Assessment of the South African anchovy resource using data from 1984 - 2009

C.L. de Moor* **and D.S. Butterworth**

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

Abstract

The assessment of the South African anchovy resource has been updated given three more years of data and a revised time series of commercial catch. The base case hypothesis has the same juvenile and adult natural mortality rates as previous assessments, but a Beverton Holt stock recruitment relationship is now assumed instead of a hockey stick with fixed inflection point based on the AIC_c selection criterion. This change has resulted in a large increase in median posterior carrying capacity from previous assessments. There has been a decrease in recruitment residual standard deviation and in recruitment serial autocorrelation with the newer assessments. The impact of this on the appropriate choice of a risk definition and threshold for the new OMP to be developed next year will be considered early in the OMP development phase. The resource abundance remains above average, with a model-estimated 1+ biomass of 3.5 million tons in November 2009, and the resource has produced 8 years of above average recruitment in the past 11 years. The harvest proportion in the past 9 years has not exceeded 0.14.

Introduction

The assessment of the South African anchovy resource has been updated from the last assessment (Cunningham and Butterworth 2007, with further updates) to take account of new data collected between 2007 and 2009. In addition there has been a change to the calculation of time series of commercial catch. The monthly cut-off lengths for recruits now vary on an annual basis in accordance with the cut-off length estimated by the annual recruit survey (de Moor *et al.* 2010). This document details the updated assessment model and gives the assessment results for the base case model and some key robustness tests.

Population Dynamics Model

The population dynamics model used for the South African anchovy resource is detailed in Appendix A. The data used in this assessment are listed in de Moor *et al.* (2010). The prior distributions for the estimated parameters were chosen to be relatively uninformative. A range of combinations of adult and juvenile natural mortality rates was examined using this model in order to select realistic values for the base case assessment.

The objective function consisting of the negative log likelihood of equation (A.7) to which the negatives of the 36 log prior distributions were added, was minimised using AD Model Builder (Otter Research Ltd. 2000) to fit the model to the observed data and estimate the parameters at the joint posterior mode. The posterior probability distributions were estimated using Markov Chain Monte Carlo (Gelman *et al*. 1995) in AD Model Builder. Two chains of 100 million samples were run for the purposes of testing convergence, with one chain beginning at the posterior mode and the other starting from a random vector. A burn-in of 60 million was discarded and the remaining chain was thinned by 1 in every 1000 to decrease any autocorrelation. Results presented in this document are based on a random sample of 5 000 from the 40 000-long chain begun at the

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

posterior mode after burn-in and thinning. A smaller sample will be used as input to the OMP testing framework due to run-time constraints.

Convergence of the chains was tested using the BOA (Bayesian Output Analysis) package (Smith 2003) and the diagnostics from the tests of Geweke (1992), Gelman and Rubin (1992), Raftery and Lewis (1992) and Heidelberger and Welch (1983) were good, indicating convergence of the chain. The autocorrelations for each estimable parameter and cross-correlations between the parameters were also low.

Robustness Tests: Natural Mortality

A number of combinations of juvenile and adult natural mortality were tested, covering the range 0.6 to 2.1 year^{-1}. The chosen base case and initial selection of robustness tests are listed in the results section.

Robustness Tests: Stock Recruitment

The following robustness tests were selected to test the sensitivity of the model to the assumption of a stock recruitment relationship (Table 1, see results section for choices made):

A_0 – Beverton Holt stock-recruitment curve, with uniform priors on steepness and carrying capacity

A_{HS} – hockey stick stock-recruitment curve, with uniform priors on the log of the maximum recruitment and the ratio of the spawning biomass at the inflection point to carrying capacity

$A_{fixedHS}$ – hockey stick stock-recruitment curve with a uniform prior on the log of the maximum recruitment, the spawning biomass at the inflection point set equal to 20% of K (to correspond to that assumed in the 2007 assessment)

A_R – Ricker stock-recruitment curve, with uniform priors on steepness and carrying capacity

A_{ModR} – 'Modified' Ricker stock-recruitment curve, with uniform priors on steepness, carrying capacity and shape parameter.

Results

Natural Mortality

Table 2 lists the various contributions to the objective function at the posterior mode for the full range of combinations of juvenile and adult natural mortality tested. The following criteria were used to distinguish "reasonable" from "unrealistic" combinations (unrealistic combinations are shaded in Table 2):

- $M_j^A \geq M_{ad}^A$;
- the ratio $k_r^A / k_N^A \in [0.5, 1.0]$, as the November spawner biomass survey is expected to have a greater coverage of the full distribution of the resource than the May recruit survey so that the latter should reflect a smaller relative bias.

One further "reality check" was provided by the criterion that the multiplicative bias for the proportion-at-age 1 in the November survey, k_p^A, should not be markedly different from 1.

There was little change in the posterior distribution as M_j^A changed for a given M_{ad}^A; given M_j^A, the posterior distribution indicated an improved fit to the data for increasing M_{ad}^A. This latter feature may, however, be an artefact of the assessment in that a higher natural mortality results in a higher loss of "memory" of cohorts, making the November survey data easier to fit. Considering k_p^A then, the following combinations were chosen for a base case and an initial set of robustness tests:

A_0 - $M_j^A = 0.9$ and $M_{ad}^A = 0.9$ (base case)

A_{M1} - $M_j^A = 1.2$ and $M_{ad}^A = 0.6$ (robustness test: worse objective function value, but a high k_p^A value)

A_{M2} - $M_j^A = 1.2$ and $M_{ad}^A = 0.9$ (robustness test: little difference from A_0 in terms of value of objective function and k_p^A)

A_{M3} - $M_j^A = 1.5$ and $M_{ad}^A = 0.9$ (robustness test: alternative M_j^A, with the objective function value not substantially worse than that for A_0 and k_p^A above 0.9)

A_{M4} - $M_j^A = 1.8$ and $M_{ad}^A = 0.9$ (robustness test: alternative M_j^A, with the objective function value not substantially worse than that for A_0 and k_p^A above 0.9)

A_{M5} - $M_j^A = 1.2$ and $M_{ad}^A = 1.2$ (robustness test: improved objective function compared to A_0, though $k_p^A = 0.87$ is on the low side).

<u>Stock-Recruitment Relationship</u>

Table 3 lists the various contributions to the objective function at the posterior mode for the alternative stock-recruitment relationships considered. Ignoring all uniform prior distributions, but considering the normal priors around the recruitment residuals as a likelihood penalty, from a frequentist perspective, AIC_C suggests that the preferred stock-recruitment relationship is the Beverton Holt. There is little difference between the estimated Beverton Holt and Ricker curves over the range of spawner biomass observed historically (Figures 1 and 2). Sufficient data points are now available to estimate the inflection point of the hockey stick curve. However, to enable comparison with the former assessment, the hockey stick curve with a fixed inflection point is maintained as an alternative, though note that the carrying capacity estimated by this alternative is lower than that for the other stock-recruitment relationships.

<u>Results at Posterior Mode</u>

The base case model fit to the data at the posterior mode is shown in Figure 3 for acoustic spawner biomass, Figure 4 for DEPM estimates of spawner biomass, Figure 5 for recruitment and Figure 6 for the proportion of 1-year-olds in the November survey. There is a positive trend over time in the standardised residuals from the model fit to the survey estimates of May recruitment. In other words, on average, the model predicts a lower recruitment than that estimated by the survey in recent years and a higher recruitment in earlier years. This trend is unaffected by the choice of stock recruitment relationship. Allowance for an increase in natural mortality after 2000 did not remove this trend. There is a negative trend with model estimates of proportion-at-age 1 in the standardised residuals from the model fit to the November survey estimated proportion-at-age 1. In other words, on average, the model predicts a lower proportion-at-age 1 when the survey estimated proportion is high. The reasons for these trends are currently unclear. Key model parameters and outputs at the posterior mode are listed in Table 4 for the base case assessment and robustness tests.

Base Case Posterior Distributions

The posterior means and CVs of the model parameters and some key outputs for A_0 are given in Table 5, with the posterior distributions of key model outputs to be used in the testing of the new OMP shown in Figure 7. Posterior distributions of annual model estimated November 1+ biomasses are shown in Figure 8.

Discussion

Samples from the posterior distributions of key model parameters and outputs, including those presented in Table 5 and Figure 7 will be used to develop the new OMP. For comparative purposes, therefore, Table 6 gives some key model parameters and outputs at the joint posterior mode for A_0, together with those from the previous assessments used to develop OMP-04 and OMP-08. The change in stock recruitment relationship, from hockey stick with a fixed inflection point to the Beverton Holt curve, has resulted in a marked increase in median posterior carrying capacity from previous assessments. There has been a decrease in recruitment residual standard deviation and in recruitment serial autocorrelation with these newest assessments. The impact of this on the appropriate choice of a risk definition and threshold for OMP-12 will be considered early in the development of the new OMP.

