residuals are given by ($i = S, A$):

$$\varepsilon^i_{y,rec} = ln\left(N^{i,obs}_{1,y,r}\right) - ln\left(k^i_{1,r}\hat{N}^i_{1,y,r}\right), \qquad 1985 \leq y \leq 2015 \qquad \text{(A.45)}$$

The standard deviations of the residuals are given by:

$$\sigma^i_{rec} = \sqrt{\frac{\sum_{y=1985}^{2015}\left(\varepsilon^i_{y,rec}\right)^2}{\sum_{y=1985}^{2015} 1}}\ ^{14}. \qquad \text{(A.46)}$$

The correlation in the residuals between the single stock or west component sardine and anchovy recruit survey estimates is:

$$\rho_{rec} = \frac{\sum_{y=1985}^{2015} \varepsilon^S_{y,rec}\varepsilon^A_{y,rec}}{\left(\sum_{y=1985}^{2015} 1\right)\sigma^S_{rec}\sigma^A_{rec}}\ ^{14}. \qquad \text{(A.47)}$$

Ratio of sardine bycatch to anchovy between January and May

The ratio of sardine bycatch to anchovy in the commercial catches from January to May is needed to simulate the 0-year-old single stock or west component sardine caught prior to the recruit survey (equation (A.11)). The relationship between the historical sardine bycatch to anchovy ratio in the catches from January to May, together with the OM prediction for the ratio of single stock or west component sardine to anchovy November recruitment, is used to provide this ratio. Only the most recent 10 years data is used in the below equations as future catches are assumed to more closely simulate those over the past decade, rather than earlier periods when fishing patterns may have differed. The constant of proportionality estimated and the associated time series of residuals are as follows:

$$k_{janmay} = exp\left\{\frac{\sum_{y=2006}^{2015} ln\left(C^{S,byc}_{y,janmay}/C^A_{y,janmay}\right) - ln\left(\hat{N}^S_{1,y-1,0}/\hat{N}^A_{1,y-1,0}\right)}{\sum_{y=2006}^{2015} 1}\right\} \qquad \text{(A.48)}$$

and

[14] The sum is taken over all years for which a survey estimate of recruitment exists.

$$\varepsilon'_{y,janmay} = ln\left(C^{S,byc}_{y,janmay}/C^{A}_{y,janmay}\right) - ln\left(k_{janmay}\hat{N}^{S}_{1,y-1,0}/\hat{N}^{A}_{1,y-1,0}\right) \qquad 2006 \le y \le 2015 \quad \text{(A.49)}$$

The standard deviation of the residuals is given by:

$$\sigma_{janmay} = \sqrt{\sum_{y=2006}^{2015}\left(\varepsilon'_{y,janmay}\right)^2 / \sum_{y=2006}^{2015} 1}. \qquad \text{(A.50)}$$

Ratio of sardine bycatch to anchovy in the commercial fishery during May

The estimated constant of proportionality and the associated time series of residuals for the juvenile single stock or west component sardine to anchovy ratio from the commercial catches during individual months May to September and October-December ($m = janmay, may, jun, jul, aug, sep, octdec$) are as follows:

$$k_m = exp\left\{\frac{\sum_{y=2006}^{2015} ln\left(C^{S,byc}_{y,m}/C^{A}_{y,m}\right) - ln\left(\hat{N}^{S}_{1,y,r}/\hat{N}^{A}_{1,y,r}\right)}{\sum_{y=2006}^{2015} 1}\right\} \text{[15]} \qquad \text{(A.51)}$$

and

$$\varepsilon'_{y,m} = ln\left(C^{S,byc}_{y,m}/C^{A}_{y,m}\right) - ln\left(k_m\hat{N}^{S}_{1,y,r}/\hat{N}^{A}_{1,y,r}\right), \qquad 2006 \le y \le 2015 \qquad \text{(A.52)}$$

The associated residual standard deviation is:

$$\sigma_m = \sqrt{\sum_{y=2006}^{2015}\left(\varepsilon'_{y,m}\right)^2 / \sum_{y=2006}^{2015} 1} \text{[15]} \qquad \text{(A.53)}$$

A correlation coefficient between the residuals in successive months, is then calculated by:

$$\rho_m = \frac{\sum_{y=2006}^{2015} \varepsilon'_{y,m-1}\varepsilon'_{y,m}}{\sigma_{m-1}\sigma_m\left(\sum_{y=2006}^{2015} 1\right)} \text{[15] [16]} \qquad \text{(A.54)}$$

[15] Summing over years for which anchovy directed catch in month m is non-zero.
[16] For ρ_{may}, month $m-1 = janmay$.

Table A1. Parameter definitions.

