Assessment of the South African anchovy resource using data from 1984 – 2019 : initial results

C.L. de Moor*

Correspondence email: *carryn.demoor@uct.ac.za*

The quantitative assessment of the South African anchovy resource has been updated from that last estimated with four more years' data and a few updates to the model structure. The model continues to assume a Beverton Holt stock recruitment relationship and time-invariant natural mortality of 1.2year^{-1}. The resource abundance is estimated to be about half of the historical (1984-2019) average, with a total biomass of 1.7 million tons in November 2019.

Introduction

The operating model of the South African anchovy resource has been updated from the last assessment which was conditioned on data collected up to and including November 2015 (de Moor 2016). Given time constraints, a number of model assumptions and prior distributions have not yet been fully tested and have simply been based on those used by de Moor (2016). These results, which are given at the joint posterior mode only, should therefore be considered 'initial'.

Methods

de Moor et al. (2020) detail the data used to condition this assessment, which have been updated from that in de Moor et al. (2016) with 4 more years' data.

The operating model used for the South African anchovy resource is detailed in Appendix A. All parameters used in this document are listed with definitions as well as parameter values, prior distributions or associated equations in Table A.1. While the base case model structure is mostly unchanged from de Moor (2016), key changes in the population dynamics model include:

i) A time invariant weight-at-length relationship is used instead of one which changes annually as the hydro-acoustic survey estimates of total biomass are independent of condition factor (de Moor 2019).

ii) A decrease in the minus length class to allow for new data in the 2cm length class.

iii) Alignment of the break-points in the length-at-age distribution to correspond with the length classes in which data are provided.

iv) Variance in the length-at-age distribution varies by quarter and not only by age.

Results

Results of model fits to data and model estimated relationships are given in Figures 1 to 11. As these are initial results they are not discussed in depth here. Of interest, however, is that spawner biomass is estimated to be lower than that estimated by de Moor (2016), that the model is unable to match the relatively high survey estimates of recruitment in June 2017 and - to a lesser extent - in June 2019, with the decreasing time series of November survey estimates from 2013 onwards and that the Beverton Holt stock recruitment relationship has a lower asymptote than that estimated by de Moor (2016).

* MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.

Discussion

This document provides an updated assessment of the South African anchovy resource, taking into account four recent year's data and a few updates to the model. This assessment should be considered initial as there has been no consideration of alternative plausible model parameters (e.g. time-invariant rate of natural mortality) or assumptions (e.g. stock-recruitment relationships). The total resource biomass in November 2019 was estimated to be 1.7 million tons – about half the historical (1984-2019) average of 3.2 million tons. This model estimates recruitment in recent years to be lower than that experienced since 2000 and therefore a lower Beverton Holt stock-recruitment relationship than that estimated by the Operating Model used when simulation testing OMP-18 (de Moor 2018).

References

de Moor CL. 2016. Assessment of the South African anchovy resource using data from 1984 – 2015: results at the posterior mode. DAFF Branch Fisheries Document: FISHERIES/2016/OCT/SWG-PEL/46.

de Moor CL. 2018. The 2018 Operational Management Procedure for the South African sardine and anchovy resources. DAFF Branch Fisheries Document: FISHERIES/2018/DEC/SEG-PEL/37.

de Moor CL. 2019. Progress towards updating the assessment of the South African sardine resource using data from 1984-2018. DEA Branch Fisheries Document: FISHERIES/2019/NOV/SWG-PEL/29.

de Moor CL and Butterworth DS. 2015. A new length-weight relationship for South African anchovy. DAFF Branch Fisheries Document: FISHERIES/2015/JUN/SWG-PEL/26.

de Moor CL, Coetzee J, Merkle D, van der Westhuizen JJ and van der Lingen C. 2016. A record of the generation of data used in the 2016 sardine and anchovy assessments. DAFF Branch Fisheries Document: FISHERIES/2016/APR/SWG-PEL/13rev.

de Moor CL, Merkle D and Coetzee J. 2020. The data used in the 2020 anchovy assessment. DEA Branch Fisheries Document: FISHERIES/2020/JAN/SWG-PEL/02.

Melo YC. 1992. The biology of the anchovy *Engraulis capensis* in the Benguela Current region. PhD thesis, University of Stellenbosch, xii + 180pp.

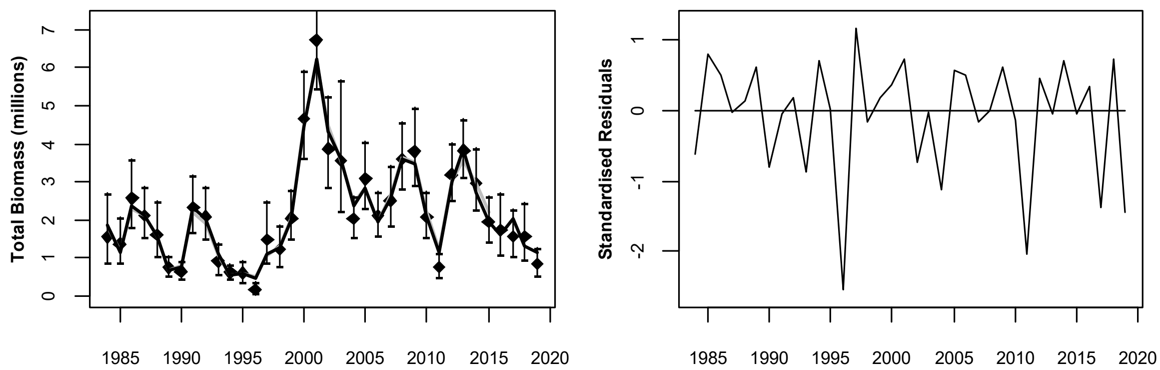

Figure 1. Acoustic survey and bias corrected model estimated for November anchovy biomass from 1984 to 2019. The survey indices are shown with 95% confidence intervals reflecting survey inter-transect variance. The standardised residuals are given in the right hand plot. The November anchovy biomass estimated by de Moor (2016) from 1984 to 2015 is shown in grey.

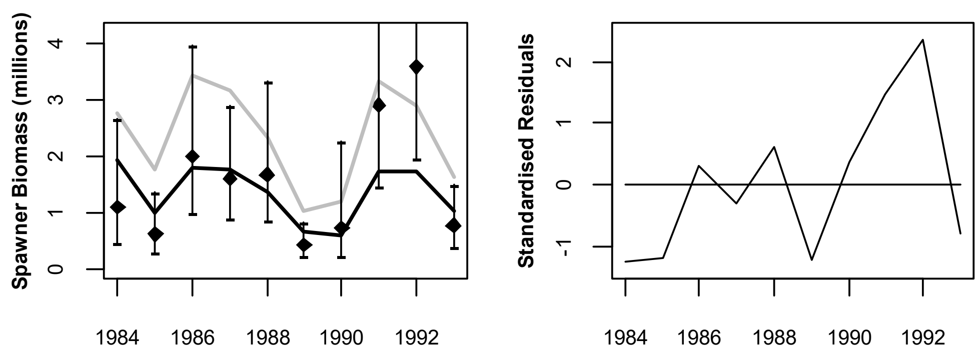

Figure 2. Daily egg production method and bias corrected model estimated November anchovy spawner biomass from 1984 to 1993. The survey indices are shown with 95% confidence intervals. The standardised residuals are given in the right hand plot. The November anchovy spawner biomass estimated by de Moor (2016) is shown in grey.