Figure 9 shows the November spawner biomass over time in relation to estimates of carrying capacity and 10% of the average 1984 to 1999 biomass, the risk threshold used to tune OMP-04 and OMP-08. This shows the resource peaked above its carrying capacity in 2001. It is clear from Figure 9 that the anchovy spawner biomass at the posterior mode has never dropped below 10% of its 1984 to 1999 average over the past 26 years, while it has historically dropped below the average 1984 to 1999 biomass 32% of the time (Table 6). To place this in context in relation to the two previous assessments, Table 7 lists the mean of the annual November biomass posterior distributions and the annual probability of falling below the average 1984 to 1999 biomass, with the mean biomasses plotted in Figure 10. The probability of historically being below 10% of the average 1984 to 1999 biomass was zero in all years for both these earlier assessments.

Summary and Future Work

This document has detailed the updated assessment of the South African anchovy resource, using data between 1984 and 2009, and provided results of the base case assumptions and some robustness tests. Using the AIC_c selection criterion, a Beverton Holt stock-recruitment relationship has been assumed for the base case, which is different from past assessments. The values for the temporarily invariant juvenile and adult natural mortality rates have remained unchanged from recent assessments. The resource abundance remains above average, with a model-estimated 1+ biomass of 3.5 million tons in November 2009, having provided 8 years of above average recruitment in the past 11 years. The harvest proportion over the past 9 years has not exceeded 0.14 (Figure 11).

As previously agreed by the Pelagic Scientific Working Group, this assessment will be updated early in 2011 to include data from November 2009 to November 2010. The updated model will be used as a basis for developing the new OMP. At that time, a larger suite of robustness tests will also be considered. These will include:

A_{10} – 10cm cut-off length for calculating the proportion of 1-year-olds in the November survey

$A_{10.5}$ – 10.5cm cut-off length for calculating the proportion of 1-year-olds in the November survey

A_{11} – 11cm cut-off length for calculating the proportion of 1-year-olds in the November survey

A_{kegg1} – negatively biased egg surveys, i.e., $k_g^A = 0.75$ (testing assumption 7 of Appendix A)

A_{kegg2} – positively biased egg surveys, i.e., $k_g^A = 1.25$ (testing assumption 7 of Appendix A)

A_{lam1} – fix the additional variance (over and above the survey sampling CV) associated with the recruit survey $(\lambda_r^A)^2 = 0$

A_{lam2} – fix the additional variance (over and above the survey sampling CV) associated with the November survey $(\lambda_N^A)^2 = 0.04$

The performance of the proposed new combined OMP for sardine and anchovy will be examined under this base case as well as under some of the robustness tests. The robustness tests chosen for Bayesian analysis, and used in the OMP development framework, will likely be those resulting in extreme or more pessimistic projections for the resources under OMP testing based on results at the posterior mode only.

References

Cunningham, C.L., and Butterworth, D.S. 2007. Assessment of the South African Anchovy Resource. Unpublished MCM document MCM/2007/SEPT/SWG-PEL/05. 29pp.

de Moor, C.L., van der Westhuizen, J.J., Durholtz D. and Coetzee, J. 2010. A Record of the Generation of Data Used in the Sardine and Anchovy Assessments. MCM Document still to come.

Gelman, A., Carlin, J.B., Stern, H.S. & Rubin, D.B. 1995. Bayesian Data Analysis. Chapman & Hall. 552pp.

Gelman, A., and Rubin, D.B. 1992. Inference from Iterative Simulation Using Multiple Sequences. Statist. Sci. 7: 457-511.

Geweke, J. 1992. Evaluating the Accuracy of Sampling-Based Approaches to the Calculation of Posterior Moments. *In* Bayesian Statistics 4. pp169-193. *Edited by* Bernardo, J.M., Berger, J.O., Dawid, A.P. and Smith, A.F.M. Oxford University Press, Oxford.

Heidelberger, P., and Welch, P.D. 1983. Simulation Run Length Control in the Presence of an Initial Transient. Operations Research. 31: 1109-1144.

Otter Research Ltd. 2000. An Introduction to AD Model Builder Version 4: For Use in Nonlinear Modeling and Statistics. Otter Research Ltd. (http://www.otter-rsch.com/)

Raftery, A.E., and Lewis, S.M. 1992. How many Iterations in the Gibbs Sampler? *In* Bayesian Statistics 4. pp763-773. *Edited by* J.M. Bernardo, J.O. Berger, A.P. Dawid and A.F.M. Smith. Oxford University Press, Oxford.

Smith, B.J. 2003. Bayesian Output Analysis Program (BOA) Version 1.0 User's Manual.

Table 1. The alternative stock-recruitment relationships considered. The parameter h^A denotes the "steepness" of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realised at a spawning biomass level of 20% of average pre-exploitation (virgin) spawning biomass K^A (shown in units of thousands of tons). For the hockey stick model, $X = \sum_{a=1}^{3} \overline{w}_a^A e^{-M_j^A-(a-1)M_{ad}^A} + \overline{w}_{4+} e^{-M_j^A-3M_{ad}^A} \frac{1}{1-e^{-M_{ad}^A}}$, where $\overline{w}_a^A$ is the average of $w_{y,a}^A$ defined in Appendix A. For the hockey stick model, a^A denotes the maximum recruitment (in billions) and b^A denotes the spawner biomass below which the expectation for recruitment is reduced below the maximum.

Robustness Test	Stock-Recruitment Relationship	$f\left(SSB_{y,N}^A\right)=$	Parameters
A_0	Beverton Holt	$\frac{\alpha^A SSB_{y,N}^A}{\beta^A + SSB_{y,N}^A}$	$h^A \sim U(0.2,1.5)$ $K^A \sim U(0,20000)$ $\alpha^A = \frac{4h^A}{5h^A-1}\frac{K^A}{X}$ $\beta^A = \frac{K^A(1-h^A)}{5h^A-1}$
A_{HS}	Hockey stick	$\begin{cases} a^A & \text{,if SSB}_{y,N}^A \geq b^A \\ \frac{a^A}{b^A} SSB_{y,N}^A & \text{,if SSB}_{y,N}^A < b^A \end{cases}$	$\ln(a^A) \sim U(0,8)$ [1] $\frac{b^A}{K^A} \sim U(0,1)$ $K^A = a^A e^{\frac{1}{2}(\sigma_r^A)^2} X$ [2]
$A_{fixedHS}$	Hockey stick	$\begin{cases} a^A & \text{,if SSB}_{y,N}^A \geq b^A \\ \frac{a^A}{b^A} SSB_{y,N}^A & \text{,if SSB}_{y,N}^A < b^A \end{cases}$	$\ln(a^A) \sim U(0,8)$ $b^A = 0.2K^A$ $K^A = a^A e^{\frac{1}{2}(\sigma_r^A)^2} X$
A_R	Ricker	$\alpha^A SSB_{y,N}^A e^{-\beta^A SSB_{y,N}^A}$	$h^A \sim U(0.2,1.5)$ $K^A \sim U(0,20000)$ $\alpha^A = \frac{1}{X}\left(\frac{h^A}{0.2}\right)^{1/0.8}$ $\beta^A = \frac{\ln(h^A/0.2)}{0.8K^A}$
A_{ModR}	Modified Ricker	$\alpha^A SSB_{y,N}^A e^{-\beta^A\left(SSB_{y,N}^A\right)^c}$	$h^A \sim U(0.2,1.5)$ $K^A \sim U(0,20000)$ $c \sim U(0,1)$ $\alpha^A = \frac{1}{X}\left(\frac{h^A}{0.2}\right)^{\frac{1}{1-0.2^c}}$ $\beta^A = \frac{\ln(h^A/0.2)}{(K^A)^c\left[1-0.2^c\right]}$

[1] Given the lack of *a priori* information on the scale of a^A, a log-scale was used.

[2] The $e^{\frac{1}{2}(\sigma_r^A)^2}$ factor corrects for bias in the mean of the log-normal distribution.

Table 2. The contributions to the objective function at the posterior mode for a range of combinations of juvenile, M_j^A, and adult, M_{ad}^A, natural mortality. The ratio of the multiplicative bias in the recruit survey to that in the November survey, k_r^A/k_N^A, and the multiplicative bias in the proportion-at-age 1 in the November survey, k_p^A, are given for diagnostic purposes. Shaded cells represent unrealistic choices in terms of the criteria applied.