	Operating Model parameters	Units	Used in Equation	Notes
$N_{j,y,a}^{i,pred}$	OM predicted numbers at age a of species i, component j, at the beginning of November in year y	billions	A.1, A.2, (A.9,A.10)	$N_{j,2015,a}^{i,pred}$ sampled from Bayesian posterior distributions of de Moor (2016c,d)
M_{ju}^{i}	Natural mortality rate of juvenile (age 0) fish of species i	year^{-1}	A.1, A.2	sampled from Bayesian posterior distributions of de Moor (2016c,d)
M_{ad}^{i}	Natural mortality rate of adult (age 1^+) fish of species i	year^{-1}	A.1, A.2	sampled from Bayesian posterior distributions of de Moor (2016c,d)
$C_{j,y,a}^{i,pred}$	OM predicted future catches at age a in year y of component j of species i	billions	A.9,(A.1, A.2)	
$C_{j,y,0bs}^{i,pred}$	OM predicted future catches at age 0 prior to the May recruit survey in year y of component j of species i	billions	A.12,A.14,(A.41)	
$B_{j,y}^{i,pred}$	OM predicted November total biomass in year y of component j of species i	Thousands of tons	A.1, A.2	
$\hat{B}_{j,y}^{i}$	OM predicted November total biomass in year y of component j of species i	Thousands of tons	(A.42)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
$SSB_{j,y}^{i,pred}$	OM predicted November spawner biomass in year y of component j of species i	Thousands of tons	A.1, A.2	
$\bar{w}_{j,a}^{i}$	Historical average November weights-at-age a of component j of species i	Grams		Weight is given by length in the OM, and thus: $w_a^A = \sum_l w_l^A A_{a,l}^{sur} = \sum_l 0.0079 \times l^{3.0979} A_{a,l}^{sur}$ $w_{j,a}^S = \frac{1}{5}\sum_{y=2011}^{2015}\sum_l w_{j,y,l}^S A_{j,y,a,l}^{sur}$ [17]

[17] This differs for each sample from the posterior distribution and thus a table of weights is not provided in this document.

Table A1. Parameter definitions.

	Operating Model parameters	Units	Used in Equation	Notes
$f^i_{j,a}$	Proportion of component j of species i that is mature at age a	-	(A.1, A.2)	Maturity is given by length in the OM, and thus: $f^A_a = \sum_l f^A_l A^{sur}_{a,l} = \sum_l A^{sur}_{a,l}/\left(1+e^{-(l-10.61)/0.66}\right)$ $f^S_{j,a} = \frac{1}{5}\sum_{y=2011}^{2015}\sum_l f^S_l A^{sur}_{j,y,a,l} = \frac{1}{5}\sum_{y=2011}^{2015}\sum_l A^{sur}_{j,y,a,l}/\left(1+e^{-(l-17.4)/0.95}\right)$
$move_{y,a}$,	Proportion of sardine at age a moving from the west to the south component in year y (2 component OM only)	-	A.3, A.4	$move_{y,a}$, $2006 \leq y \leq 2015$, sampled from Bayesian posterior distributions of de Moor (2016d)
ϕ	The proportion of 2⁺-year-olds which move from the west to the south component in year y is this time-invariant proportion ϕ of the 1-year-olds moving in year y	-	A.4	
a^i_j	Stock-recruitment parameter for component j of species i (e.g. maximum median recruitment in Hockey Stick stock-recruitment relationship)	e.g. billions	(A.5)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
b^i_j	Stock-recruitment parameter for component j of species i (e.g. spawner biomass below which median recruitment declines)	e.g. thousands of tons	(A.5)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
$\varepsilon^i_{j,y}$	Standardised November recruitment residual for component j of species i in year y		A.6	$\varepsilon^i_{j,2014}$ sampled from Bayesian posterior distributions of de Moor (2016c,d)
$\sigma^i_{j,r}$	Standard deviation of the recruitment residuals for component j of species i		(A.5)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)

Table A1. Parameter definitions.