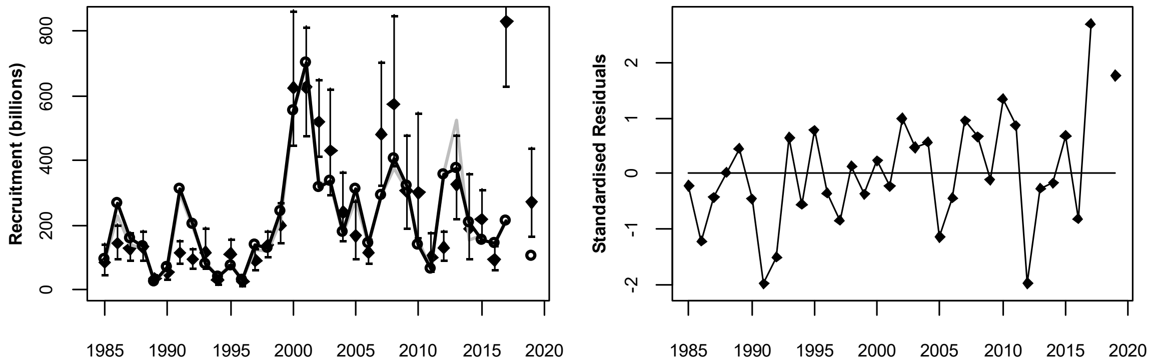

Figure 3. Acoustic survey and bias corrected model estimated (black with open circles) anchovy recruitment numbers from May 1985 to May 2019. The survey indices are shown with 95% confidence intervals reflecting survey inter-transect. Note that additional survey variance is estimated included in the model, and not shown in this figure. The standardised residuals are given in the right hand plot. The November anchovy biomass estimated by de Moor (2016) from 1984 to 2015 is shown in grey.

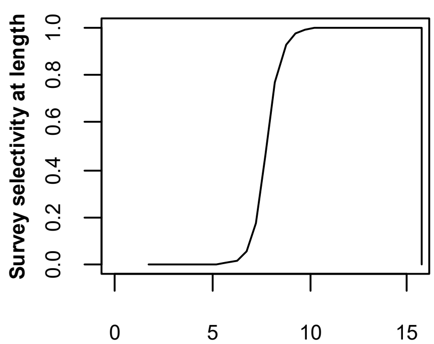

Figure 4. Model estimated trawl survey selectivity at length.

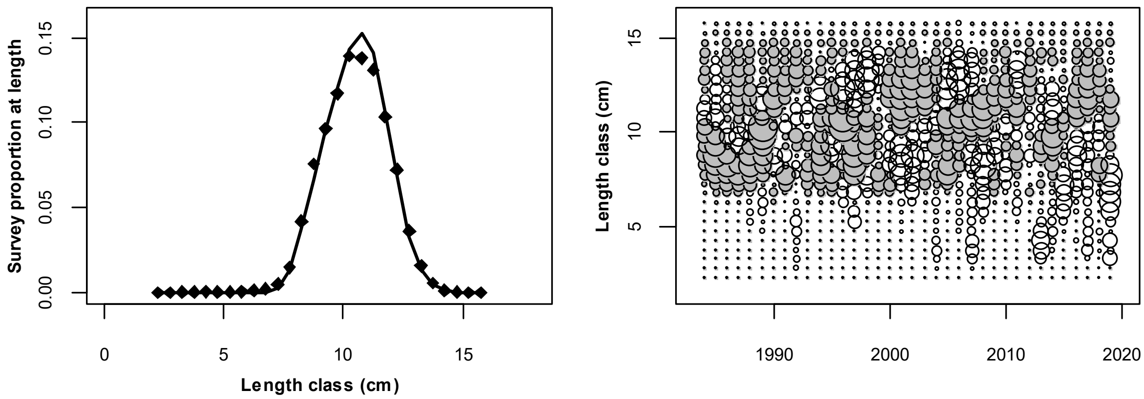

Figure 5. Average (over all years) model predicted and observed proportions-at-length in the November survey trawls. The standardised residuals are given in the bubble plot; the size of the bubbles are proportional to the absolute value of the residuals, while the shaded bubbles show negative and the unshaded bubbles show positive residuals.

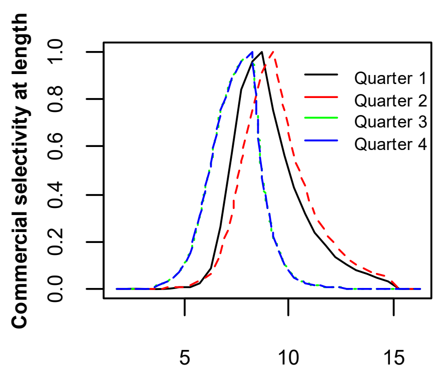

Figure 6. Model estimated quarterly commercial survey selectivity at length.