M_j^A	M_{ad}^A	Posterior	-ln(L_{Nov})	-ln(L_{Egg})	-ln(L_{Rec})	-ln(L_{Prop})	-ln(Prior)	k_r^A	k_N^A	k_r^A/k_N^A	k_p^A
0.6	0.6	81.36	1.44	9.88	11.32	36.80	21.92	1.27	1.56	1.22	1.09
0.6	0.9	60.77	-4.09	7.86	8.10	27.10	21.80	1.19	1.15	0.97	0.96
0.6	1.2	48.75	-8.50	6.54	6.72	22.06	21.94	1.14	0.94	0.82	0.87
0.6	1.5	42.44	-11.60	5.69	6.23	20.15	21.97	1.12	0.82	0.73	0.80
0.6	1.8	39.47	-13.54	5.18	6.09	20.05	21.68	1.11	0.74	0.67	0.76
0.6	2.1	38.15	-14.73	4.91	6.09	20.69	21.20	1.10	0.69	0.63	0.72
0.9	0.6	82.13	1.95	10.03	11.24	36.52	22.39	1.28	1.40	1.10	1.09
0.9	0.9	61.27	-3.78	7.96	7.96	26.94	22.18	1.19	1.03	0.86	0.96
0.9	1.2	49.11	-8.33	6.63	6.57	21.98	22.27	1.15	0.84	0.73	0.87
0.9	1.5	42.72	-11.49	5.77	6.08	20.11	22.26	1.12	0.73	0.65	0.80
0.9	1.8	39.70	-13.45	5.26	5.94	20.01	21.95	1.11	0.66	0.60	0.76
0.9	2.1	38.36	-14.67	4.98	5.95	20.65	21.45	1.10	0.61	0.56	0.72
1.2	0.6	82.92	2.47	10.17	11.20	36.24	22.83	1.28	1.26	0.99	1.09
1.2	0.9	61.79	-3.50	8.06	7.88	26.81	22.53	1.19	0.92	0.77	0.96
1.2	1.2	49.50	-8.19	6.71	6.49	21.92	22.56	1.15	0.75	0.65	0.87
1.2	1.5	43.03	-11.40	5.84	6.00	20.07	22.52	1.12	0.65	0.58	0.80
1.2	1.8	39.97	-13.39	5.33	5.86	19.98	22.19	1.11	0.59	0.53	0.76
1.2	2.1	38.61	-14.62	5.04	5.88	20.62	21.69	1.10	0.54	0.49	0.72
1.5	0.6	83.71	2.98	10.30	11.21	35.98	23.24	1.28	1.13	0.88	1.10
1.5	0.9	62.33	-3.24	8.15	7.88	26.68	22.86	1.19	0.82	0.69	0.96
1.5	1.2	49.92	-8.06	6.78	6.49	21.87	22.84	1.15	0.66	0.58	0.87
1.5	1.5	43.38	-11.33	5.91	6.00	20.04	22.77	1.13	0.57	0.51	0.80
1.5	1.8	40.27	-13.34	5.39	5.86	19.95	22.42	1.11	0.52	0.47	0.76
1.5	2.1	38.90	-14.58	5.09	5.89	20.60	21.90	1.10	0.48	0.44	0.72
1.8	0.6	84.50	3.48	10.41	11.27	35.73	23.61	1.28	1.01	0.79	1.10
1.8	0.9	62.89	-3.00	8.23	7.93	26.57	23.15	1.19	0.73	0.61	0.96
1.8	1.2	50.36	-7.97	6.84	6.57	21.83	23.09	1.15	0.59	0.51	0.87
1.8	1.5	43.76	-11.29	5.96	6.07	20.02	22.99	1.13	0.51	0.45	0.80
1.8	1.8	40.61	-13.31	5.44	5.94	19.93	22.62	1.11	0.46	0.41	0.76
1.8	2.1	39.22	-14.57	5.14	5.98	20.57	22.09	1.11	0.43	0.39	0.72
2.1	0.6	85.30	3.96	10.51	11.37	35.50	23.95	1.28	0.90	0.71	1.10
2.1	0.9	63.46	-2.80	8.29	8.06	26.48	23.43	1.19	0.65	0.54	0.97
2.1	1.2	50.83	-7.90	6.89	6.72	21.80	23.32	1.15	0.52	0.45	0.87
2.1	1.5	44.20	-11.29	5.97	6.26	20.09	23.16	1.14	0.45	0.40	0.80
2.1	1.8	41.05	-13.31	5.44	6.14	20.02	22.76	1.13	0.41	0.36	0.76
2.1	2.1	39.65	-14.54	5.14	6.19	20.66	22.21	1.12	0.38	0.34	0.72

Table 3. The contributions to the objective function at the posterior mode for alternative stock-recruit relationships.

	A_0	A_{HS}	$H_{fixedHS}$	A_R	A_{ModR}
Posterior	61.268	61.628	65.744	61.302	61.302
$-\ln(L_{Nov})$	-3.78	-3.30	-6.87	-3.69	-3.69
$-\ln(L_{Egg})$	7.96	8.10	7.22	7.99	7.99
$-\ln(L_{Rec})$	7.96	7.77	9.52	7.92	7.92
$-\ln(L_{Prop})$	26.94	26.73	28.33	26.91	26.91
-ln(Prior)	22.18	22.33	27.54	22.18	22.18
# parameters	36	36	35	36	37
Sample size (i.e. data points)	87	87	87	87	87
AIC	194.54	195.26	201.49	194.60	196.60
AIC_c	247.82	248.54	250.90	247.88	253.99
h^A	0.34			0.34	0.33
K^A	4094	4176	3039	4021	4726
c					0.11
a^A		437	284		
b^A		2197	608		

Table 4. Key parameter values estimated at the joint posterior mode together with key model outputs for the base case assessment and robustness tests. All parameters are defined in the Appendix. Fixed values are given in **bold**. Numbers are reported in billions and biomass in thousands of tons.

	A_0	A_{M1}	A_{M2}	A_{M3}	A_{M4}	A_{M5}	A_{HS}	$A_{fixedHS}$	A_R	A_{ModR}
SR curve	Beverton Holt						Hockey stick	Hockey stick, fix b^A	Ricker	Modified Ricker
M_j^A	**0.9**	**1.2**	**1.2**	**1.5**	**1.8**	**1.2**	**0.9**	**0.9**	**0.9**	**0.9**
M_{ad}^A	**0.9**	**0.6**	**0.9**	**0.9**	**0.9**	**1.2**	**0.9**	**0.9**	**0.9**	**0.9**
$N_{1983,0}^A$	156.43	179.35	203.49	265.41	347.04	224.70	156.2	154.28	156.41	156.8
$N_{1983,1}^A$	141.26	106.49	141.31	141.35	141.39	180.66	141.17	137.77	141.26	141.67
$N_{1983,2}^A$	0.0049	0.0048	0.0049	0.0049	0.0049	0.0049	0.0049	0.0050	0.0049	0.0049
$N_{1983,3}^A$	0.0048	0.0048	0.0048	0.0048	0.0048	0.0049	0.0048	0.0050	0.0048	0.0048
k_N^A	1.189	1.277	1.190	1.191	1.192	1.148	1.178	1.233	1.187	1.189
k_r^A	1.027	1.258	0.917	0.817	0.728	0.746	1.019	1.069	1.026	1.027
k_r^A / k_N^A	0.864	0.986	0.770	0.686	0.610	0.650	0.865	0.867	0.864	0.864
k_p^A	0.963	1.094	0.964	0.964	0.965	0.870	0.964	0.957	0.963	0.963
$\left(\sigma_p^A\right)^2$	0.465	0.951	0.460	0.456	0.452	0.316	0.458	0.518	0.464	0.467
$\left(\lambda_N^A\right)^2$	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
$\left(\lambda_r^A\right)^2$	0.081	0.113	0.080	0.080	0.080	0.068	0.079	0.096	0.080	0.081
$\hat{B}_{2009,N}^A$	3489	3222	3478	3467	3456	3571	3530	3312	3497	3487
$\bar{B}_{Nov}^A$ [3]	1103	1031	1103	1102	1102	1148	1109	1080	1104	1104
K^A	4094	4018	3977	3863	3750	3894	4176	3039	4021	4726
a^A							437	284		
b^A							2197	608		
h^A	0.339	0.383	0.330	0.321	0.314	0.308			0.335	0.327
σ_r^A	0.588	0.603	0.596	0.604	0.611	0.157	0.591	0.759	0.588	0.588
η_{2008}^A	0.260	0.332	0.261	0.263	0.264	0.212	0.262	0.679	0.235	0.257
s_{cor}^A	0.221	0.290	0.226	0.231	0.236	0.157	0.223	0.527	0.217	0.226

[3] OMP-04 and OMP-08 were developed using Risk defined as "the probability that adult anchovy biomass falls below 10% of the average adult anchovy biomass between November 1984 and November 1999 at least once during the projection period of 20 years".