Operating Model parameters		Units	Used in Equation	Notes
$s^{i}_{j,cor}$	Recruitment serial correlation for component j of species i		(A.6)	
$\omega^{i}_{j,y}$	Random variable	-	A.6	$\omega^{i}_{j,y} \sim N(0,1)$
τ	The proportion of the directed >14cm sardine TAC assumed caught west of Cape Agulhas. The ≤14cm sardine bycatch with directed >14cm sardine is assumed to be proportioned west/south of Cape Agulhas in the same manner as the TAC.	-	A.8	
$S^{S}_{j,a}$	Commercial selectivity-at-age a of sardine component j	-	(A.9,A.10)	Sampled from Bayesian posterior distributions of de Moor (2016d). Selectivity is estimated by length in the OM, and thus: $S^{S}_{j,a} = \frac{1}{5}\sum_{y=2011}^{2015}\sum_{l} 0.5\left(S^{S}_{j,y,2,l}A^{com}_{j,y,2,a,l} + S^{S}_{j,y,3,l}A^{com}_{j,y,3,a,l}\right)$ [18], $0 \leq a \leq 5^{+}$
$F_{j,y}$	Commercial fishing mortality of sardine component j in year y	-	A.10 (A.9)	
$\overline{w}^{i}_{j,ac}$	Historical average weights-at-age a in the catches from component j of species i	grams	(A.10)	Table A2
$\acute{\tau}_{j}$	Proportion of the ≤14cm and >14cm sardine TAB with round herring[19] assumed caught west of Cape Agulhas	-	(A.10,A.14,A.15)	$\acute{\tau}_{1} = 1$ and $\acute{\tau}_{2} = 1$
$TAB^{S,draw}_{big,y}$	>14cm sardine bycatch with round herring and anchovy in year y			Randomly sampled from historical bycatches (Figure A1)
ω	Proportion of the directed >14cm sardine TAC used to set the ≤14cm sardine TAB with directed sardine fishing	-		$\omega = 0.07$

[18] The average over quarters 2 and 3 is assumed since in past years, on average, 11% of the directed catch was in quarter 1 and 15% in quarter 4, while 43% and 32% were in quarters 2 and 3, respectively.
[19] The >14cm TAB also allows for some bycatch with anchovy.

Table A1. Parameter definitions.

	Operating Model parameters	Units	Used in Equation	Notes
$\omega_{j,y}^{draw}$	Proportion of the directed >14cm sardine TAC simulated to be caught as ≤14cm sardine bycatch from component j in year y	-	(A.14)	Randomly sampled from historical proportions (Figure A2)
γ_y	Percentage of the initial anchovy TAC used to set the initial ≤14cm sardine TAB with anchovy	-	(A.16)	Equation given as part of Harvest Control Rules
r_y	Ratio of juvenile sardine to anchovy "in the sea" during May	-	A.17 (A.16)	
$r_{y,sur}$	Ratio of juvenile sardine to anchovy observed during the May recruit survey	-	A.18 (A.17)	Observed data input to the Harvest Control Rule
$r_{y,com}$	Ratio of juvenile sardine to anchovy in May commercial catches	-	A.19 (A.17)	Observed data input to the Harvest Control Rule; simulated during OMP testing as A.19
$N_{j,y,r}^{i,obs}$	Acoustic survey estimate of recruitment of component j of species i for May/June of year y	Billions	(A.18)	Observed data input to the Harvest Control Rule; simulated during OMP testing by equation A.36
$N_{j,y,r}^{i,pred}$	OM predicted recruitment of component j of species i in November $y-1$, projected forward to the time of the recruit survey in May/June y	billions	A.41,(A.19)	
$\widehat{N}_{j,y,r}^{i}$	OM predicted recruitment of component j of species i in November $y-1$, projected forward to the time of the recruit survey in May/June y	Billions	(A.45)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
k_{janmay}	Estimated bias in residuals for juvenile sardine: anchovy from commercial catches between January and May	-	A.48,(A.14)	
σ_{janmay}	Standard deviation from the residuals for juvenile sardine: anchovy from commercial catches between January and May	-	A.50,(A.14)	
$\varepsilon_{y,janmay}$	Residuals for juvenile sardine: anchovy from commercial catches between January and May	-	A.49 (A.50)	
k_m	Estimated bias in residuals for juvenile sardine: anchovy from commercial catches during month m	-	A.51 (A.19,A.22)	

Table A1. Parameter definitions.

	Operating Model parameters	Units	Used in Equation	Notes
$\varepsilon_{y,m}$	Residuals for juvenile sardine: anchovy from commercial catches during month m	-	A.20, A.23 (A.18,A.22)	
σ_m	Standard deviation from the residuals for juvenile sardine: anchovy from commercial catches during month m	-	A.53 (A.19,A.22)	
ρ_m	Correlation coefficient between the residuals for juvenile sardine: anchovy from commercial catches during months $m-1$ and m	-	A.54 (A.20,A.23)	
$C_{y,m}^{A,pred}$	OM predicted anchovy catch in month m of year y, for use in calculating the drop-off in small sardine bycatch with anchovy	Thousands of tons	A.24-A.28 (A.21)	
p_m	Average proportion of total anchovy catch during July to December that is taken in month m	-	(A.25-A.28)	
$B_{j,y}^{i,obs}$	November acoustic survey estimate of total biomass of component j of species i in year y	Thousands of tons	A.31	Observed data input to the Harvest Control Rule; simulated during OMP testing by equation A.31
$k_{j,N}^{i}$	Multiplicative bias associated with the acoustic survey estimate of November total biomass of component j of species i	-	(A.31)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
$\varepsilon_{j,y,Nov}^{i}$	Residuals in the simulated observation of November survey estimate of total biomass from OM predicted November biomass in year y of component j of species i	-	A.32,A.33(A.31)	
$\tilde{\sigma}_{j,y,Nov}^{i}$	Standard deviation of the residuals $\varepsilon_{j,y,Nov}^{i}$, being the November survey sampling CV	-	A.34,A.35,(A.32,A.33)	
ρ_{Nov}	Correlation in the residuals between sardine and anchovy November survey estimates of total biomass	-	A.44 (A.33)	