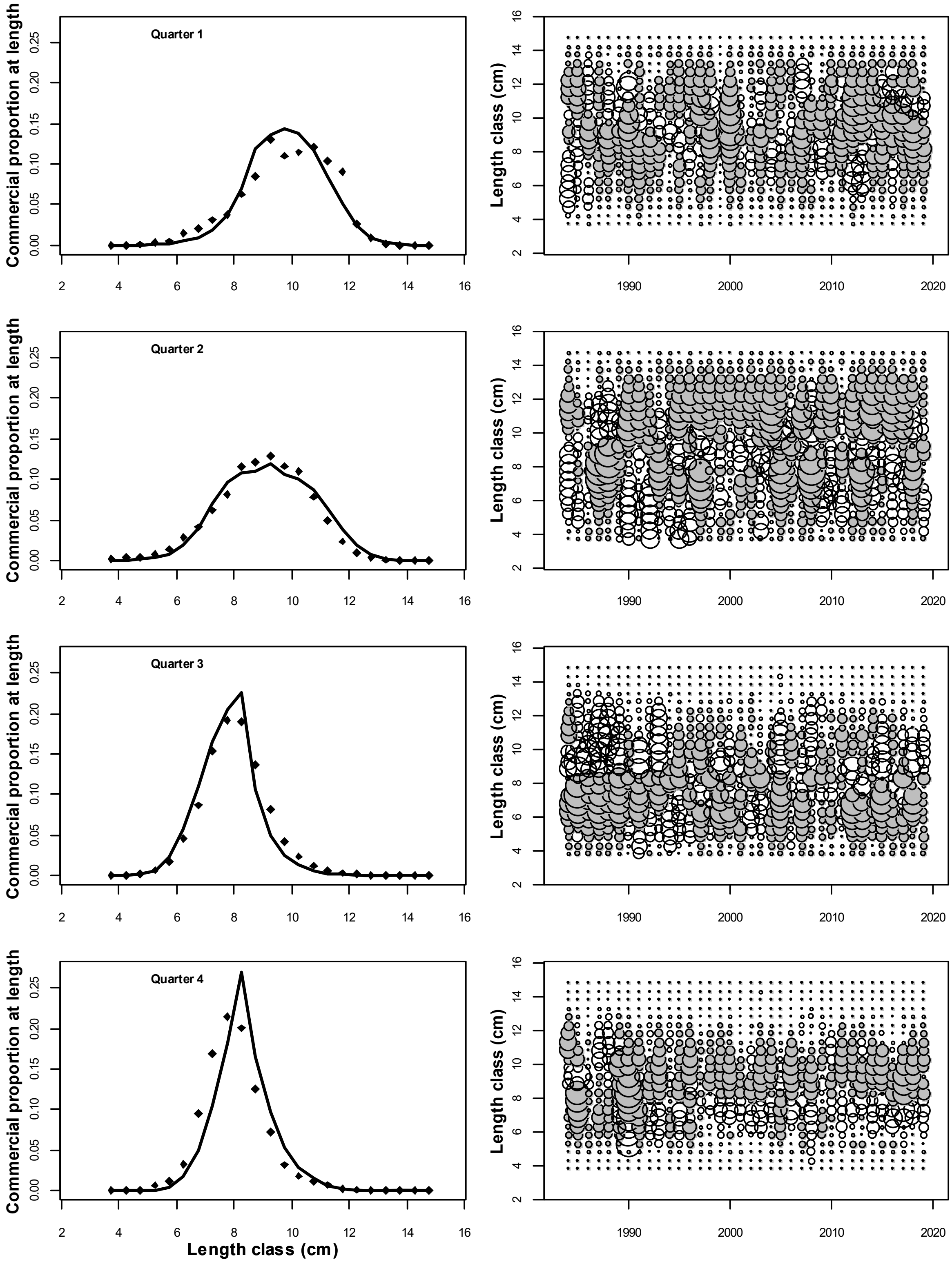

Figure 7. Average (over all years) model predicted and observed proportions-at-length in the quarterly commercial catch. The standardised residuals are given in the bubble plot; the size of the bubbles are proportional to the absolute value of the residuals, while the shaded bubbles show negative and the unshaded bubbles show positive residuals.

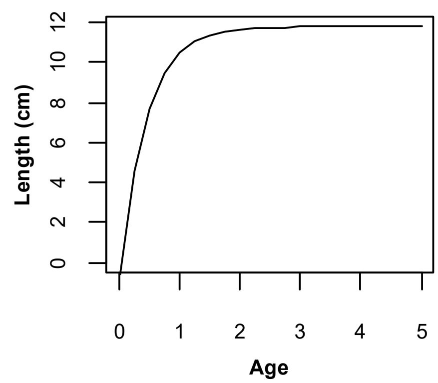

Figure 8. The model estimated von Bertalanffy growth curve, where integer ages are taken to correspond to November.

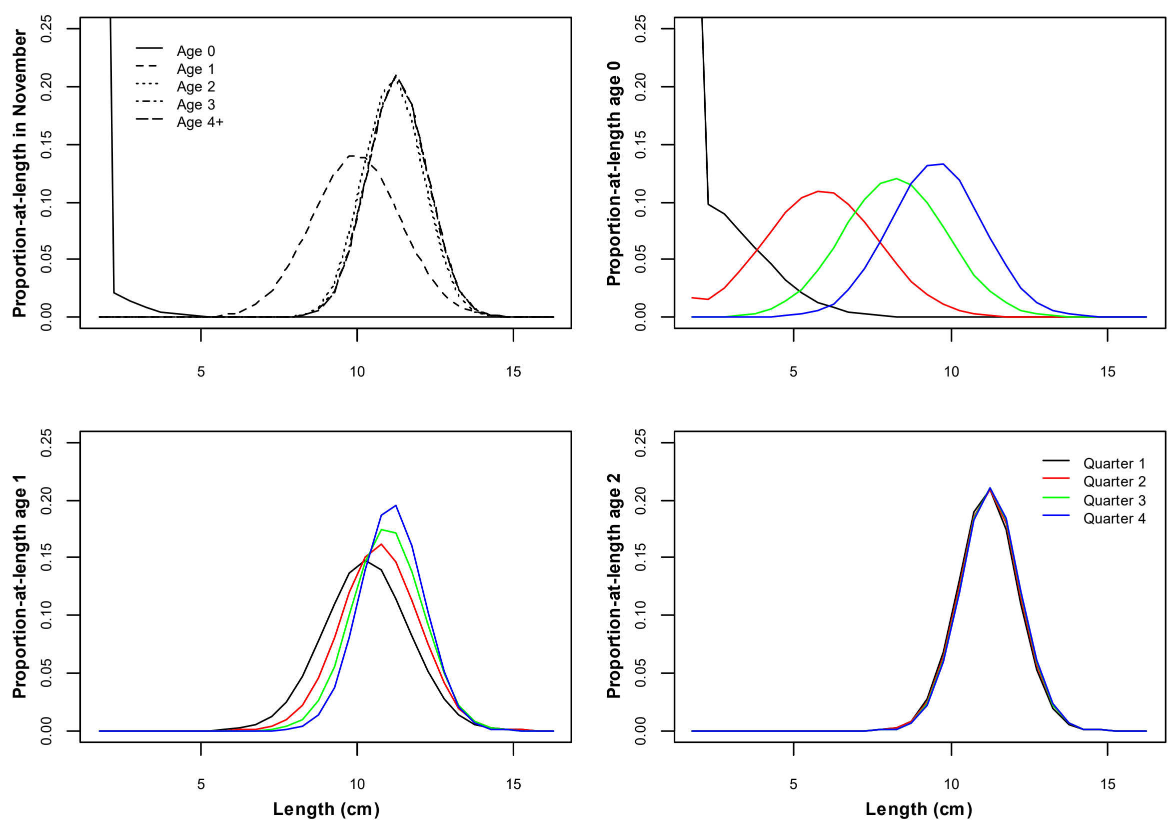

Figure 9. The model estimated distributions of proportions-at-length for each ages 0, 1 and 2, given at the middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken) and the distributions for all ages at 1 November (corresponding to the time of the biomass survey).