Table 5. The posterior means and CVs of key model parameters and outputs for A_0.

Parameter	Mean	Median	CV
k_N^A	1.092	1.085	0.12
k_R^A	0.992	0.979	0.14
k_p^A	0.941	0.945	0.05
$\left(\lambda_r^A\right)^2$	0.186	0.173	0.44
$N_{1983,0}^A$	186	179	0.31
$N_{1983,1}^A$	148	145	0.36
$N_{1983,2}^A$	0.005	0.005	0.58
$N_{1983,3}^A$	0.005	0.005	0.58
$\hat{N}_{2009,1}^A$	188	183	0.27
$\hat{N}_{2009,2}^A$	108	107	0.22
$\hat{N}_{2009,3}^A$	29	28	0.26
$\hat{N}_{2009,4+}^A$	9.7	9.5	0.19
$\hat{B}_{2009,N}^A$	3777	3721	0.17
$\overline{B}_{Nov}^A$	1243	1236	0.12
K^A	4686	4212	0.41
h^A	0.33	0.33	0.19
η_{2005}^A	0.184	0.191	2.13
σ_r^A	0.734	0.720	0.17
s_{cor}^A	0.187	0.186	0.55

Table 6. A comparison of key parameters and outputs at the joint posterior median for the updated anchovy base case assessment, A_0, to the previous assessments. Biomass is given in thousands of tons and numbers in billions. "Starting" values refer to those used to commence future projections.

		Previous Assessment (used to develop OMP-04)	Previous Assessment (used to develop OMP-08)	A_0
Starting numbers at age	$\hat{N}^A_{2003,1}$, $\hat{N}^A_{2006,1}$, $\hat{N}^A_{2009,1}$	133	52	183
	$\hat{N}^A_{2003,2}$, $\hat{N}^A_{2006,2}$, $\hat{N}^A_{2009,2}$	39	46	107
	$\hat{N}^A_{2003,3}$, $\hat{N}^A_{2006,3}$, $\hat{N}^A_{2006,3}$	74	8	28
	$\hat{N}^A_{2003,4}$, $\hat{N}^A_{2006,4+}$, $\hat{N}^A_{2006,4+}$	24	16	10
Starting estimated spawner biomass	$\hat{B}^A_{2003,N}$, $\hat{B}^A_{2006,N}$, $\hat{B}^A_{2009,N}$	3102	1770	3721
Juvenile natural mortality	M^A_j	0.9 (fixed)	0.9 (fixed)	0.9 (fixed)
Adult natural mortality	M^A_{ad}	0.9 (fixed)	0.9 (fixed)	0.9 (fixed)
Bias for November survey	k^A_N	1.22	1.23	1.08
Bias for recruit survey	k^A_r	0.93	1.03	0.98
Stock-recruitment parameters	a^A	216	249	
	b^A	498	585	
	K^A	2492	2925	4212
	h^A			0.33
Last estimated recruitment residual	η^A_{2002}, η^A_{2005}, η^A_{2008}	0.789	-0.360	0.191
Recruitment residual standard deviation	σ^A_r	0.883	0.856	0.720
Recruitment serial correlation	s^A_{cor}	0.474	0.430	0.186
Average 1984 – 1999 biomass	$\overline{B}^A_{Nov}$	1169	1103	1236

Table 7. The mean posterior annual November biomass for this assessment and previous assessments, together with the annual probability of November biomass being below the average 1984 to 1999 biomass.

Year	Mean November Biomass			Probability of November Biomass being below 1984-1999 average		
	2004 Assessment	2007 Assessment	2010 Assessment	2004 Assessment	2007 Assessment	2010 Assessment
1984	1313	1401	1521	0.32	0.13	0.16
1985	1134	1083	1236	0.64	0.60	0.54
1986	2016	1887	2009	0.00	0.00	0.00
1987	1678	1656	1787	0.00	0.00	0.00
1988	1241	1194	1300	0.33	0.27	0.33
1989	719	656	740	1.00	1.00	1.00
1990	646	622	721	1.00	1.00	1.00
1991	1923	1754	1912	0.00	0.00	0.00
1992	1673	1429	1657	0.00	0.01	0.00
1993	1082	898	1027	0.83	0.98	0.98
1994	631	555	640	1.00	1.00	1.00
1995	494	432	504	1.00	1.00	1.00
1996	435	486	563	1.00	1.00	1.00
1997	1038	967	1027	0.77	0.82	0.90
1998	1170	1164	1297	0.55	0.42	0.41
1999	1713	1686	1947	0.01	0.00	0.00
2000	3759	3804	4264	0.00	0.00	0.00
2001	5388	4623	5145	0.00	0.00	0.00
2002	3983	3828	4380	0.00	0.00	0.00
2003	3131	2877	3322	0.00	0.00	0.00
2004		2130	2489		0.00	0.00
2005		2289	2594		0.00	0.00
2006		1798	2076		0.00	0.00
2007			2453			0.00
2008			3343			0.00
2009			3777			0.00

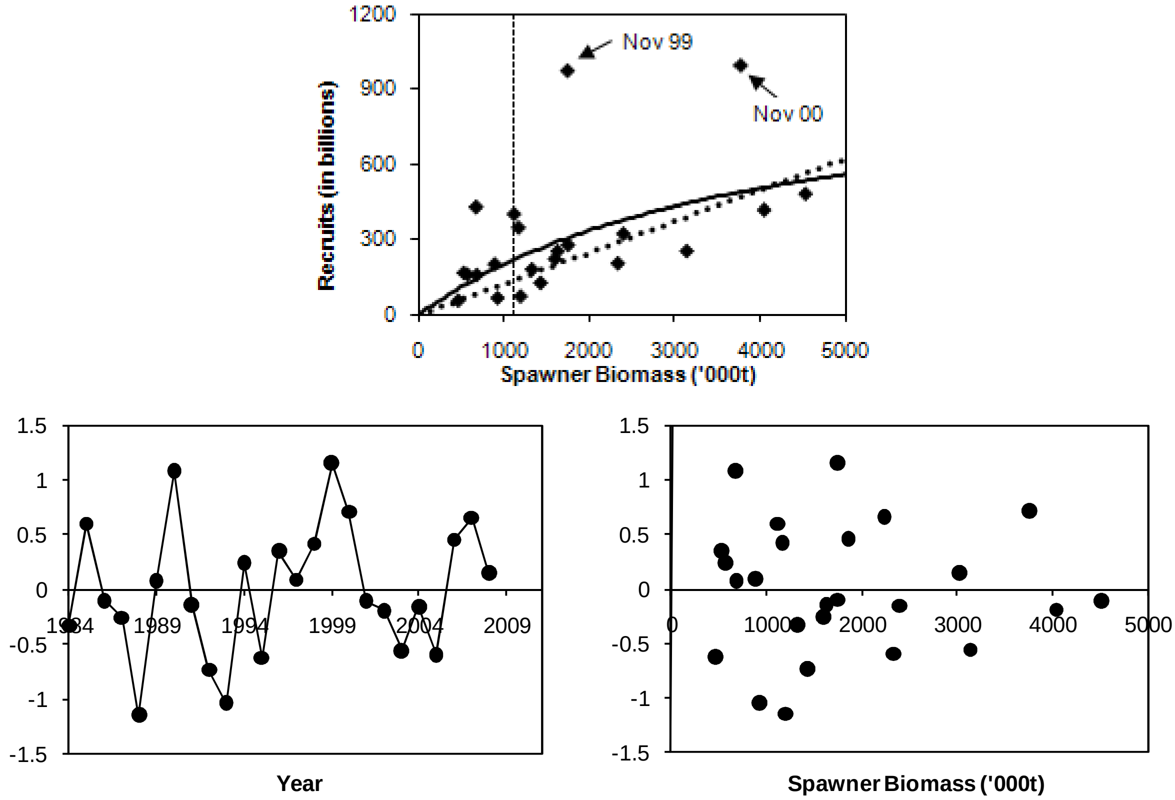

Figure 1. Model predicted anchovy recruitment (in November) plotted against spawner biomass from November 1984 to November 2008 for A_0, with the Beverton Holt stock-recruit relationship. The vertical thin dashed line indicates the average 1984 to 1999 spawner biomass (used in the definition of risk in OMP-04 and OMP-08). The dotted line indicates the replacement line. The standardised residuals from the fit are given in the lower plots, against year and against spawner biomass.