Table A1. Parameter definitions.

	Operating Model parameters	Units	Used in Equation	Notes
φ_{ac}	CV associated with the factors which cause bias in the sardine acoustic survey estimates and which vary inter-annually rather than remain fixed over time			$(\varphi_{ac})^2 = 0.227$ from de Moor and Butterworth 2016a
$(\lambda_{j,N}^i)^2$	Additional variance (over and above the survey sampling CV and $(\varphi_{ac})^2$) associated with the November survey of component j of species i			
$k_{j,r}^i$	Multiplicative bias associated with the acoustic survey estimate of May recruitment of component j of species i	-	(A.36)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
$\varepsilon_{j,y,rec}^i$	Residuals in the simulated observation of May survey estimate of recruitment from OM predicted recruitment in year y of component j of species i	-	A.37,A.38,(A.36)	
$\tilde{\sigma}_{j,y,rec}^i$	Standard deviation of the residuals $\varepsilon_{j,y,rec}^i$, being the May recruit survey sampling CV	-	A.39,A.40,(A.37,A.38)	
ρ_{rec}	Correlation in the residuals between sardine and anchovy survey estimates of recruitment	-	A.47 (A.38)	
$(\lambda_{j,r}^i)^2$	Additional variance (over and above the survey sampling CV) associated with the May recruit survey of component j of species i			
$C_{y,m}^A$	Observed anchovy catch from landings that have targeted anchovy during month m,($m = janmay, may, jun, jul, aug, sep, octdec$) in year y	Thousands of tons	(A.48,A.49)	Observed data
$C_{y,m}^{S,byc}$	Observed <14cm sardine bycatch during from landings that have targeted anchovy during month m,($m = janmay, may, jun, jul, aug, sep, octdec$) in year y	Thousands of tons	(A.48,A.49)	Observed data
$\widehat{N}_{j,y,0}^i$	OM predicted recruitment of component j of species i in November y	Billions	(A.48,A.495)	Sampled from Bayesian posterior distributions of de Moor (2016c,d)
K_j^i	Average pristine level ("carrying capacity") for component j of species i	Thousands of tons		Sampled from Bayesian posterior distributions of de Moor (2016c,d)

Table A2. Average 1984 to 2015 weights-at-age (in grams) from the historical catches ($\overline{w}^{i}_{j,ac}$, $i = S, A$). As sardine catch weight-at-age is not directly available, the average over all years is taken from proxy-annual catch weights-at-age calculated[20] as an average of the November survey weight at age a in year $y-1$ and weight-at-age $a+1$ in year y.

	Sardine single stock			Sardine west component	
	'Normal' years	'Peak' years		'Normal' years	'Peak' years
$\overline{w}^{S}_{1,0c}$	20.86	13.18	$\overline{w}^{S}_{1,0c}$	17.99	18.09
$\overline{w}^{S}_{1,1c}$	60.57	49.58	$\overline{w}^{S}_{1,1c}$	58.56	58.81
$\overline{w}^{S}_{1,2c}$	88.62	82.95	$\overline{w}^{S}_{1,2c}$	87.48	87.62
$\overline{w}^{S}_{1,3c}$	97.35	95.77	$\overline{w}^{S}_{1,3c}$	95.04	95.07
$\overline{w}^{S}_{1,4c}$	99.53	99.14	$\overline{w}^{S}_{1,4c}$	96.60	96.60
$\overline{w}^{S}_{1,5+c}$	99.95	99.80	$\overline{w}^{S}_{1,5+c}$	96.85	96.85
	Sardine south component			**Anchovy**	
	'Normal' years	'Peak' years			
$\overline{w}^{S}_{2,0c}$	16.01	16.04	$\overline{w}^{A}_{0c}$	5.48	
$\overline{w}^{S}_{2,1c}$	53.11	53.31	$\overline{w}^{A}_{1c}$	12.70	
$\overline{w}^{S}_{2,2c}$	81.37	81.50			
$\overline{w}^{S}_{2,3c}$	90.14	90.17			
$\overline{w}^{S}_{2,4c}$	92.28	92.29			
$\overline{w}^{S}_{2,5+c}$	92.69	92.69			

[20] At the joint posterior mode for each baseline OM.