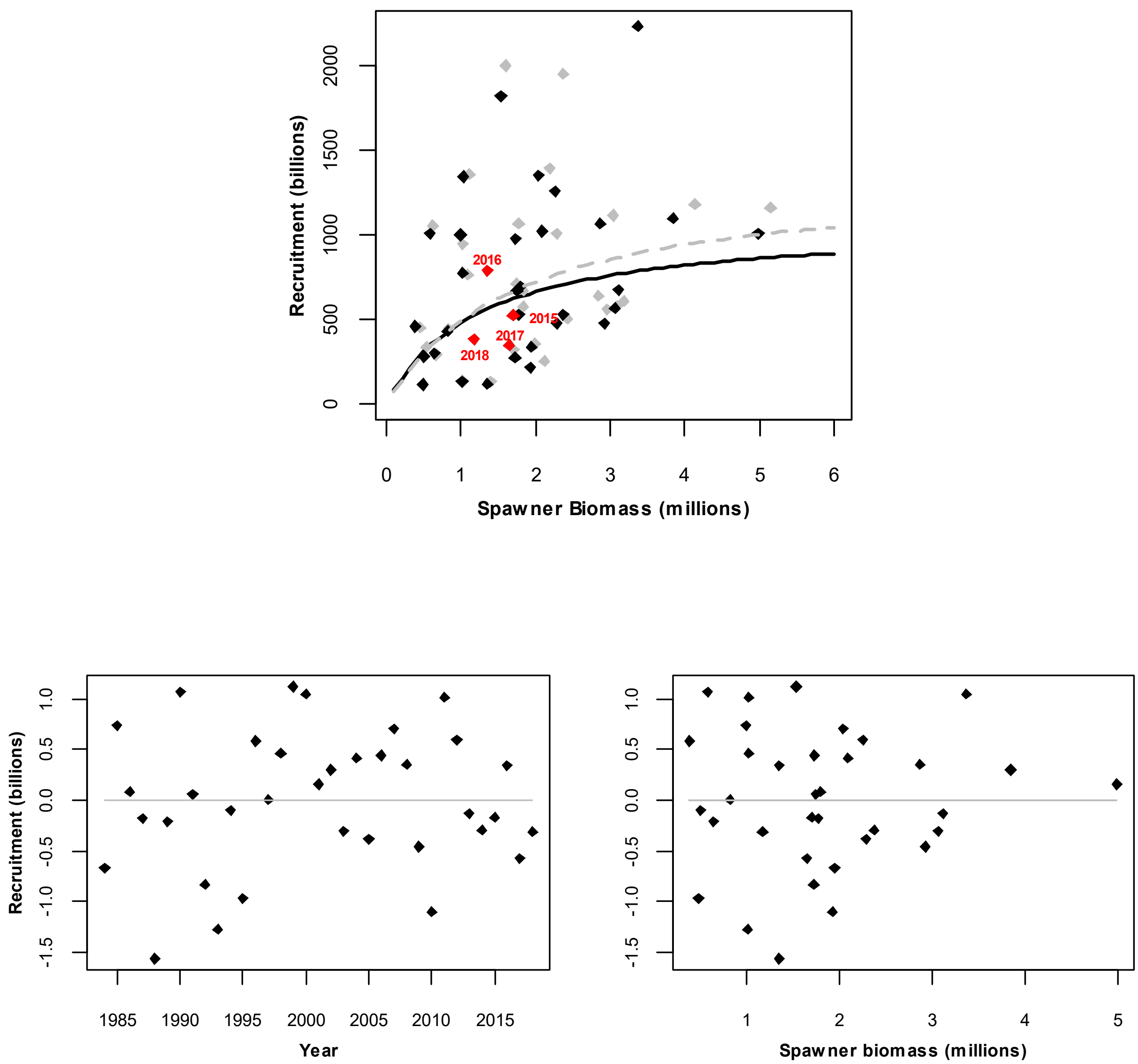

Figure 10. Model predicted anchovy recruitment (in November) plotted against spawner biomass from November 1984 to November 2018 with the Beverton Holt stock recruitment relationship. The grey line and points correspond to that estimated from November 1984 to 2014 by de Moor (2016). The standardised residuals from the fit are given in the lower plots, against year and against spawner biomass.

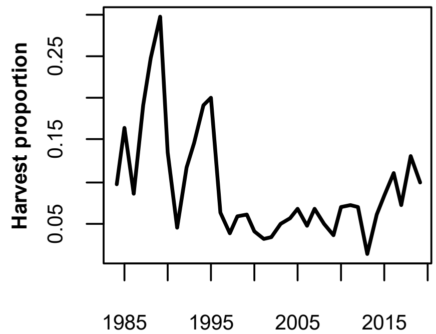

Figure 11. The model estimated historical harvest proportion (catch by mass as a proportion of total biomass).

Appendix A: Bayesian operating model for the South African anchovy resource

In the below equations a "$\frown$" is used to represent an estimate of a quantity (e.g. biomass) from a source external to this model (e.g. a survey). Model predicted quantities are represented by terms without any additional super-/sub-scripts other than dependencies on, for example, year, length etc.

Model Assumptions

1) All fish have a birthdate of 1 November.
2) Anchovy mature according to a length-based ogive with an L_{50} of 10.6cm.
3) A plus group of age 4 is used.
4) A minus length class of 2cm and a plus length class of 16cm is used.
5) Natural mortality is age-invariant for fish aged 1 and older.
6) Two hydro-acoustic surveys are held each year: the first takes place in November and provides an index of abundance of the total biomass; the second is in May/June (known as the recruit survey) and provides an index of abundance of recruitment.
7) The November and recruit surveys provide relative indices of abundance of unknown bias.
8) The egg survey observations (derived from data collected during the earlier November surveys) provide estimates of spawner biomass in absolute terms.
9) The survey designs have been such that they result in survey estimates of abundance whose bias is invariant over time.
10) Pulse fishing occurs four times a year, in the middle of each quarter of the assessment year (November to October).

Population Dynamics

The basic dynamic equations for anchovy, based on Pope's approximation (Pope, 1984), are as follows, where $y_1 = 1984$ and $y_n = 2019$.

Numbers-at-age at 1 November

$$N^A_{y,a} = \left(\left(\left(\left(N^A_{y-1,a-1}e^{-M^A_{a-1,y}/8} - C^A_{y,1,a-1}\right)e^{-M^A_{a-1,y}/4} - C^A_{y,2,a-1}\right)e^{-M^A_{a-1,y}/4} - C^A_{y,3,a-1}\right)e^{-M^A_{a-1,y}/4} - C^A_{y,4,a-1}\right)e^{-M^A_{a-1,y}/8}$$

$$y_1 \le y \le y_n\ ,\ 1 \le a \le 3$$

$$\begin{aligned} N^A_{y,4+} = & \left(\left(\left(\left(N^A_{y-1,3}e^{-M^A_{3,y}/8} - C^A_{y,1,3}\right)e^{-M^A_{3,y}/4} - C^A_{y,2,3}\right)e^{-M^A_{3,y}/4} - C^A_{y,3,3}\right)e^{-M^A_{3,y}/4} - C^A_{y,4,3}\right)e^{-M^A_{3,y}/8} \\ & + \left(\left(\left(\left(N^A_{y-1,4+}e^{-M^A_{4+,y}/8} - C^A_{y,1,4+}\right)e^{-M^A_{4+,y}/4} - C^A_{y,2,4+}\right)e^{-M^A_{4+,y}/4} - C^A_{y,3,4+}\right)e^{-M^A_{4+,y}/4} - C^A_{y,4,4+}\right)e^{-M^A_{4+,y}/8} \end{aligned}$$

$$y_1 \le y \le y_n \qquad \text{(A.1)}$$

Numbers-at-length at 1 November

The model estimated numbers-at-length range from a 1.5cm minus group to a 16cm plus group, denoted 1.5^- and 16^+, respectively, in the remaining text. The length class sizes are 0.5cm and, where length is used in an equation, the mid-point of the length class is used. The model predicted numbers-at-length at the time of the survey are:

$N_{y,l}^{A} = \sum_{a=0}^{4+} A_{a,l}^{sur} N_{y,a}^{A}$ $\qquad y_1 \leq y \leq y_n,\ 1.5^{-}cm \leq l \leq 16^{+}cm$ (A.2)

The model predicted numbers-at-length of ages 1+ only are given by:

$N_{y,l}^{A,1+} = \sum_{a=1}^{4+} A_{a,l}^{sur} N_{y,a}^{A}$ $\qquad y_1 \leq y \leq y_n,\ 1.5^{-}cm \leq l \leq 16^{+}cm$ (A.3)

