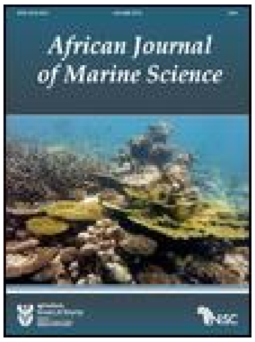

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The 2004 re-assessment of the South African sardine and anchovy populations to take account of revisions to earlier data and recent record abundances

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Hydroacoustic surveys off the coast of South Africa over the early years of the 21st century indicated that both the sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus* populations had simultaneously reached record abundances. The South African pelagic fishery is regulated using an Operational Management Procedure (OMP). The OMP in use at that time had been developed using data from the two populations prior to this rapid and substantial increase in abundances. This paper documents the revised assessments that were urgently required to provide a basis to update the OMP. These assessments resulted in a changed perception of the status and productivity of these populations. In particular, estimates of the stock-recruitment relationships and the extent of variation about them, which play a key role in evaluating risk when developing OMPs, altered substantially from estimates derived from earlier assessments.

Keywords: anchovy, assessment, sardine, South Africa, stock recruitment

Introduction

Sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus* form the backbone of the South African pelagic fishery, the second most valuable fishery in monetary terms in South Africa. Due to their short lifespan and variable recruitment, sardine and anchovy populations worldwide have shown large fluctuations in abundance over time (Schwartzlose et al. 1999). The South African sardine catch peaked in the early 1960s (De Oliveira 2003), but dropped sharply thereafter and remained low from the late 1960s until the mid-1990s. The anchovy-directed fishery began following the fall in the sardine landings in the mid-1960s (Butterworth 1983), and anchovy landings dominated the pelagic fishery from the late 1960s to the mid-1990s (Figure 1, De Oliveira 2003).

Hydroacoustic surveys in the early years of the 21st century indicated that both anchovy and sardine were simultaneously at peak abundance (de Moor et al. 2008). This was the first substantial increase in sardine biomass since the 1960s.

The management of these populations must take into account specific characteristics such as the relatively short lifespan of the fish (e.g. Barange et al. 2009) and that the two species can shoal together as juveniles leading to bycatch related difficulties (De Oliveira and Butterworth 2004). This trade-off between maximising fishing effort on the two species has resulted in a joint Operational Management Procedure (OMP) (e.g. Butterworth et al. 1997, De Oliveira et al. 2008) being employed to recommend the total allowable catch (TAC) and bycatch for both species (De Oliveira and Butterworth 2004, Cunningham and Butterworth 2005a). The OMP is developed and simulation-tested based upon operating models of the underlying dynamics of the species which in turn are provided by the most recent assessment of the sardine and anchovy populations. The OMP put in place following the turn of the century (OMP-02; De Oliveira and Butterworth 2004) had been developed using data up to November 1999 for sardine and May 2000 for anchovy (De Oliveira 2003). Given the rapid and substantial increase in abundance in the two species after 1999, the OMP for these species needed to be revised based on the new perception of the stocks, and updated assessments of the South African sardine and anchovy populations were therefore required. This paper documents these updated assessments and considers the change in the perception of the dynamics of these populations that resulted, not only due to the new data spanning the simultaneous peaks in abundance of both species but also to a revision in the time-series of hydroacoustic estimates of abundance.

The paper first discusses the historical survey abundance and catch data used to estimate the operating model parameters, and the changes in these data from the preceding assessments of the South African sardine and anchovy

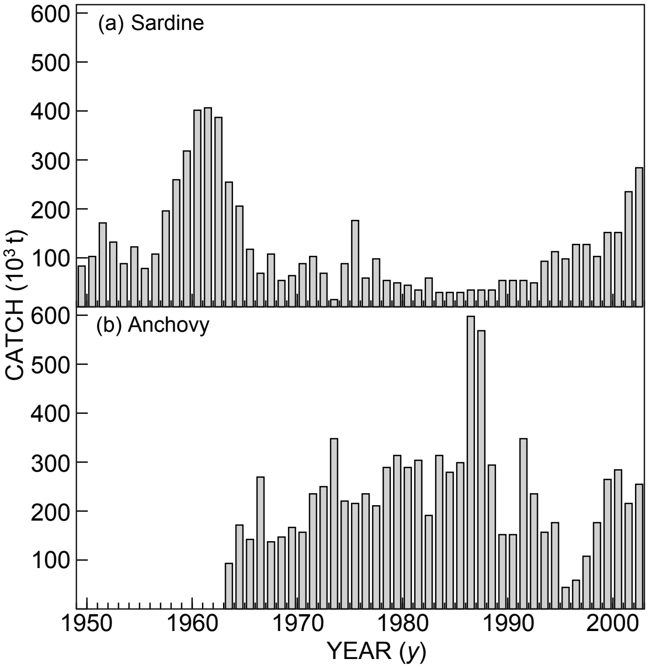

Figure 1: Annual catch of (a) sardine and (b) anchovy from 1950 to 2003. The data from 1980 are used in the assessments. The year *y* indicated refers to the period from November of year *y*−1 to October of year *y*