Table A3. Anchovy catch (in thousands of tons) from landings that have targeted* anchovy ($C^{A}_{y,m}$), for five-month ("janmay"), five single month ("may", "jun", "jul", "aug", "sep"), and a three-month ("octdec") periods, with the associated recorded landings of <14cm sardine bycatch ($C^{S,byc}_{y,m}$, also in thousands of tons).

Year	$C^{A}_{y,janmay}$	$C^{A}_{y,may}$	$C^{A}_{y,jun}$	$C^{A}_{y,jul}$	$C^{A}_{y,aug}$	$C^{A}_{y,sep}$	$C^{A}_{y,octdec}$	$C^{S,byc}_{y,janmay}$	$C^{S,byc}_{y,may}$	$C^{S,byc}_{y,jun}$	$C^{S,byc}_{y,jul}$	$C^{S,byc}_{y,aug}$	$C^{S,byc}_{y,sep}$	$C^{S,byc}_{y,octdec}$
1987	377.5	14.9	50.6	78.5	67.9	24.4	#	1.1	0.3	1.0	1.2	1.0	0.2	#
1988	252.5	50.1	74.3	60.7	70.4	38.7	73.9	1.0	0.8	1.9	0.4	0.5	0.1	0.3
1989	233.4	83.0	39.2	13.7	#	#	#	5.1	2.7	1.2	0.3	#	#	#
1990	88.6	36.3	59.5	0.5	0.2	0.0	#	3.2	1.9	3.5	0.0	0.0	0.0	#
1991	90.7	22.7	51.4	6.1	1.0	0.0	#	2.8	0.4	1.6	0.0	0.0	0.0	#
1992	178.6	58.8	34.6	44.3	56.3	26.2	4.8	3.2	1.5	2.3	2.1	2.5	0.3	0.0
1993	110.9	13.0	0.8	10.8	67.0	38.4	3.0	2.3	1.2	0.2	0.6	1.6	0.6	0.1
1994	94.6	38.8	17.1	0.2	29.2	2.8	#	5.2	3.1	1.6	0.0	2.2	0.0	#
1995	56.0	13.1	35.1	31.7	37.2	1.7	11.3	2.5	1.3	4.1	5.1	5.9	0.1	1.7
1996	20.9	9.2	13.4	0.2	#	#	0.0	3.2	1.3	1.5	0.0	#	#	0.0
1997	0.6	0.5	0.7	20.0	10.1	21.3	3.3	0.1	0.1	0.3	1.4	0.7	2.9	0.8
1998	39.7	22.4	42.0	11.9	3.7	4.3	1.2	4.8	3.4	4.2	0.9	0.2	0.5	0.1
1999	30.3	18.9	28.2	20.0	33.2	51.5	13.9	1.7	1.3	2.1	0.5	0.7	0.7	0.2
2000	103.1	41.2	15.7	50.8	55.0	34.1	5.8	3.1	1.0	0.8	0.3	0.2	0.0	0.0
2001	84.1	32.7	44.9	10.1	30.0	50.9	62.3	3.4	2.2	2.6	1.1	3.3	1.0	0.8
2002	35.0	6.6	48.6	48.1	33.8	43.5	0.3	0.9	0.3	1.8	1.3	5.5	2.3	0.0
2003	41.1	23.2	77.5	47.9	16.7	39.8	28.7	3.9	2.0	3.9	1.1	0.1	0.2	0.5
2004	58.5	38.6	20.2	65.4	22.4	15.6	0.7	3.5	2.9	0.5	0.7	0.6	0.2	0.0
2005	133.6	55.8	21.2	42.0	27.0	42.9	10.9	2.7	1.3	0.4	0.4	0.3	0.5	0.2
2006	19.0	7.0	31.1	35.5	20.6	22.4	1.9	0.9	0.6	1.7	1.8	0.9	1.6	0.1
2007	77.0	57.6	31.0	34.4	37.3	43.5	27.2	2.3	1.5	0.4	0.2	0.1	0.1	0.2
2008	69.9	34.9	21.1	26.3	59.1	28.8	58.6	1.6	1.5	0.6	0.3	0.5	0.1	0.1
2009	53.6	18.6	8.8	38.2	35.2	27.7	8.9	1.0	0.3	0.3	0.4	0.6	0.1	0.1
2010	63.3	14.8	39.2	65.6	39.4	4.9	0.1	6.3	2.5	5.4	3.9	1.3	0.0	0.1
2011	42.9	22.0	16.5	39.3	13.8	#	#	4.3	3.1	1.2	2.8	1.2	#	#
2012	162.9	57.7	32.0	43.9	21.8	31.7	12.4	5.3	2.3	0.7	0.3	0.2	0.1	0.0
2013	43.9	17.7	12.5	3.4	3.5	8.0	6.3	3.2	0.0	0.0	0.0	0.0	0.1	0.0
2014	162.9	42.9	3.9	21.9	19.2	21.1	8.6	5.8	0.0	0.0	0.1	0.0	0.0	0.0
2015	172.0	68.4	28.5	29.0	4.3	0.2	0.8	12.7	4.6	0.4	0.1	0.0	0.0	0.0