The proportion of anchovy of age a that fall in the length group l at 1 November matrix, $A_{a,l}^{sur}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$A_{a,l}^{sur} \sim N\left(L_{\infty}\left(1 - e^{-\kappa(a-t0)}\right), \vartheta_a^2\right)$ $\qquad 0 \leq a \leq 4^{+},\ 1.5^{-}cm \leq l \leq 16^{+}cm$ (A.4)[1]

Natural mortality

Natural mortality is modelled to vary annually around a median as follows:

$M_{0,y}^{A} = \bar{M}_{j}^{A} e^{\varepsilon_{j,y}}$ with $\varepsilon_{1984}^{j} = \eta_{1984}^{j}$ and $\varepsilon_{y}^{j} = \rho\varepsilon_{y-1}^{j} + \eta_{y}^{j}\sqrt{1-\rho^2}$, $y > y_1$ (A.5)

$M_{1+,y}^{A} = \bar{M}_{ad}^{A} e^{\varepsilon_{ad,y}}$ with $\varepsilon_{1984}^{ad} = \eta_{1984}^{ad}$ and $\varepsilon_{y}^{ad} = \rho\varepsilon_{y-1}^{ad} + \eta_{y}^{ad}\sqrt{1-\rho^2}$, $y > y_1$ (A.6)

Biomass associated with the November survey

$B_{y}^{A} = \sum_{l=1.5^{-}}^{16^{+}} N_{y,l}^{A} w_{l}^{A}$ $\qquad y_1 \leq y \leq y_n$ (A.7)

November spawner biomass

Anchovy are assumed to mature from age 1 and thus the spawning stock biomass is:

$SSB_{y}^{A} = \sum_{l=1.5^{-}}^{16^{+}} f_{l}^{A} N_{y,l}^{A,1+} w_{l}^{A}$ $\qquad y_1 \leq y \leq y_n$ (A.8)

Commercial selectivity

Commercial selectivity-at-length is assumed to follow the logistic shape, with a dome at high lengths. Commercial selectivity is assumed to vary by quarter, but remain unchanged over time. Selectivity-at-lengths less than the smallest observed length class (3.5cm) and greater than the largest observed length class (14.5cm) are taken to be zero. Thus we have:

$$S_{y,q,l} = \begin{cases} 0 & 1.5^{-}cm \leq l \leq 3cm \\ 1/\left(1 + e^{\psi_q(l - l50_q)}\right) & 3.5cm \leq l \leq S_{q}^{break} \\ S_{y,q,l-1} e^{\delta_q} & S_{q}^{break} \leq l \leq 14.5cm \\ 0 & 15cm \leq l \leq 16^{+}cm \end{cases} \qquad y_1 \leq y \leq y_n,\ 1 \leq q \leq 4$$ (A.9)[2]

Commercial selectivity-at-age is given by:

$S_{y,q,a} = \sum_{l=1.5^{-}}^{16^{+}} A_{q,a,l}^{com} S_{y,q,l}$ $\qquad y_1 \leq y \leq y_n,\ 1 \leq q \leq 4,\ 0 \leq a \leq 4^{+}$ (A.10)

The proportion of anchovy of age a that fall in the length group l in quarter q, $A_{q,a,l}^{com}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A_{q,a,l}^{com} \sim N\left(L_{\infty}\left(1 - e^{-\kappa(a+(2q-1)/8-t0)}\right), \left(1 - \frac{2q-1}{8}\right)\vartheta_a^2 + \frac{2q-1}{8}\vartheta_{a+1}^2\right)$$

$1 \leq q \leq 4,\ 0 \leq a \leq 4^{+},\ 1.5^{-}cm \leq l \leq 16^{+}cm$ (A.11)[3]

---

[1] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

[2] These selectivities-at-length are renormalized so that the maximum is 1.

[3] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

Commercial catch

Anchovy quarterly pulse catches are split between ages using a model estimated selectivity:

$$C_{y,1,a}^A = N_{y-1,a}^A e^{-M_{a,y}^A/8} S_{y,1,a} F_{y,1}$$

$$C_{y,2,a}^A = \left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} S_{y,2,a} F_{y,2}$$

$$C_{y,3,a}^A = \left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} S_{y,3,a} F_{y,3}$$

$$C_{y,4,a}^A = \left(\left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,3,a}^A\right) e^{-M_{a,y}^A/4} S_{y,4,a} F_{y,4}$$

$$y_1 \le y \le y_n,\ 0 \le a \le 4^+ \qquad \text{(A.12)}$$

In the equations above the difference in the year subscript between the catch-at-age and initial numbers-at-age is because these numbers-at-age pertain to November of the previous year.

The fished proportion of the available biomass from the anchovy fishery is estimated by:

$$F_{y,1} = \frac{\sum_{m=11}^{12} \sum_{l=3.5}^{14.5} C_{y-1,m,l}^{RLF} + \sum_{l=3.5}^{14.5} C_{y,1,l}^{RLF}}{\sum_{a=0}^{4^+} N_{y-1,a}^A e^{-M_{a,y}^A/8} S_{y,1,a}}$$

$$F_{y,2} = \frac{\sum_{m=2}^{4} \sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4^+} \left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} S_{y,2,a}}$$

$$F_{y,3} = \frac{\sum_{m=5}^{7} \sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4^+} \left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} S_{y,3,a}}$$

$$F_{y,4} = \frac{\sum_{m=8}^{10} \sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4^+} \left(\left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,3,a}^A\right) e^{-M_{a,y}^A/4} S_{y,4,a}}[4] \qquad y_1 \le y \le y_n \text{ (A.13)}$$

A penalty is imposed within the model to ensure that $S_{y,l} F_{y,q} < 0.95$ for all l.

Recruitment

Recruitment at the beginning of November is assumed to fluctuate lognormally about a stock-recruitment curve (see Table 1):

$$N_{y,0}^A = f\left(SSB_y^A\right) e^{\varepsilon_y^A} \qquad y_1 \le y \le y_n \qquad \text{(A.14)}$$

Number of recruits at the time of the recruit survey

The following equation projects $N_{y,0}^A$ to the start of the recruit survey, taking natural and fishing mortality into account:

$$N_{y,r}^A = \left(\left(\left(N_{y-1,0}^A e^{-M_{0,y}^A/8} - C_{y,1,0}^A\right) e^{-M_{0,y}^A/4} - C_{y,2,0}^A\right) e^{-(1/8+0.5t_y/12)M_{0,y}^A} - C_{y,0bs}^A\right) e^{-(0.5t_y/12)M_{0,y}^A}$$

$$y_2 \le y \le y_n \qquad \text{(A.15)}$$

The recruit catch from 1 May to the day before the survey is calculated as follows

$$C_{y,0bs}^A = \left(\left(N_{y-1,0}^A e^{-M_{0,y}^A/8} - C_{y,1,0}^A\right) e^{-M_{0,y}^A/4} - C_{y,2,0}^A\right) e^{-(1/8+0.5t_y/12)M_{0,y}^A} S_{y,3,0} F_{y,bs} \qquad y_2 \le y \le y_n \text{ (A.16)}$$

where

[4] The range of length classes used in these summation matches the range of length classes in the observations which is a smaller range than the maximum range modelled of 2⁻cm to 16⁺cm.

$$F_{y,bs} = \frac{\sum_{l=3.5}^{14.5} C_{y,bs,l}^{RLF}}{\sum_{a=0}^{4^+}\left(\left(N_{y-1,a}^{A}e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right)e^{-M_{a,y}^{A}/4} - C_{y,2,a}^{A}\right)e^{-(1/8+0.5t_y/12)M_{a,y}^{A}} S_{y,3,a}} \qquad y_2 \le y \le y_n \quad \text{(A.17)}$$

A penalty is imposed within the model to ensure that $S_{y,l}F_{y,bs} < 0.95$ for all l.