populations are highlighted. The assessment methods used are then detailed and the results shown. Finally, the implications of the resultant change in the perceptions of the status and productivity of these populations are discussed.

Data

The data used in these models included annual estimates of 1+ (adult) biomass during November from 1984 to 2003 and of recruits (0-year-olds) during May from 1985 to 2003 from hydroacoustic surveys (Table 1, Figures 2, 3). The survey strategy has remained essentially unchanged over time so that any survey bias is reasonably assumed to be constant. In addition, a series of egg survey abundance estimates, derived from data collected during the November surveys from 1984 to 1991, provide absolute indices of abundance for anchovy (Table 1, Figure 4). Furthermore, sardine proportions-at-age 1–5 and anchovy proportions-at-age 1 have been estimated from the November surveys from 1988 to 1999 for sardine and 1988 to 2000 for anchovy (Tables App.1.1, App.2.1, Figures 5 and 6).

The complete series of hydroacoustic estimates of 1+ biomass and recruitment were updated from those used in the previous assessments (De Oliveria 2003) to account for signal saturation in earlier generation echosounders. Prior to 1997, the SIMRAD EK400 echosounder, and echosounders used earlier, saturated at approximately −29 dB, thereby setting any signal higher than −29 dB to −29 dB, i.e. it 'capped' signals at this maximum level (Barange et al. 1999,

Table 1: The annual November acoustic survey estimate of sardine and anchovy 1+ (adult) biomass, the annual May acoustic survey estimate of sardine and anchovy recruitment, the annual November egg survey estimate of anchovy spawner biomass and the annual* sardine and anchovy catch. Where applicable, CVs are given in parentheses

Year	Sardine			Anchovy			
	November 1+ biomass (t)	May recruitment (billions)	Catch (t)	November 1+ biomass (t)	November spawner biomass (t)	May recruitment (billions)	Catch (t)
1980			50 887				315 219
1981			46 342				291 949
1982			35 146				306 161
1983			60 080				191 546
1984	42 101 (0.60)		27 178	1 586 014 (0.27)	1 100 000 (0.45)		314 175
1985	71 045 (0.40)	3.143 (0.24)	30 843	1 449 263 (0.19)	616 000 (0.40)	91.736 (0.18)	279 923
1986	210 505 (0.40)	4.754 (0.55)	30 639	2 596 782 (0.18)	2 001 000 (0.35)	121.755 (0.17)	299 589
1987	167 415 (0.55)	8.040 (0.47)	34 345	2 164 863 (0.16)	1 606 000 (0.30)	115.694 (0.16)	600 565
1988	143 061 (0.40)		34 435	1 640 715 (0.22)	1 679 000 (0.35)	111.836 (0.16)	569 737
1989	371 413 (0.25)		36 265	797 247 (0.18)	421 000 (0.35)	29.395 (0.19)	297 429
1990	344 418 (0.35)		56 403	697 133 (0.20)	723 000 (0.58)	45.517 (0.27)	151 603
1991	580 488 (0.28)	5.245 (2.33)	52 186	2 500 349 (0.16)	2 913 000 (0.35)	82.699 (0.17)	151 047
1992	429 002 (0.37)	13.836 (0.37)	52 518	2 230 894 (0.16)		101.114 (0.18)	349 040
1993	610 535 (0.28)	24.671 (0.35)	48 791	1 189 180 (0.20)		98.691 (0.22)	235 793
1994	780 638 (0.26)	6.210 (0.46)	94 538	708 204 (0.17)		30.071 (0.19)	156 020
1995	814 005 (0.31)	38.583 (0.28)	111 027	642 795 (0.21)		134.256 (0.18)	177 866
1996	663 407 (0.24)	8.191 (0.65)	96 986	212 634 (0.35)		26.772 (0.19)	42 525
1997	1 180 688 (0.27)	42.850 (0.13)	126 943	1 190 899 (0.24)		111.890 (0.17)	60 718
1998	1 612 106 (0.25)	14.540 (0.26)	126 956	1 318 069 (0.20)		136.740 (0.13)	107 867
1999	1 564 311 (0.22)	12.000 (0.29)	101 410	2 099 735 (0.15)		161.110 (0.15)	179 370
2000	2 386 953 (0.48)	36.390 (0.37)	151 991	4 505 615 (0.11)		550.110 (0.18)	267 511
2001	2 500 338 (0.14)	69.280 (0.15)	153 425	7 925 531 (0.13)		631.950 (0.13)	285 083
2002	4 138 252 (0.22)	71.780 (0.20)	235 753	3 858 376 (0.16)		460.050 (0.11)	215 767
2003	3 175 604 (0.19)	63.450 (0.25)	284 820	3 668 638 (0.23)		379.520 (0.18)	255 969