* A landing is assumed to have targeted anchovy when the ratio anchovy : (anchovy + directed sardine + horse mackerel + round herring) exceeds 0.5 (in terms of mass).
[#] As no anchovy were landed during these months, sardine bycatch with anchovy is not applicable.

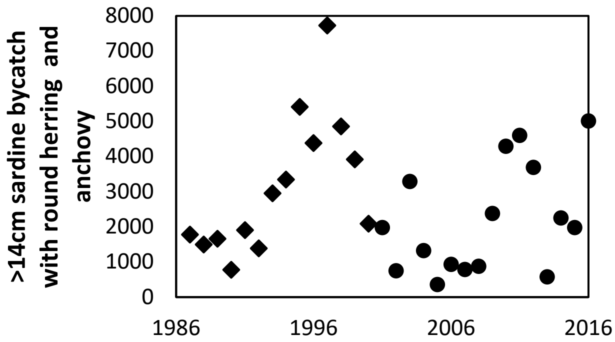

Figure A1. The historical >14cm sardine bycatch with round herring and anchovy. The circles are data from Johan de Goede and the diamonds are data from Jan van der Westhuizen. The distribution from which future samples are made (equation A.10) consists of the observations from the most recent 10 years only.

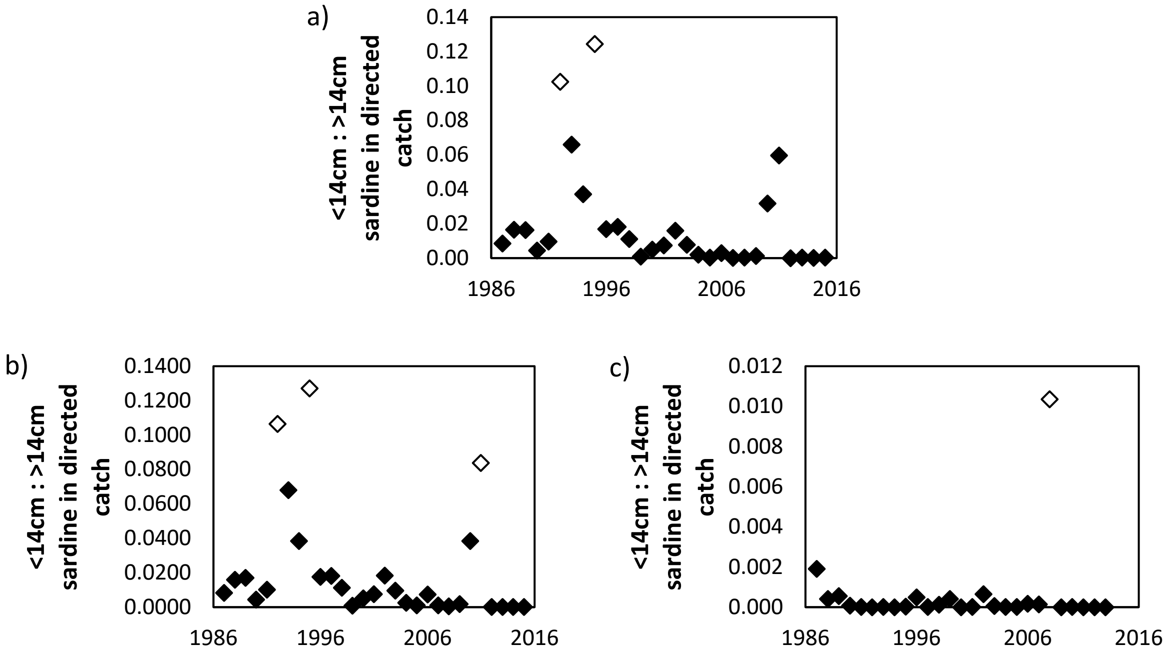

Figure A2. The historical ratio of ≤14cm sardine to >14cm sardine in the directed sardine fishery for a) all catch, b) catch west of Cape Agulhas and c) catch south of Cape Agulhas. The open diamonds indicate historical ratios above the ratio used to set the ≤14cm sardine TAB with directed >14cm sardine TAC; these are set at the maximum values (of 7% for a single-area directed sardine TAC and the west-area TAC and 1% for the south-area TAC) in the distribution from which future samples, $\omega_{j,y}^{draw}$, are made (equations A.14, A.15 and A.21).