Proportion-at-length associated with the November survey

The model predicted proportion-at-length associated with the November survey is[5]:

$$p_{y,l}^{A} = \frac{N_{y,l}^{A} S_l^{survey}}{\sum_{l=2}^{15.5} N_{y,l}^{A} S_l^{survey}} \qquad y_1 \le y \le y_n, \quad \text{(A.18)}$$

where

$$S_l^{survey} = \begin{cases} 0 & l = 1.5^- \\ \frac{1}{1+exp(-(l-l^{sur})/\delta^{sur})} & 2cm \le l \le 15.5cm \\ 0 & l = 16^+ \end{cases} \qquad \text{(A.19)}$$

Proportion-at-length associated with the commercial catch

The commercial catch-at-length from the anchovy fishery is:

$$C_{y,1,l}^{A} = \sum_{a=0}^{4+} N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} A_{1,a,l}^{com} S_{y,1,l} F_{y,1}$$

$$C_{y,2,l}^{A} = \sum_{a=0}^{4+} \left(N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right) e^{-M_{a,y}^{A}/4} A_{2,a,l}^{com} S_{y,2,l} F_{y,2}$$

$$C_{y,3,l}^{A} = \sum_{a=0}^{4+} \left(\left(N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right) e^{-M_{a,y}^{A}/4} - C_{y,2,a}^{A}\right) e^{-M_{a,y}^{A}/4} A_{3,a,l}^{com} S_{y,3,l} F_{y,3}$$

$$C_{y,4,l}^{A} = \sum_{a=0}^{4+} \left(\left(\left(N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right) e^{-M_{a,y}^{A}/4} - C_{y,2,a}^{A}\right) e^{-M_{a,y}^{A}/4} - C_{y,3,a}^{A}\right) e^{-M_{a,y}^{A}/4} A_{4,a,l}^{com} S_{y4,,l} F_{y,4}$$

$$y_1 \le y \le y_n,\ 1.5^- cm \le l \le 16^+ cm \qquad \text{(A.20)}$$

The model predicted proportion-at-length by quarter in the commercial catch[6] is:

$$p_{y,q,l}^{coml,A} = \frac{C_{y,q,l}^{A}}{\sum_{l=3.5}^{14.5} C_{y,q,l}^{A}} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4,\ 3.5cm \le l \le 14.5cm \quad \text{(A.21)}$$

Fitting the Model to Observed Data (Likelihood)

The survey observations of abundance are assumed to be log-normally distributed. The standard errors of the log-distributions for the survey observations of adult biomass and recruitment numbers are approximated by the CVs of the untransformed distributions and a further additional variance parameter. A “sqrt(p)” formulation, rather than the “adjusted lognormal” (“Punt-Kennedy”, Punt and Kennedy 1997) error distribution formulation, is assumed for the estimated proportions-at-length particularly as it can deal with occasional zero observations more easily. This “sqrt(p)” formulation mimics a multinomial form for the error distribution by forcing near-equivalent variance-mean relationship for the error distributions. The negative log-likelihood function is given by:

$$-lnL = -lnL^{Nov} - lnL^{Egg} - lnL^{rec} - lnL^{surpropl} - lnL^{compropl} \qquad \text{(A.22)}$$

where

[5] Note the model predicted survey proportion of lengths 1.5⁻cm and 16⁺cm is zero, given a zero survey trawl selectivity in equation (A.19). This is consistent with the range of length classes in the observed trawl survey proportions-at-length.
[6] Note there model predicted commercial catch of lengths <3.5cm and >14.5cm is zero, from a zero commercial selectivity in equation (A.9). This is consistent with the range of length classes in the observed commercial proportions-at-length.

$$-lnL^{Nov} = \frac{1}{2}\sum_{y=y_1}^{y_n}\left\{\frac{\left(ln\hat{B}_y^A - ln\left(k_N^A B_y^A\right)\right)^2}{\left(\sigma_{y,N}^A\right)^2 + \left(\lambda_N^A\right)^2} + ln\left(2\pi\left(\left(\sigma_{y,N}^A\right)^2 + (\lambda_N^A)^2\right)\right)\right\} \quad \text{(A.23)}$$

$$-lnL^{Egg} = \frac{1}{2}\sum_{y=y_1}^{1993}\left\{\frac{\left(ln\hat{B}_{y,egg}^A - ln\left(k_g^A SSB_y^A\right)\right)^2}{\left(\sigma_{y,egg}^A\right)^2} + ln\left(2\pi\left(\sigma_{y,egg}^A\right)^2\right)\right\} \quad \text{(A.24)}$$

$$-lnL^{rec} = \frac{1}{2}\sum_{y=y_1+1}^{2017}\left\{\frac{\left(ln\hat{N}_{y,r}^A - ln\left(k_r^A N_{y,r}^A\right)\right)^2}{\left(\sigma_{y,r}^A\right)^2 + \left(\lambda_r^A\right)^2} + ln\left(2\pi\left(\left(\sigma_{y,r}^A\right)^2 + (\lambda_r^A)^2\right)\right)\right\} + \left\{\frac{\left(ln\hat{N}_{y,r}^A - ln\left(k_r^A N_{y,r}^A\right)\right)^2}{\left(\sigma_{y,r}^A\right)^2 + \left(\lambda_r^A\right)^2} + ln\left(2\pi\left(\left(\sigma_{y,r}^A\right)^2 + (\lambda_r^A)^2\right)\right)\right\} \quad \text{(A.25)}$$

$$-lnL^{surpropl} = w_{propl}^{sur}\sum_{y=y_1}^{y_n}\sum_{l=2}^{15.5}\left\{\frac{\left(\sqrt{\hat{p}_{y,l}^A} - \sqrt{p_{y,l}^A}\right)^2}{2\left(\sigma_{sur}^A\right)^2} + ln\left(\sigma_{sur}^A\right)\right\}^{7} \quad \text{(A.26)}$$

$$-lnL^{compropl} = w_{propl}^{com}\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=3.5}^{14.5}\left\{\frac{\left(\sqrt{\hat{p}_{y,q,l}^{A,coml}} - \sqrt{p_{y,q,l}^{A,coml}}\right)^2}{2\left(\sigma_{com}^A\right)^2} + ln\left(\sigma_{com}^A\right)\right\} \quad \text{(A.27)}$$

[7] Although strictly there may be bias in the proportions of length-at-age data, no bias is assumed in this assessment. The effect of such a bias is assumed to be small.