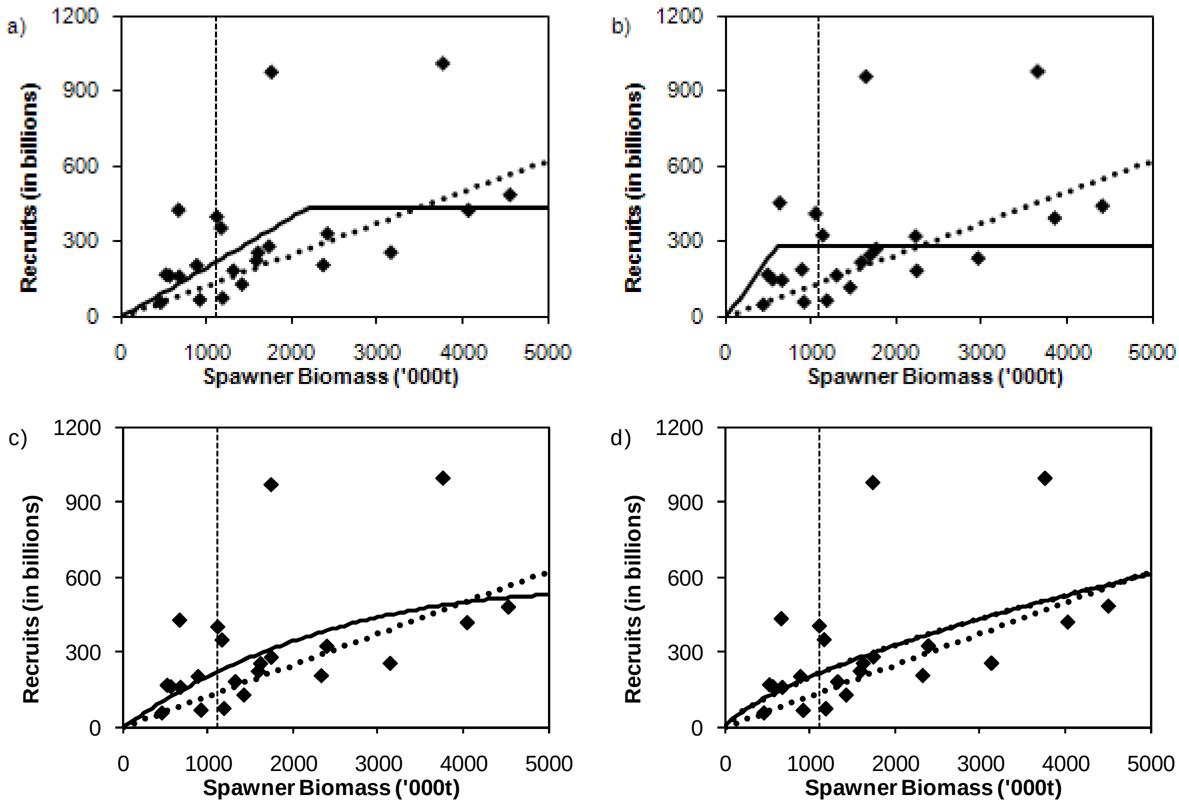

Figure 2. Stock-recruit relationships for a) A_{HS}, b) $A_{fixedHS}$, c) A_{R}, and d) A_{ModR}.

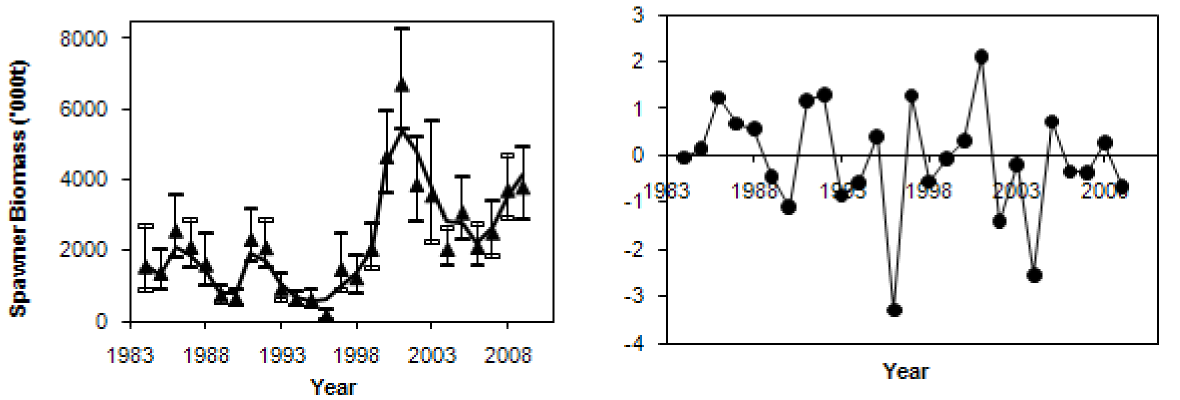

Figure 3. Acoustic survey results and A_0 model estimates for November anchovy spawner biomass from 1984 to 2009. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

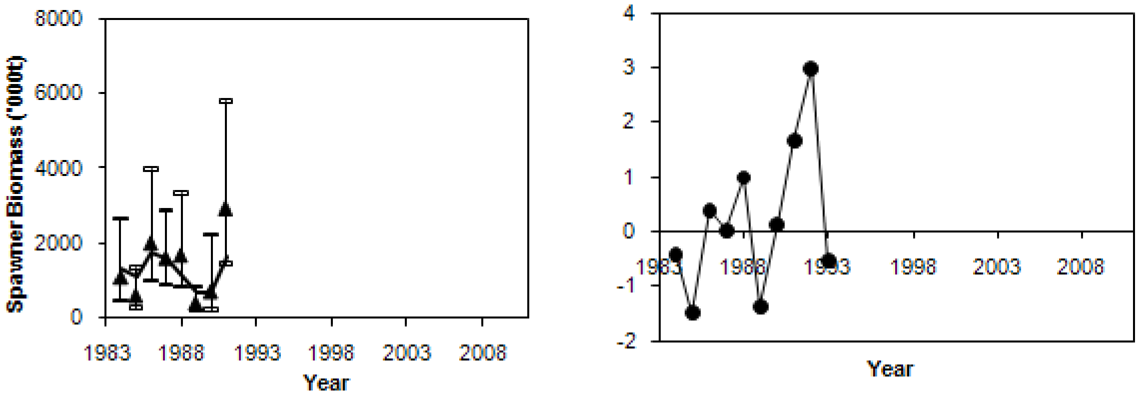

Figure 4. Egg survey results and A_0 model estimates for November anchovy spawner biomass from 1984 to 1991. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

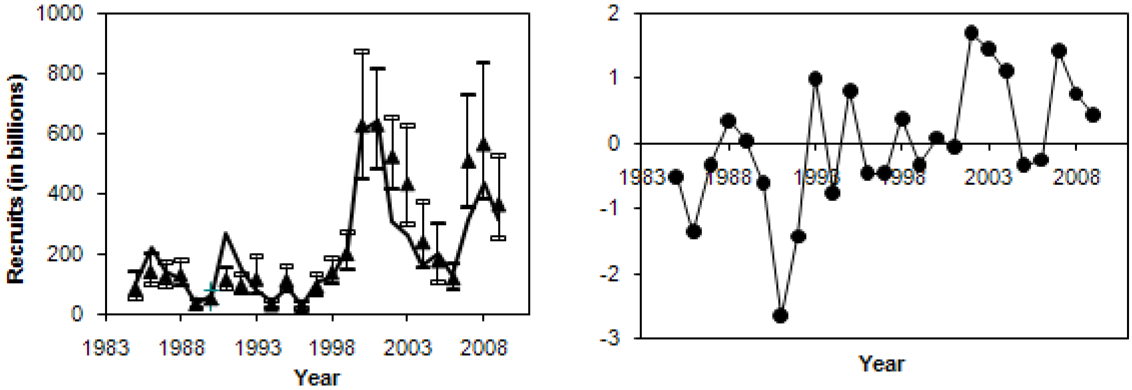

Figure 5. Acoustic survey results and A_0 model estimates for anchovy recruitment numbers from May 1985 to May 2009. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