* The convention used is that this annual period, denoted by *y*, runs from November of calendar year *y*–1 to October of calendar year *y*

Coetzee et al. 2008). Since 1997, the SIMRAD EK500 echosounder has been able to provide ‘uncapped’ biomass estimates. In addition, comparable capped estimates of biomass were generated by setting the maximum signal threshold of the SIMRAD EK500 data to −29 dB at the analysis stage.

Uncapped estimates of recruit and 1+ biomass from November 1984 to November 1996 were calculated using predictive regressions based on non-linear regressions between the known capped and uncapped estimates of recruit and 1+ biomass from May 1997 to May 2003 (for methodology see de Moor et al. 2008[1]).

In addition to the correction for signal saturation in earlier generation echosounders, the updated November 1+ biomass estimates incorporated new estimates of target strength for sardine and anchovy, and the affects of attenuation in dense sardine schools (Coetzee et al. 2008[1]). Uncapped 1+ biomass estimates using the new acoustic target strength expressions were available from November 1997 to 2003, and those that in addition took attenuation of dense sardine schools into consideration were available from November 1998 to 2002. The means and CVs of these corrections were used to adjust the uncapped estimates of 1+ biomass from November 1984 to 1998 to account for new target strength expressions and for attenuation for sardine.

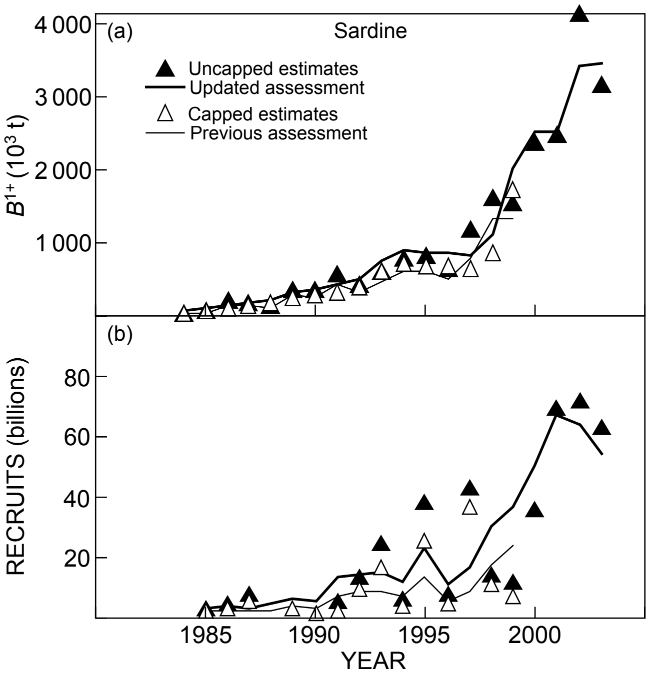

Figure 2: Observed and model-predicted of (a) November sardine 1+ biomass (B^{+1}) and (b) May sardine recruitment numbers using uncapped data from 1984/1985 to 2003. The November uncapped data are also adjusted for new estimates of target strength and attenuation. The capped estimates and model predicted 1+ biomass and recruitment numbers from the previous assessment using capped data from 1984/1985 to November 1999 (De Oliveira 2003) are also shown

Some slight revisions were made to the catch data from 1987 used in the previous assessment, and four further years’ data were included (Table 1, Figure 1). In the absence of age–length keys from sardine commercial data for recent years, an average age–length key was calculated from those from 1997 to 1999 and used to calculate the catches-at-age from 2000 to 2003. (Although the problems of such