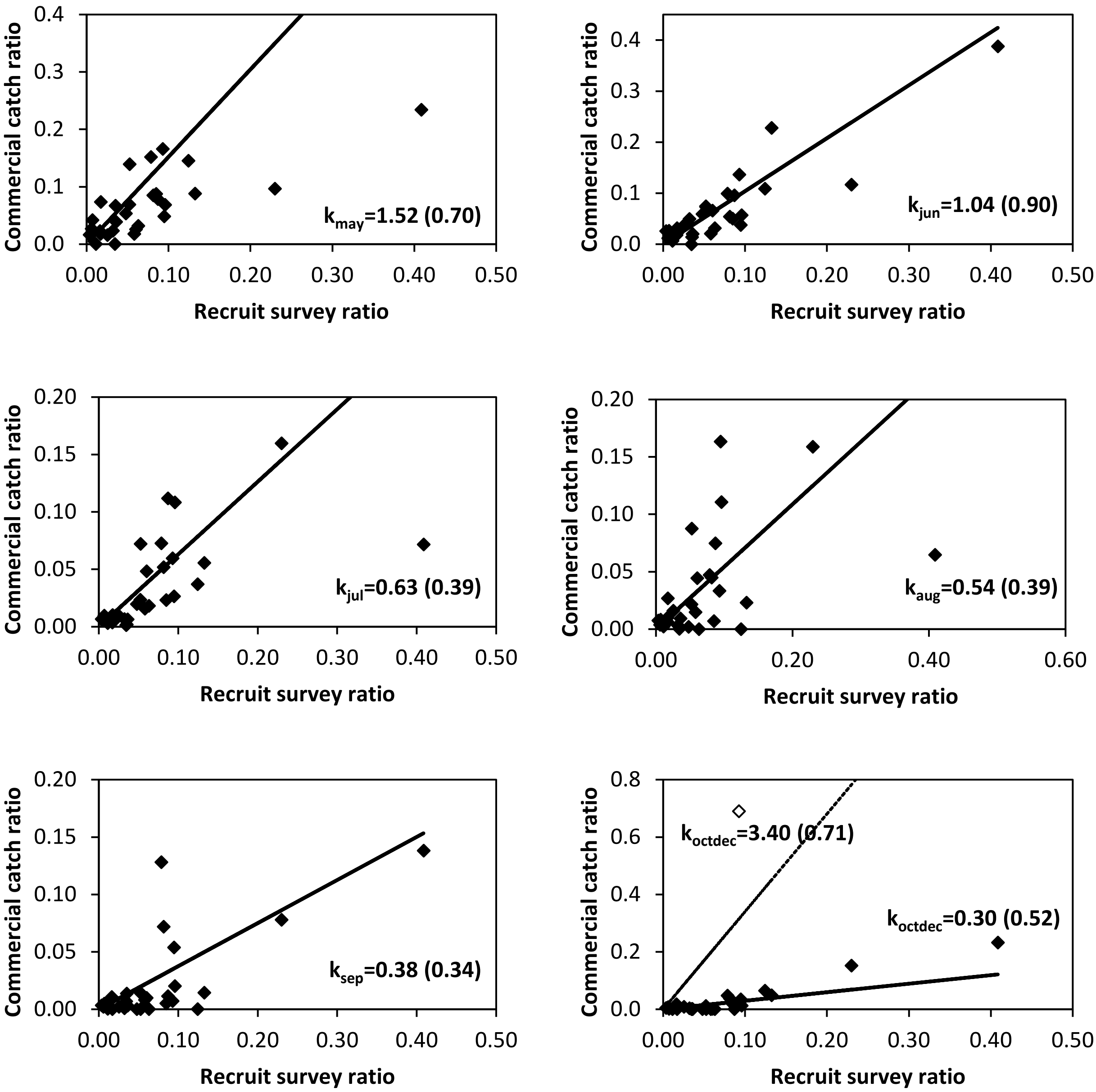

Figure A3. The regressions of the ratio of small sardine bycatch : anchovy[21] in the monthly commercial catch against that observed in the recruit survey, i.e. minimising $\sum_{y=2006}^{2015}\left[\left(C_{y,m}^{S,byc}/C_{y,m}^{A}\right)-k_m\left(N_{1,y,r}^{S,obs}/N_{1,y,r}^{A,obs}\right)\right]^2$ w.r.t. k_m. The outliers of commercial ratio of 0.69 in October to December 2010 (shown as an open diamond) is removed, as this could have been biased by the mid-water trawl experiments which occurred during this time. The regression including this outlier is given by the dotted line. The k_m's obtained when considering all years (1987-2015) are also given in brackets.