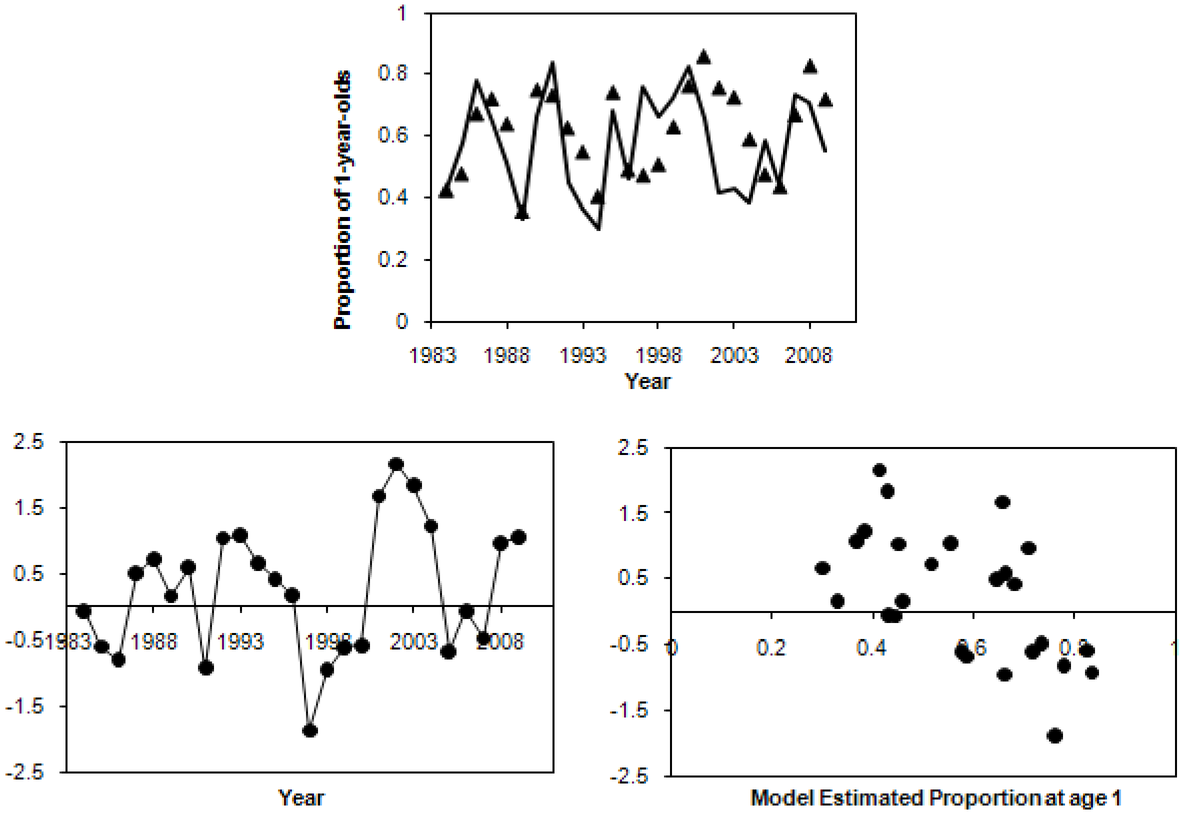

Figure 6. Acoustic survey results and A_0 model estimates for proportions of 1-year-olds in the November survey from 1984 to 2009. The standardised residuals from the fit are given in the lower plots, against year and against model estimates of proportions at age 1.

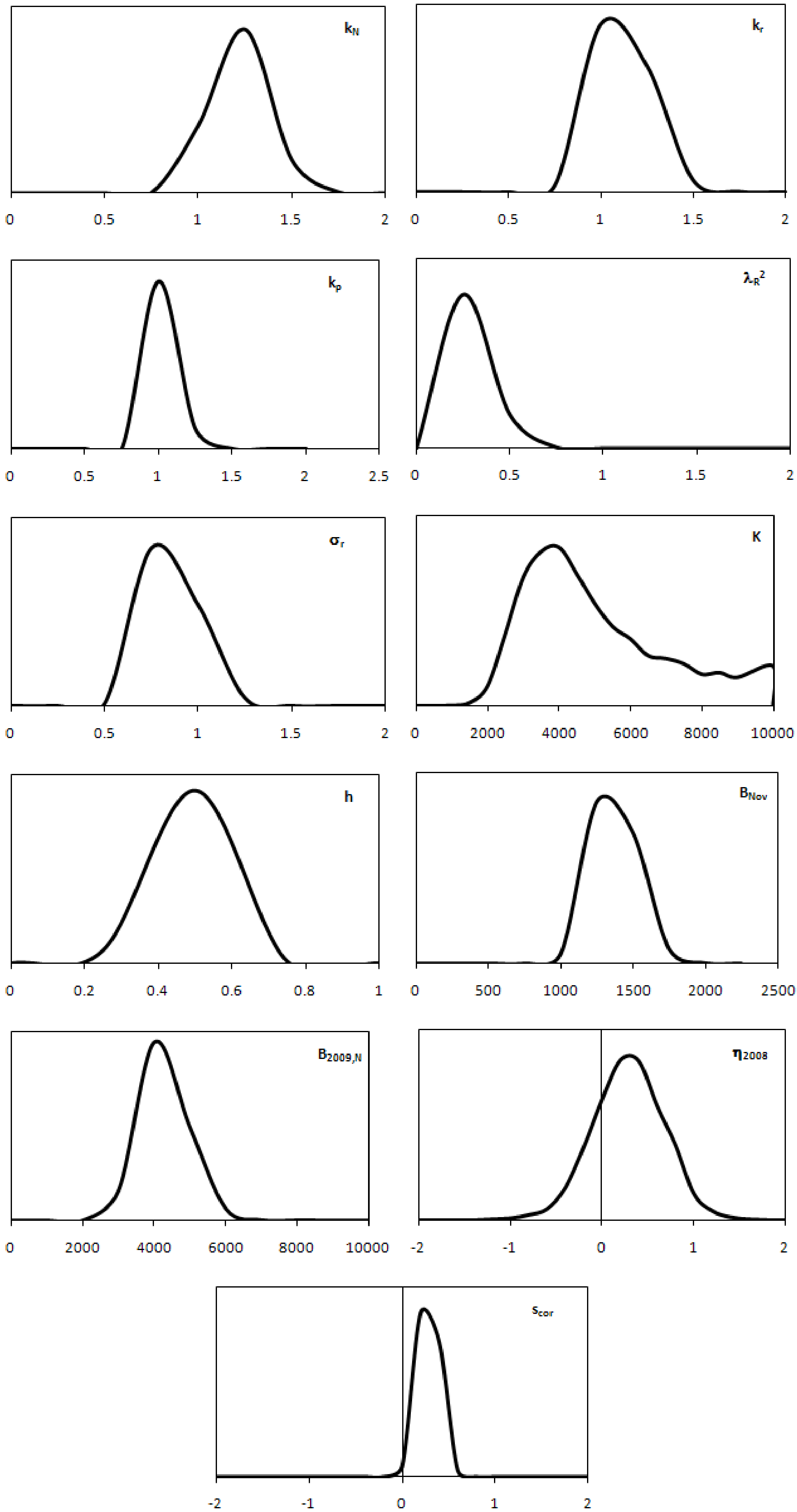

Figure 7. Posterior distributions for key model parameters and outputs for A_0. The parameters are defined in Table 4 and in the Appendix. Biomasses are displayed in thousands of tons.