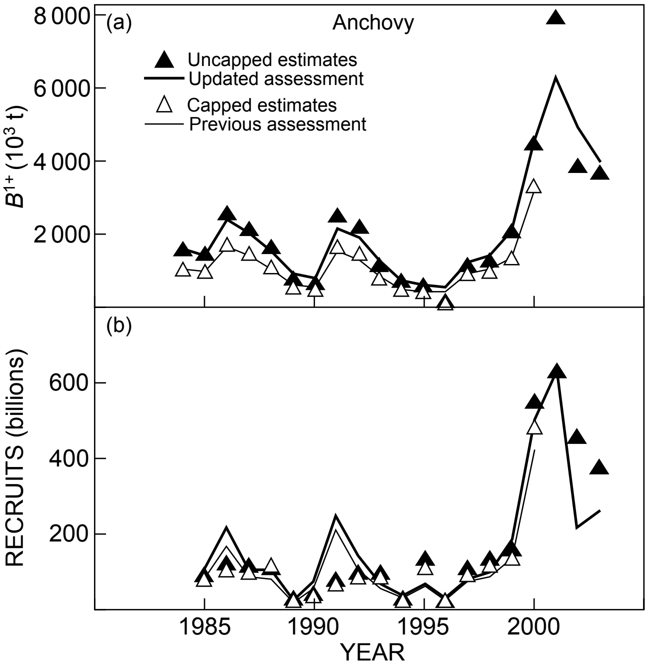

Figure 3: Observed and model-predicted (a) November anchovy 1+ biomass (B^{+1}) and (b) May anchovy recruitment numbers using uncapped data from 1984/1985 to 2003. The November uncapped data are also adjusted for new estimates of target strength. The capped estimates and model predicted 1+ biomass and recruitment numbers from the previous assessment using capped data from 1984/1985 to May 2000 (De Oliveira 2003) are also shown

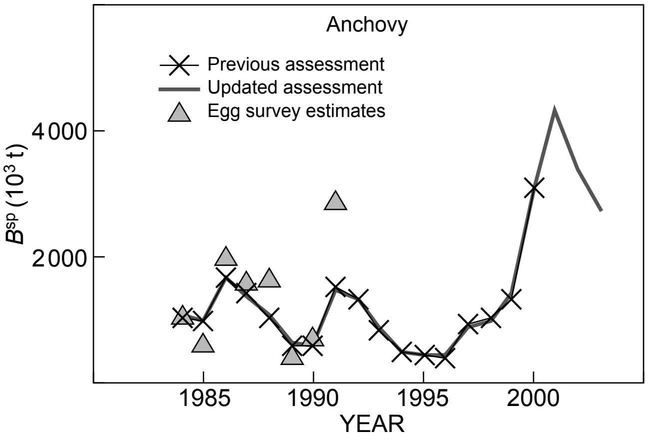

Figure 4: Model-predicted November anchovy spawner biomass from the previous assessment (De Oliveira 2003) and the updated assessment fitted to egg survey estimates of abundance between 1984 and 1991

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[1] At the time of this assessment, not all the data reported in this reference were available, so that the actual calibration factor values used here differed