Table A.1. Assessment model parameters and variables.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N^A_{y,a}$	Model predicted numbers-at-age a at the beginning of November in year y	Billions		A.1	
	$N^A_{1983,a}$	Initial numbers-at-age a	Billions	$N^A_{1983,0} \sim N(51, 30^2)$ $N^A_{1983,1} \sim N(143, 20^2)$ $N^A_{1983,2} \sim N(349, 6.5^2)$	$N^A_{1983,3} = N^A_{1983,2} e^{-M^A_{2,1}}$ $N^A_{1983,4^+} = N^A_{1983,3} \frac{e^{-M^A_3}}{1-e^{-M}}$	Assumed $M^A_{ad,1983} = M^A_{ad,1984}$
	$N^A_{y,l}$	Model predicted numbers-at-length l at the beginning of November in year y	Billions		A.2	
	$N^{A,1+}_{y,l}$	Model predicted numbers-at-length length l at the beginning of November in year y of anchovy ages 1+ only	Billions		A.3	
	B^A_y	Model predicted total biomass at the beginning of November in year y	Thousand tons		A.7	
	w^A_l	Mean mass of anchovy of length l[8] (in cm) during November	Grams	$w^A_l = 0.0079 \times l^{3.0979}$		Using model viii) in November from de Moor and Butterworth (2015)
	SSB^A_y	Model predicted spawning biomass at the beginning of November in year y	Thousand tons		A.8	
	f^A_l	Proportion of anchovy of length l (in cm) that are mature	-	$f^l_y = 1/\left(1 + e^{-(l-10.61)/0.66}\right)$		Figure A.1
Catch	$C^A_{y,q,a}$	Model predicted number of anchovy of age a caught during quarter q[9] from 1 November $y-1$ to 31 October y	Billions		A.12	
	$F_{y,q}$	Fished proportion in quarter q of year y for a fully selected length class l	-		A.13	
	$C^A_{y,0bs}$	Number of recruits caught between 1 May and the day before the start of the recruit survey in year y	Billions		A.16	
	$F_{y,bc}$	Fished proportion between 1 May and the day before the start of the recruit survey in year y	-		A.17	

[8] Where length is required in an equation, the mid-point of the length class is used.
[9] The quarters are $q = 1$: November-January; $q = 2$: February-April; $q = 3$: May-July; $q = 4$: August-October.

Table A.1 (continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
`Natural Mortality	M_a^A	Rate of natural mortality of age a	Year^{-1}		A.5 and A.6	From de Moor (2016)
	$\bar{M}_j^A$	Median rate of natural mortality for age-0 anchovy	Year^{-1}	1.2		
	$\bar{M}_{ad}^A$	Median rate of natural mortality for 1+ anchovy	Year^{-1}	1.2		
	ε_y^j	Annual residuals about natural mortality rate for age-0 anchovy	-		A.5	
	ε_y^{ad}	Annual residuals about natural mortality rate for 1+ anchovy	-		A.6	
	η_y^j	Normally distributed error in calculating ε_y^j	-	$\sim N(0, \sigma_j^2)$		
	η_y^{ad}	Normally distributed error in calculating ε_y^{ad}	-	$\sim N(0, \sigma_{ad}^2)$		
	σ_j	Standard deviation in the annual residuals η_y^j	-	0		From de Moor (2016)
	σ_{ad}	Standard deviation in the annual residuals η_y^{ad}	-	0		From de Moor (2016)
	ρ	Annual autocorrelation coefficient	-	0		From de Moor (2016)
Selectivity	S_l^{survey}	November survey trawl selectivity-at-length l	-		A.19	
	l^{sur}	Length class number at which the survey selectivity-at-length is 50%	Length class	$U(3,21)$ [10]		
	δ^{sur}	Steepness of the survey selectivity-at-length relationship		$U(0.005,5)$		
	$S_{y,q,l}$	Commercial selectivity-at-length l during quarter q of year y	-		A.9	
	$S_{y,q,a}$	Commercial selectivity-at-age a during quarter q of year y	-		A.10	
	ψ_q	Steepness of ascending limb of logistic part of commercial selectivity curve during quarter q	-	$\sim U(-10,0)$, $\psi_2 = \psi_3 = \psi_4$		Uninformative
	$l50_q$	Length at which ascending limb of logistic part of commercial selectivity is 50% during quarter q	Cm	$\sim U(3,10)$, $l50_3 = l50_4$		Uninformative
	δ_q	Rate of exponential decrease in commercial selectivity at large lengths during quarter q	-	$\delta_1 = \delta_2 \sim N(-0.38, 0.5^2)$ $\delta_3 = \delta_4 \sim N(-0.75, 0.04^2)$		See Appendix B
	S_q^{break}	Length at which commercial selectivity starts to decrease during quarter q	Length class	$S_1^{break} = 15$; $S_2^{break} = 16$; $S_3^{break} = S_4^{break} = 14$		From de Moor (2016)

[10] Length class 3 corresponds to 2.5cm, length class 21 corresponds to 11.5cm and length classes 14-16 correspond to 8.5-9.5cm.

Table A.1 (Continued).

	Parameter/ Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Recruitment	h^A	Steepness associated with the stock-recruitment curve[11]	-	$\sim U(0.2,1)$		
	K^A	Carrying capacity	Thousand tons	$K^A/1000 \sim U(0,10)$		
	α^A	Stock-recruitment curve parameter, related to h^A and K^A, for Beverton Holt and Ricker curves	-	$\alpha^A = \frac{4h^A K^A}{(5h^A-1)\left(\sum_{a=1}^{3} f_a^A w_a^A e^{-\bar{M}_j^A-(a-1)\bar{M}_{ad}^A} + f_{4+}^A w_{4+}^A e^{-\bar{M}_j^A-3\bar{M}_{ad}^A}/\left(1-e^{-\bar{M}_{ad}^A}\right)\right)}$ $f_a^A = \sum_{l=1.5^-}^{16^+} f_l^A A_{a,l}^{sur}$ and $w_a^A = \sum_{l=1.5^-}^{16^+} w_l^A A_{a,l}^{sur}$		
	β^A	Stock-recruitment curve parameter, related to h^A and K^A, for Beverton Holt and Ricker curves	Thousand tons	$\beta^A = \frac{(1-h^A)K^A}{(5h^A-1)}$		
	ε_y^A	Annual lognormal deviation of recruitment	-	$\sim N(0,(\sigma_r^A)^2)\ , y_1 \le y \le 1999$ $\sim N\left(0,\left(\sigma_{r,2000+}^A\right)^2\right), 2000 \le y \le y_{n-1}$		
	$(\sigma_r^A)^2$	Variance in the residuals (lognormal deviation) about the stock recruitment curve	-	$\sim U(0.16,10)$		Lower bound chosen to restrict the influence of the stock recruitment curve on the assessment results
	$N_{y,r}^A$	Model predicted number of recruits at the time of the recruit survey in year y	Billions		A.15	

[11] The proportion of the median virgin recruitment that is realised at a spawning biomass level of 20% of average pre-exploitation (virgin) spawning biomass, K^A.