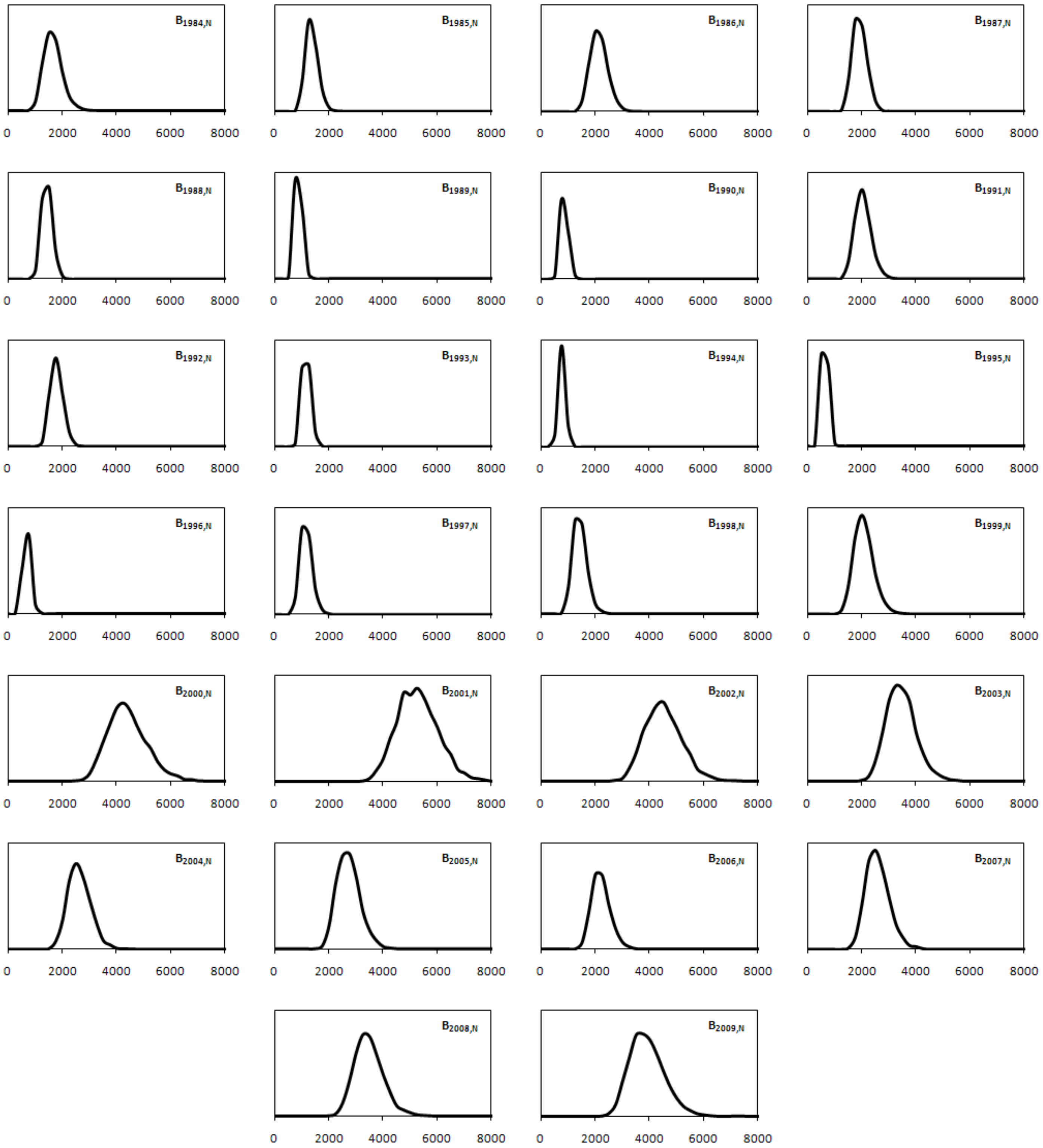

Figure 8. The posterior pdfs of model predicted November 1+ biomass for A_0.

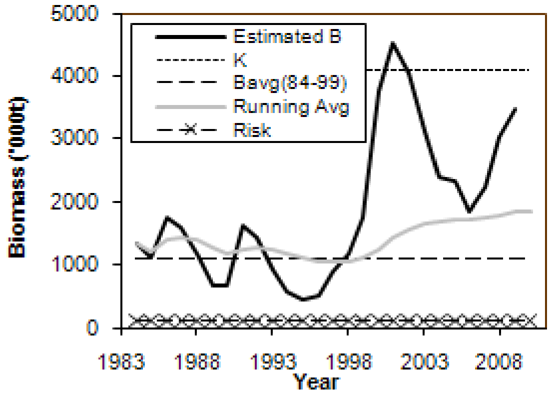

Figure 9. The base case model estimated November anchovy spawner biomass, plotted together with estimates of the carrying capacity, the average November 1984 to 1999 spawner biomass and 10% of this average. This last quantity was used as the risk threshold in developing OMP-04 and OMP-08. The running average (from 1984 to year *y*) spawner biomass is also shown.

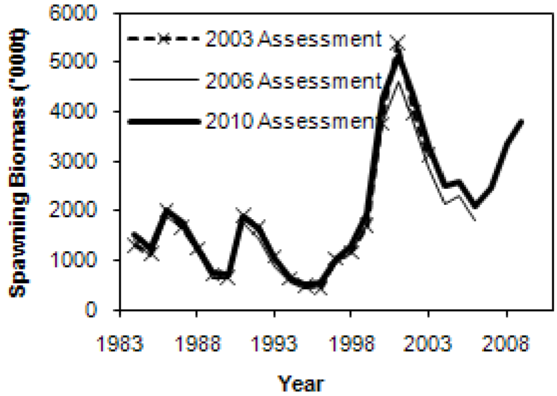

Figure 10. The mean posterior annual November biomass for A_0 and previous assessments.

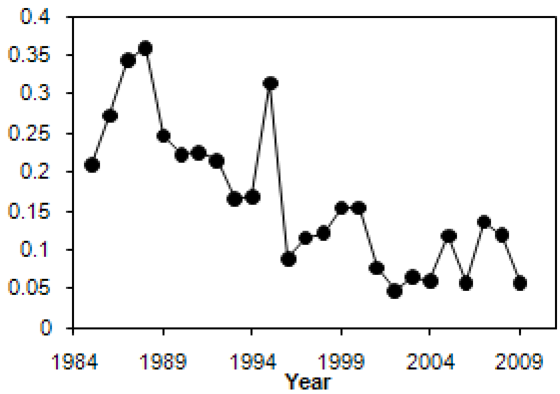

Figure 11. The historic harvest proportion (catch by mass to 1+ biomass) for anchovy from A_0.

APPENDIX: Bayesian Assessment Model for the South African Anchovy Resource

Model Assumptions

1) All fish have a theoretical birthdate of 1 November.
2) Anchovy spawn for the first time (and are called adult anchovy) when they turn one year old.
3) A plus group of age 4 is used, thus assuming that natural mortality is the same for age 4 and older ages.
4) Two acoustic surveys are held each year: the first takes place in November and surveys the adult stock; the second is in May/June (known as the recruit survey) and surveys juvenile anchovy.
5) The November acoustic survey provides a relative index of abundance of unknown bias.
6) The recruit survey provides a relative index of abundance of unknown bias.
7) The egg survey observations (derived from data collected during the earlier November surveys) provide absolute indices of abundance.
8) The survey designs have been such that they result in survey estimates of abundance whose bias is invariant over time.
9) Pulse fishing occurs five months after 1 November for 1-year-old anchovy; for 0-year-old anchovy this occurs 7½ months after 1 November prior to 1999, and 8½ months after 1 November from 1999 onwards; these two ages (0 and 1) are the only ages targeted by the fishery.
10) Catches are measured without error. (Selectivity of age 0 and age 1 anchovy varies from year to year. This would prove problematic were model predicted catch to be estimated and fitted to observed catch, but here the observed catches-at-age are directly incorporated into the dynamics.)
11) Natural mortality is year-invariant for juvenile and adult fish, and age-invariant for adult fish.

Population Dynamics

The basic dynamic equations for anchovy are as follows, where $y_n = 2009$.

Numbers-at-age at 1 November

$$N^A_{y,1} = (N^A_{y-1,0}e^{-(7.5)M^A_j/12} - C^A_{y,0})e^{-(4.5)M^A_j/12} \qquad y = 1984,\ldots,1998$$

$$N^A_{y,1} = (N^A_{y-1,0}e^{-(8.5)M^A_j/12} - C^A_{y,0})e^{-(3.5)M^A_j/12} \qquad y = 1999,\ldots,y_n$$

$$N^A_{y,2} = (N^A_{y-1,1}e^{-5M^A_{ad}/12} - C^A_{y,1})e^{-7M^A_{ad}/12} \qquad y = 1984,\ldots,y_n$$

$$N^A_{y,3} = N^A_{y-1,2}e^{-M^A_{ad}} \qquad y = 1984,\ldots,y_n$$

$$N^A_{y,4+} = N^A_{y-1,3}e^{-M^A_{ad}} \qquad y = 1984$$

$$N^A_{y,4+} = N^A_{y-1,3}e^{-M^A_{ad}} + N^A_{y-1,4+}e^{-M^A_{ad}} \qquad y = 1985,\ldots,y_n \qquad \text{(A.1)}$$

where

$N^A_{y,a}$ is the number (in billions) of anchovy of age *a* at the beginning of November in year *y*;

$C^A_{y,a}$ is the number (in billions) of anchovy of age *a* caught from 1 November in year $y-1$ to 31 October in year y;

M^A_j is the natural mortality (in year^{-1}) of juvenile anchovy (i.e. fish of age 0); and

M^A_{ad} is the natural mortality (in year^{-1}) of adult anchovy (i.e. fish of age 1+).