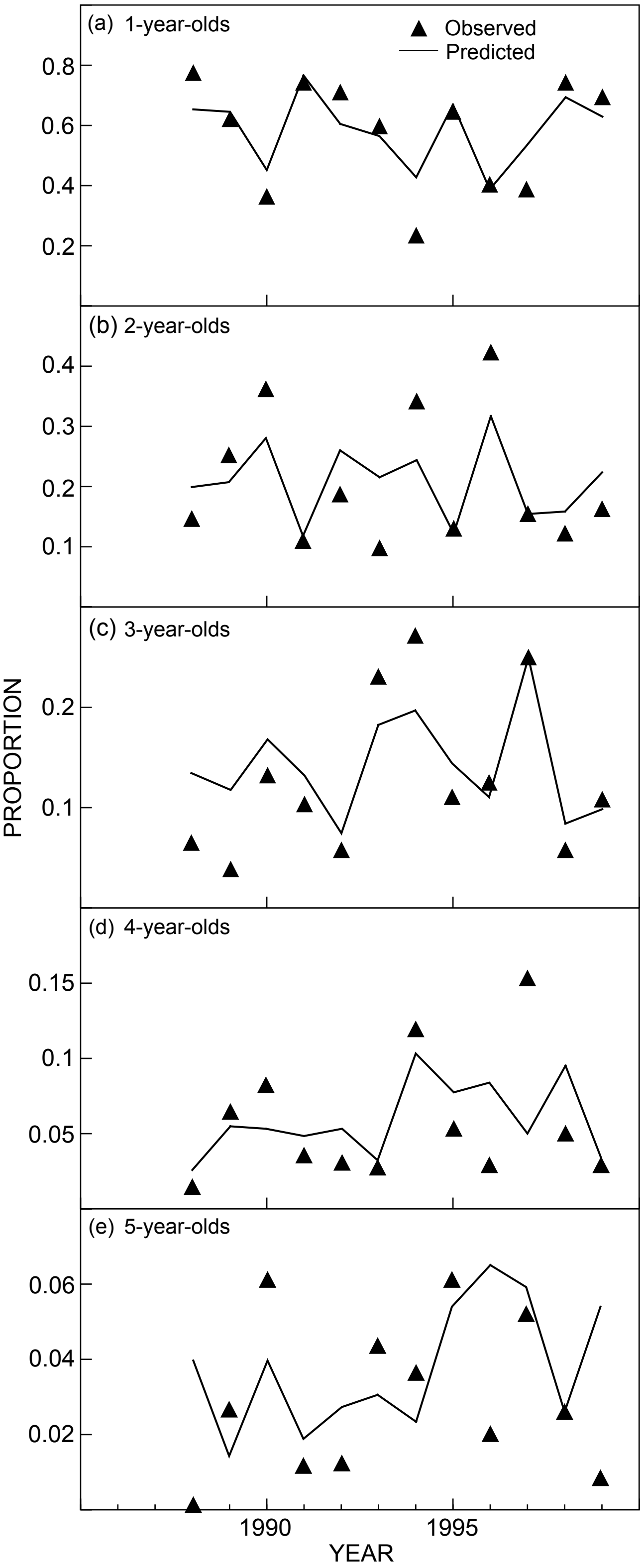

Figure 5: Observed and model-predicted sardine proportions-at-age in the November surveys from 1988 to 1999 (note that the vertical axis scales differ)

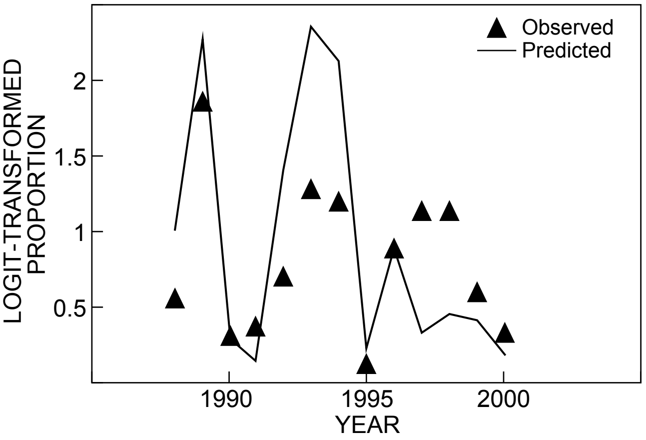

Figure 6: Observed and model-predicted anchovy logit-transformed proportion of 1-year-olds in the November surveys from 1988 to 2000

an approach were realised, it was nevertheless considered desirable to include this information in this manner to inform estimates of fishing selectivity.) A more conservative, 'slower growth' age–length key was considered in a robustness test (Cunningham and Butterworth 2005b).

Assessment method

The South African anchovy and sardine populations were modelled using age structured production models. These models are fully described in Appendices 1 and 2 for sardine and anchovy respectively. The key new features in these models compared to the previous assessments (De Oliveira 2003) are that the assessments were extended to include estimating the stock-recruitment curve parameters within the overall fit of the assessment model to the data, and that Bayesian estimation was used.

Tables App.1.3 and App.2.2 list the values adopted for the fixed parameters and prior distributions for the estimable parameters for the sardine and anchovy models respectively. A probability distribution function (pdf) for the overall bias in the sardine November survey was calculated by drawing 10 000 samples from the individual pdfs for each source of error (see Table 2 and Figure 7). The median of this pdf was used as a fixed parameter for this assessment (Table App.1.3). Note that this means that expert assessment of errors associated with the survey suggest a best estimate of the extent of underestimation, as reflected by the associated multiplicative bias, of 1⁄0.720 = 1.39. Further combinations of values for these parameters were considered in robustness tests (Cunningham and Butterworth 2005b).