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Multiplicative bias	k_N^A	Multiplicative bias associated with the November acoustic survey	-	$ln(k_N^A) \sim U(-100,0.7)$		Uninformative, corresponds to upper bound of $k_N^A \sim 2$
	k_g^A	Multiplicative bias associated with the November egg survey	-	1.0		From de Moor (2016)
	k_r^A	Multiplicative bias associated with the recruit survey	-	$k_r^A / k_N^A \sim U(0,1)$		Recruit survey assumed to cover less of the recruits than the November survey covers of the total biomass
Proportions-at-length and growth	$p_{y,l}^A$	Model predicted proportion-at-length l associated with the November survey in year y	-		A.18	
	$A_{a,l}^{sur}$	Proportion of anchovy-at-age a that fall in the length group l in November	-		A.4	
	$p_{y,q,l}^{com,A}$	Model predicted proportion-at-length l in the commercial catch during quarter q of year y	-		A.21	
	$A_{q,a,l}^{com}$	Proportion of anchovy-at-age a that fall in the length group l in quarter q	-		A.11	
	L_∞	Maximum length (in expectation) of anchovy	Cm	$\sim N(11.05, 1.105^2)$		From de Moor (2016)
	κ	Annual somatic growth rate of anchovy	Year^{-1}	$\frac{\kappa \times L_\infty}{10} \sim N(2.915, 0.292^2)$		From de Moor (2016)
	t_0	Age at which the length (in expectation) is zero	Year	$\sim N(0.112, 0.1^2)$		From de Moor (2016)
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$\vartheta_0 \sim N(2.0, 0.15^2)$ $\vartheta_1 \sim N(1.2, 0.18^2)$ $\vartheta_{2^+} \sim N(1.0, 0.1^2)$		From de Moor (2016)
Further output	s_{cor}^A	Recruitment serial correlation	-	$\frac{\sum_{y=y_1}^{y_n-1} \varepsilon_y^A \varepsilon_{y+1}^A}{\sqrt{\sum_{y=y_1}^{y_n-2} \left(\varepsilon_y^A\right)^2 \sum_{y=y_1}^{y_n-2} \left(\varepsilon_{y+1}^A\right)^2}}$		
	$\eta_{y_n-1}^A$	Standardised recruitment residual value for final year	-		$\frac{\varepsilon_{y_n-1}^A}{\sigma_{r,2000^+}^A}$	

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Likelihood	$-lnL^{Nov}$	Contribution to the negative log likelihood from the model fit to the November total survey biomass data	-		A.23	
	$-lnL^{Egg}$	Contribution to the negative log likelihood from the model fit to the November egg survey spawner biomass data			A.24	
	$-lnL^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A.25	
	$-lnL^{surpropL}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A.26	
	$-lnL^{compropL}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A.27	
	$(\lambda_N^A)^2$	Additional variance, over and above $\left(\sigma_{y,N}^A\right)^2$, associated with the November survey	-	0		See robustness tests
	$(\lambda_r^A)^2$	Additional variance, over and above $\left(\sigma_{y,r}^A\right)^2$, associated with the recruit survey		$\sim U(0{,}100)$		Uninformative
	w_{prop}^{sur}	Weighting applied to the survey proportion-at-length data	-	0.2		To allow for autocorrelation[12]
	σ_{sur}^A	Standard deviation associated with the survey proportion-at-length data	-	$\sqrt{\sum_{y=y_1}^{y_n}\sum_{l=7}^{13}\left(\sqrt{\hat{p}_{y,l}^A}-\sqrt{p_{y,l}^A}\right)^2 \Big/ \sum_{y=y_1}^{y_n}\sum_{l=7}^{13}1}$		Closed form solution[13]
	w_{prop}^{com}	Weighting applied to the commercial proportion-at-length data	-	0.05		To allow for autocorrelation[14]
	σ_{com}^A	Standard deviation associated with the commercial proportion-at-length data	-	$\sqrt{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=5}^{12}\left(\sqrt{\hat{p}_{y,q,l}^{A,coml}}-\sqrt{p_{y,q,l}^{A,coml}}\right)^2 \Big/ \sum_{y=y}^{y_n}}$ 8		Closed form solution[15]

[12] Based upon data being available ~5 times more frequently than annual age data which contain maximum information content on this
[13] A shorter range of lengths ($7cm \le l \le 13cm$) is used given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.
[14] Based upon data being available ~4x5 times more frequently than annual age data which contain maximum information content on this
[15] A shorter range of lengths ($5cm \le l \le 12cm$) is used given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

Table A.2. Assessment model data, detailed in de Moor et al. (2020).

Quantity	Description	Units / Scale	Shown in Figure
$C_{y,m,l}^{RLF}$	Observed number of anchovy in length class l caught during month m of year y[16]	Billions	
$C_{y,bs}^{RLF}$	Observed number of anchovy in length class l caught from 1 May to the day before the start of the recruit survey in year y	Billions	
t_y	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\hat{B}_y^A$	Acoustic survey estimate of total biomass from the November survey in year y	Thousand tons	Figure 1
$\sigma_{y,Nov}^A$	Survey sampling CV associated with $\hat{B}_y^A$ that reflects survey inter-transect variance	-	Figure 1
$\hat{B}_{y,egg}^A$	Egg survey estimate of spawner biomass from the November survey in year y	Thousand tons	Figure 2
$\sigma_{y,egg}^A$	Survey sampling CV associated with $\hat{B}_{y,egg}^A$ estimated from inter-transect variance		Figure 2
$\hat{N}_{y,r}^A$	Acoustic survey estimate of recruitment from the recruit survey in year y	Billions	Figure 3
$\sigma_{y,r}^A$	Survey sampling CV associated with $\hat{N}_{y,r}^A$ that reflects survey inter-transect variance	-	Figure 3
$\hat{p}_{y,l}^A$	Observed proportion (by number) of anchovy in length group l in the November survey of year y	-	
$\hat{p}_{y,q,l}^{A,com}$	Observed proportion (by number) of anchovy commercial catch in length group l during quarter q of year y		

[16] This is the observed length-frequency adjusted such that the expected mass calculated using the weight-at-length relationship matches the observed catch in tons (de Moor et al. 2020). The weight-at-length relationship applied to these commercial data is taken to vary by month, as obtained from fitting an inverted normal distribution for the "a parameter" to monthly commercial data from 1984 to 1996 (de Moor and Butterworth 2015).

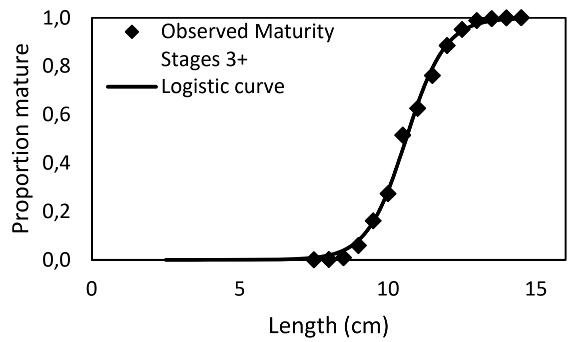

Figure A.1. From de Moor (2016). The logistic curve fitted to stages 3+ proportions of sexually mature male and female anchovy sampled during the November surveys in 1985 and 1986 (Melo 1992). Sexual maturity was assumed for maturity stages 3 and higher (Melo pers. comm.). The four sets of data were combined for each length class into the single observation used in this plot. This was done by weighting each of the four observations of numbers of sexually mature males/females by the total numbers of males/females observed by length class, i.e. $f_i^{A,obs} = \frac{\sum_i mature^i \times total^i}{\sum_i total^i}$, where $i = 1, \ldots, 4$ denotes each of the four data sets.