Biomass associated with the November survey

$$\hat{B}^A_{y,N} = \sum_{a=1}^{4+} N^A_{y,a} w^A_{y,a} \qquad y = 1984, \ldots, y_n \qquad \text{(A.2)}$$

where:

$\hat{B}^A_{y,N}$ is the biomass (in thousand tons) of adult anchovy at the beginning of November in year *y*, which are taken to be associated with the November survey; and

$w^A_{y,a}$ is the mean mass (in grams) of anchovy of age *a* sampled during the November survey of year *y*.

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

$$SSB^A_{y,N} = \sum_{a=1}^{4+} N^A_{y,a} w^A_{y,a} \qquad y = 1984, \ldots, y_n \qquad \text{(A.3)}$$

Recruitment

Recruitment at the beginning of November is assumed to fluctuate lognormally about a stock-recruitment curve:

$$N^A_{y,0} = f\left(SSB^A_{y,N}\right)e^{\varepsilon^A_y} \qquad y = 1984, \ldots, y_{n-1} \qquad \text{(A.4)}$$

where

ε^A_y is the annual lognormal deviation of anchovy recruitment.

Table 1 list the forms considered for the function *f*.

Number of recruits at the time of the recruit survey

The following equation projects $N^A_{y,0}$ to the start of the recruit survey, taking natural and fishing mortality into account, and assuming pulse fishing of juveniles at 1 May (based on historic data).

$$\hat{N}^A_{y,r} = (N^A_{y-1,0} e^{-0.5 M^A_j} - C^A_{y,0bs}) e^{-t^A_y \times M^A_j / 12} \qquad y = 1985, \ldots, y_n \qquad \text{(A.5)}$$

where

$\hat{N}^A_{y,r}$ is the number (in billions) of juvenile anchovy at the time of the recruit survey in year *y*;

$C^A_{y,0bs}$ is the number (in billions) of juvenile anchovy caught between 1 November and the day before the start of the recruit survey in year *y*;

t_y^A is the time lapsed (in months) between 1 May and the start of the recruit survey that provided the estimate $N_{y,rec}^A$ in year *y*.

Proportions of 1-year-olds associated with November survey

$$\hat{p}_{y,1}^A = \frac{N_{y,1}^A}{\sum_{a=1}^{4+} N_{y,a}^A} \qquad y = 1984, \ldots, y_n \qquad \text{(A.6)}$$

where

$\hat{p}_{y,1}^A$ is the proportion of 1-year-old anchovy at the beginning of November in year *y*, which is taken to be associated with the November survey.

Fitting the Model to Observed Data (Likelihood)

The observations are assumed to be log-normally distributed, and sampling CVs (squared) of the untransformed survey observations are used to approximate the "sampling" component of the total variance of the corresponding log-distributions. The proportions of 1-year-olds are first logit-transformed before being used in the likelihood[4]. Thus we have:

$$\begin{aligned}
-\ln L = & \tfrac{1}{2}\sum_{y=1984}^{yn}\left\{\frac{\left(\ln B_{y,N}^A - \ln(k_N^A \hat{B}_{y,N}^A)\right)^2}{(\sigma_{y,N}^A)^2 + (\lambda_N^A)^2} + \ln\left[2\pi\left((\sigma_{y,N}^A)^2 + (\lambda_N^A)^2\right)\right]\right\} \\
& + \tfrac{1}{2}\sum_{y=1984}^{1991}\left\{\frac{\left(\ln B_{y,egg}^A - \ln(k_g^A \hat{B}_{y,N}^A)\right)^2}{(\sigma_{y,egg}^A)^2} + \ln\left[2\pi(\sigma_{y,egg}^A)^2\right]\right\} \\
& + \tfrac{1}{2}\sum_{y=1985}^{yn}\left\{\frac{\left(\ln N_{y,r}^A - \ln(k_r^A \hat{N}_{y,r}^A)\right)^2}{(\sigma_{y,r}^A)^2 + (\lambda_r^A)^2} + \ln\left[2\pi\left((\sigma_{y,r}^A)^2 + (\lambda_r^A)^2\right)\right]\right\} \\
& + \frac{1}{2}\sum_{y=1984}^{yn}\left\{\frac{\left(\ln\left(p_{y,1}^A/\left(1-p_{y,1}^A\right)\right) - \ln\left(k_p^A \hat{p}_{y,1}^A/\left(1-k_p^A \hat{p}_{y,1}^A\right)\right)\right)^2}{\left(\sigma_p^A\right)^2} + \ln\left[2\pi\left(\sigma_p^A\right)^2\right]\right\}
\end{aligned} \qquad \text{(A.7)}$$

where

$B_{y,N}^A$ is the acoustic survey estimate (in thousand tons) of adult anchovy biomass from the November survey in year *y*, with associated CV $\sigma_{y,N}^A$ and constant of proportionality (multiplicative bias) k_N^A;

$B_{y,egg}^A$ is the egg survey estimate (in thousand tons) of adult anchovy biomass from the November survey in year *y*, with associated CV $\sigma_{y,egg}^A$ and constant of proportionality k_g^A;

$N_{y,r}^A$ is the acoustic survey estimate (in billions) of anchovy recruitment from the recruit survey in year *y*, with associated CV $\sigma_{y,r}^A$ and constant of proportionality k_r^A;

[4] This transformation proved adequate, resulting in no heteroscedasticity in the residuals of the logit transformation.

$p_{y,1}^A$ is an estimate of the proportion (by number) of 1-year-old anchovy in the November survey of year *y*,. For the base case assessment an average Prosch age length key is used to derive these proportions;

k_p^A is a multiplicative bias associated with the proportion of 1-year-olds in the November survey;

$(\lambda_{N/r}^A)^2$ is the additional variance (over and above the survey sampling CV $\sigma_{y,N/r}^A$ that reflects survey inter-transect variance) associated with the November/recruit surveys;

σ_p^A is the standard deviation associated with the proportion of 1-year-olds in the November survey, which is estimated in the fitting procedure by:

$$\sigma_p^A = \sqrt{\sum_{y=1984}^{2006}\left[\ln\left(p_{y,1}^A \big/ \left(1 - p_{y,1}^A\right)\right) - \ln\left(k_p^A \hat{p}_{y,1}^A \big/ \left(1 - k_p^A \hat{p}_{y,1}^A\right)\right)\right]^2 \Big/ \sum_{y=1984}^{2006} 1}$$

Fixed Parameters

Four parameters are fixed externally in this assessment (see main text for reasons and for variations for robustness tests):

M_j^A and M_{ad}^A (values given in main text), $\left(\lambda_N^A\right)^2 = 0$, and $k_g^A = 1$, as the egg survey estimates of abundance are assumed to be absolute.

Estimable Parameters and Prior Distributions

The recruitments are assumed to fluctuate lognormally about the stock-recruitment curve:

$$\varepsilon_y^A \sim N\left(0, \left(\sigma_r^A\right)^2\right) \quad , \qquad y = 1984, ..., y_{n-1}$$

The remaining estimable parameters are defined as having the near non-informative prior distributions:

$\ln\left(k_N^A\right) \sim U\left(-100, 0.7\right)$ (upper bound corresponding to $k_N^A = 2$)

$\ln\left(k_r^A\right) \sim U\left(-100, 0.7\right)$ (upper bound corresponding to $k_r^A = 2$)

$\ln\left(k_p^A\right) \sim U\left(-100, 0.7\right)$ (upper bound corresponding to $k_p^A = 2$)

$\left(\lambda_r^A\right)^2 \sim U\left(0, 100\right)$

$\left(\sigma_r^A\right)^2 \sim U\left(0, 10\right)$

$N_{1983,a}^A \sim U(0, 500)$, $a = 0,1$

$N_{1983,a}^A \sim U(0, 0.01)$, $a = 2,3$

$h^A \sim U(0.2, 1.5)$

$\ln\left(K^A\right) \sim U(4.6, 9.2)$ (corresponding to a range of about [100 000t; 1 000 000t] for K^A)

Further Outputs

Recruitment serial correlation:

$$s_{cor}^{A} = \frac{\sum_{y=1984}^{yn-2} \varepsilon_y \varepsilon_{y+1}}{\sqrt{\left(\sum_{y=1984}^{yn-2} \varepsilon_y^2\right)\left(\sum_{y=1984}^{yn-2} \varepsilon_{y+1}^2\right)}} \qquad \text{(A.9)}$$

and the standardised recruitment residual value for 2005:

$$\eta_{yn-1}^{A} = \frac{\varepsilon_{yn-1}^{A}}{\sigma_r^{A}}. \qquad \text{(A.10)}$$

are also required as input into the OMP.