The Bayesian integration was implemented numerically using the Markov Chain Monte Carlo method (Gelman et al. 1995) in AD Model Builder (Otter Research Ltd 2000). The numerical routine applied to a function consisting of the negative log-likelihood given in Equation App.1.6 for sardine or App.2.6 for anchovy, together with the negative of the 36 log-prior distributions for sardine or 29 for anchovy. Convergence to the posterior distribution was tested using

Table 2: Distribution parameters for the different sources of error contributing to hydroacoustic survey estimates of November sardine 1+ biomass (based on Table 1 of BENEFIT 2000)

Error	Minimum	Likely (lower)	Likely (midpoint)	Likely (upper)	Maximum	Nature
Target strength	0.50	0.80	1.00	1.20	1.50	Constant
Calibration						
(On-axis sensitivity)	0.90	0.95	1.00	1.05	1.10	Random*
(Beam factor)	0.75	0.90	1.00	1.10	1.25	Constant
Surface schooling	1.00	1.05	1.075	1.10	1.15	Variable
Target identification	0.50	0.90	1.00	1.10	1.50	Random
Weather effects	1.01	1.05	1.15	1.25	2.00	Variable

* Note that for the purposes of this simulation, ‘random’ and ‘variable’ factors are treated in the same manner

the Bayesian Output Analysis package (Smith 2005). A chain was accepted as having converged only once the diagnostics from the tests of Geweke (1992), Gelman and Rubin (1992), Raftery and Lewis (1992) and Heidelberger and Welch (1983) were all passed for all parameters. The autocorrelations for each estimable parameter and cross-correlations between the parameters were also monitored to assess if further thinning or re-parameterisation was required.

The chains from which resampling was conducted for the results that follow were based on 40 000 000 samples each. A burn-in of 15 000 000 was discarded and the remaining chain was thinned by 1 000 to decrease any autocorrelation.

Results

The model fits to the November sardine 1+ biomasses and the May sardine recruitment numbers are shown in Figure 2. The increase in the sardine biomass from the previous survey series of capped estimates of abundance to the uncapped estimates of abundance, corrected for target strength and attenuation, is clear, although the differences for the recruitment numbers were not as substantial as those for the 1+ biomasses (Figure 2). The model fits to the November anchovy 1+ biomasses and the May anchovy recruitment numbers are shown in Figure 3. Figure 4 shows the model fit to the November anchovy egg survey estimates of spawner biomass. The changes in survey series estimates from capped to uncapped were not as large as that for sardine. However, it is clearly evident from Figures 2–4 that there were simultaneous record levels in both sardine and anchovy biomass and recruitment in the most recent years of these assessments. These figures clearly reflect the change in perceptions of stock dynamics brought about not only by the recent peak abundances, but also by the update in the hydroacoustic data to account for receiver saturation, and for new target strength expressions and sardine attenuation effects in the November survey.

The model fits to the sardine proportions-at-age and the logit-transformed anchovy proportion-at-age 1 in the November survey are shown in Figures 5 and 6 respectively. The fits suggest considerable noise in these data.

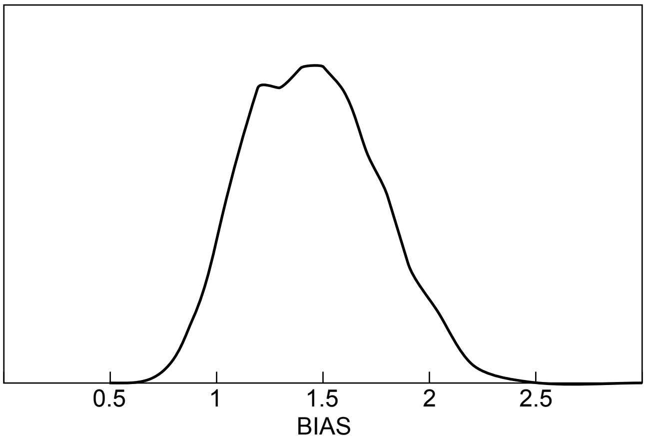

Figure 7: The probability distribution function for the overall bias in the November sardine biomass survey, calculated by drawing 10 000 samples from the individual probability distribution functions for each source of error (based on Table 1 of BENEFIT 2000)

A key change in the perception of the sardine population dynamics relates to the stock recruitment relationship (Figure 8, Table 3). Both the estimated maximum (deterministic) recruitment, and the threshold biomass below which recruitment decreases linearly from this maximum, increased substantially compared to the previous assessment. In contrast, the combination of the updated series of survey abundance estimates and the recent peak in anchovy abundance and recruitment did not result in a substantial change to the estimated anchovy stock recruitment curve (Figure 9, Table 4).

The standard deviation of the sardine recruitment residuals (σ_r^S) was lower at the posterior mode in this updated assessment compared to the previous assessment (Table 3), whereas that of the anchovy recruitment residuals (σ_r^A) was substantially higher (Table 4). The posterior pdfs are shown in Figure 10 for sardine and Figure 11 for anchovy. The minimum prior bound of 0.4 had little effect on the posterior distribution for σ_r^A (Figure 11).