[21] For cases where anchovy is the most common species by mass in the landing

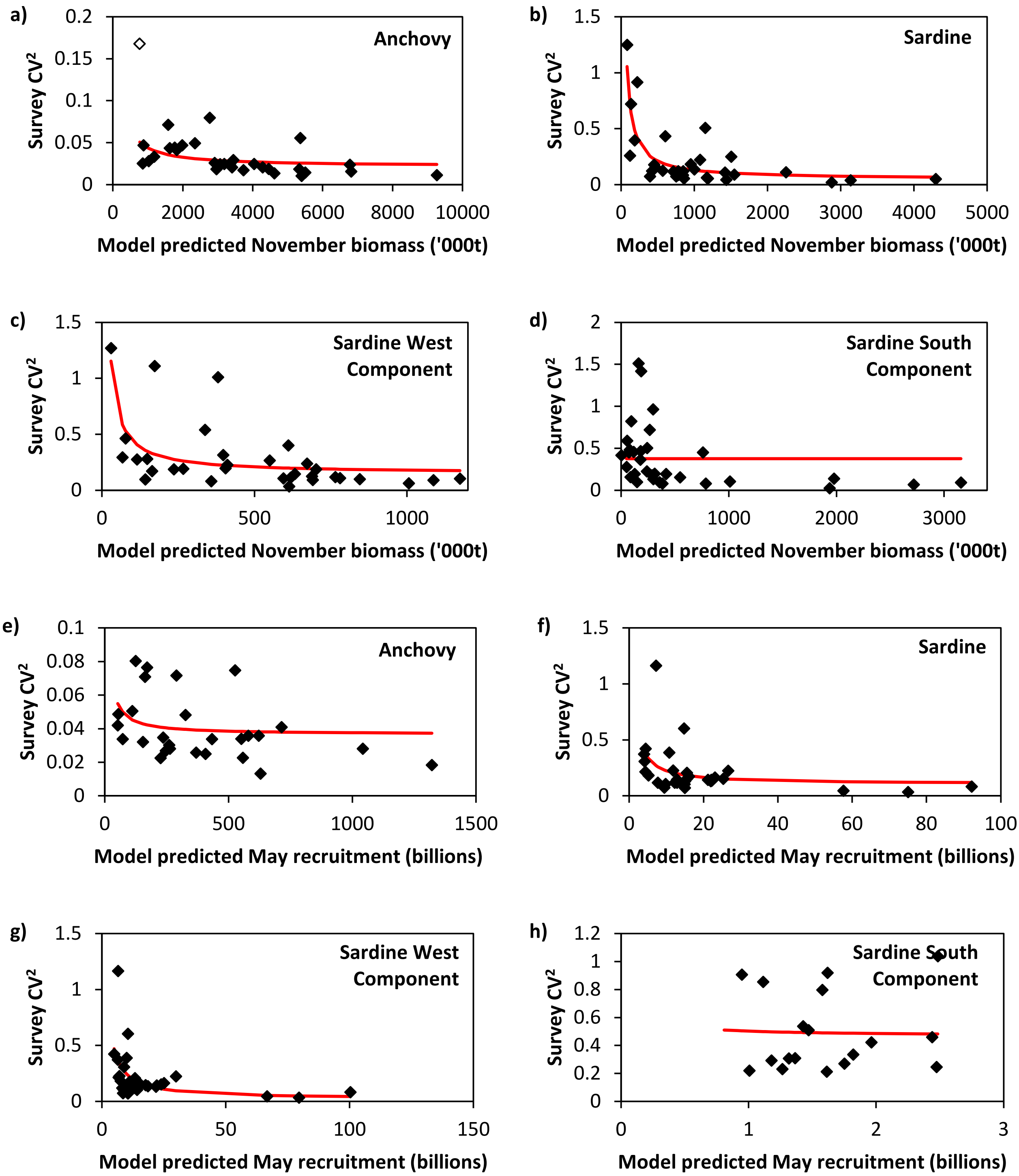

Figure A4. The regressions between observed survey CV^2 and model predicted abundance for a) anchovy November, b) sardine single stock November, c) sardine west component November, d) sardine south component November, e) anchovy May, f) sardine single stock May, g) sardine west component May and h) sardine south component May, for use in equations (A.29), (A.30), (A.32) and (A.33). In b) the outlier (767,0.17) was excluded from the regression.