Another parameter whose value has important implications for future projections is the recruitment serial correlation. This increased compared to the previous assessment for anchovy and decreased for sardine. Thus, it is more likely that a poor/good recruitment year class of anchovy will be followed by another poor/good year class than had previously been thought.

The sardine proportion-at-age 1 in the November survey was estimated to be positively biased whereas the

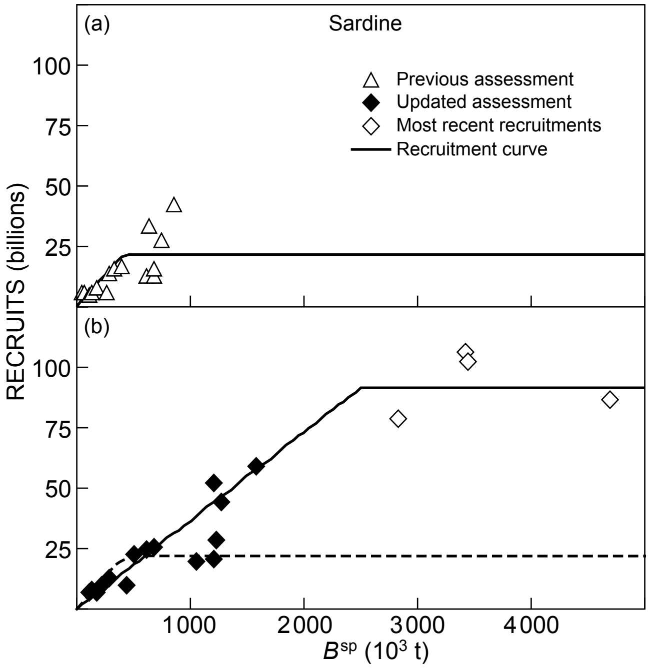

Figure 8: Model-predicted sardine November recruitment plotted against spawner biomass (a) from November 1984 to 1998 using the previous assessment (De Oliveira 2003) and (b) from 1984 to 2002 using the updated assessment. The four most recent recruitments are shown and the stock recruitment curves estimated using the assessments are also shown, with the curve from the previous assessment reproduced on plot (b) (dashed line)

proportion-at-age 2 was negatively biased (Table 3), i.e. the observed proportions-at-age 1 tend to be greater than the true proportions and the observed proportions-at-age 2 tend to be less than the true values. The 95% probability interval for the bias in the anchovy November survey showed this bias to most likely be positive (Table 4).

The posterior median sardine November 1+ biomass in 2003 was 4.9 million t (Table 3). This biomass was estimated to range between 19% and 130% of carrying capacity (95% probability interval), with a median of 72% (Table 3, Figure 12). The posterior median anchovy November 1+ biomass in 2003 was 3.1 million t (Table 4). This biomass was estimated to range between 69% and 197% of carrying capacity (95% probability interval), with a median of 123% (Table 4, Figure 13).

Discussion

The hydroacoustic survey time-series upon which the assessments of the South African sardine and anchovy populations are primarily based have been revised not only to include new data for recent years, but to also take account of corrections for signal saturation in earlier generation echosounders, new target strength expressions in the estimates of November 1+ (adult) biomass, and attenuation effects in dense sardine schools during the November survey. This paper has detailed the updated assessments of both populations, taking these revised time-series into account. The new data, together with these updated assessments, clearly show that both populations simultaneously

Table 3: Key parameters and outputs at the joint posterior mode and the median of the marginal posterior distributions for the sardine assessment. A comparison is made to the maximum likelihood estimate of some parameters from the previous assessment which considered data to November 1999 (De Oliveira 2003). Biomasses are given in thousands of tonnes and numbers in billions. Values in bold are fixed as input rather than estimated when fitting the assessment model to the data. No entry is given where a result is not applicable

Parameter		Previous assessment	Updated assessment		
		Maximum likelihood estimate	Joint posterior mode	Marginal posterior median	95% probability interval
Juvenile natural mortality	M^S_{ju}	**1.000**	**1.000**		
Adult natural mortality	M^S_{ad}	**0.400**	**0.400**		
Biases for November and recruit surveys	k^S_N	**1.000**	**0.720**		
	k^S_r	0.954	1.045	1.018	[0.670; 1.494]
Biases for proportions-at-age in November surveys	$k^S_{p,1}$	1.135	1.189	1.197	[1.077; 1.333]
	$k^S_{p,2}$	0.788	0.781	0.785	[0.659; 0.934]
	$k^S_{p,3}$	1.113	1.043	1.041	[0.845; 1.289]
	$k^S_{p,4}$	1.004	0.884	0.875	[0.626; 1.217]
	$k^S_{p,5}$	1.250	1.006	0.982	[0.627; 1.532]
Stock-recruitment parameters	a^S	21.6	91.8	94.6	[64.3; 145.6]
	$a^S_{79\text{–}83}$		3.2	3.0	[2.0; 4.1]
	b^S	414	2 570	2 858	[1 199; 11 842]
	K^S	1 552	6 267	6 754	[3 323; 26 541]
	σ^S_r	0.499	0.400	0.491	[0.405; 0.691]
Current recruitment residual	ε^S_{2002}		−0.037	0.129	[−1.428; 1.616]
Recruitment serial correlation	s^S_{cor}	0.374	0.236	0.213	[−0.147; 0.500]
Current 1+ biomass	$\hat{B}^S_{2003,Nov}$		4 476	4 861	[3 359; 6 991]
Current depletion	$\hat{B}^S_{2003,Nov}/K^S$		0.762	0.723	[0.190; 1.298]
Average 1991–1994 1+ biomass*			898	936	[756; 1 182]

* This level is used as the threshold for defining risk, see Cunningham and Butterworth (2004)

reached record levels of abundance in the early years of this century, following consecutive years of good recruitment. In addition, the revised sardine time-series has increased substantially from that used in the previous assessment. The simultaneous peak of both the South African sardine and anchovy is in contrast to previous postulates that peaks in abundance in sardine and anchovy populations are negatively correlated (e.g. Schwartzlose et al. 1999).

The updated assessments presented here have resulted in an altered perception of the status and productivity of the populations from the previous assessment (De Oliveira 2003). One of the key areas in which there has been such a change in perception concerns the stock-recruitment relationships. In these assessments, the parameters of the stock-recruitment curves were estimated within the overall fit of the assessment model to the data, allowing for greater self-consistency. The estimated sardine stock recruitment curve altered dramatically, with substantial increases in both the maximum (deterministic) recruitment and the threshold biomass below which recruitment would be expected to decrease linearly from the maximum (Figure 8). The standard deviation of residuals about this curve (which has important implications for evaluating risk) was estimated to be slightly lower than for the previous assessment (Table 3).

In contrast, the anchovy stock recruitment curve at the posterior mode did not alter substantially from that for the previous assessment (Figure 9). However, the large increase in the standard deviation of residuals about this curve from that estimated in the previous assessment has important implications for future projections of the population and associated management decisions. Consequently, the anchovy population became considered to be able to sustain higher natural fluctuations to lower (and higher) abundances. The larger underlying standard deviation in recruitment residuals means that the population concerned

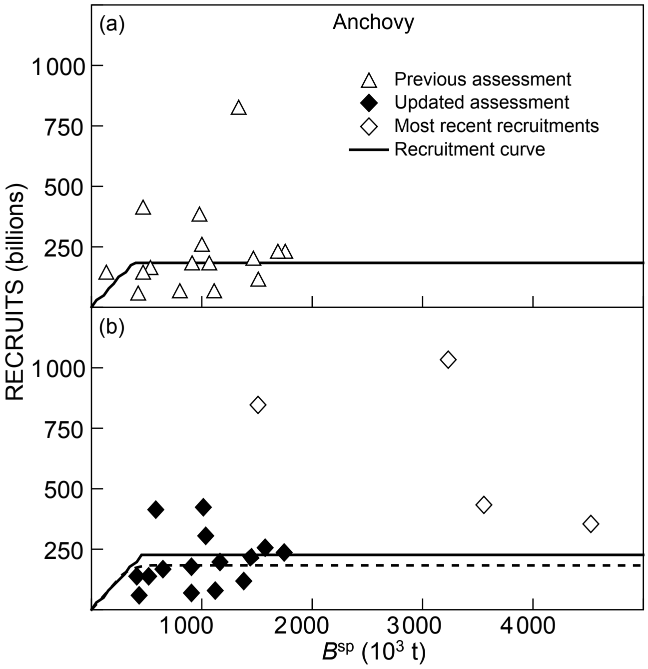

Figure 9: Model-predicted anchovy November recruitment plotted against spawner biomass (a) from November 1984 to 1999 using the previous assessment (De Oliveira 2003) and (b) from 1984 to 2002 using the updated assessment. The four most recent recruitments are shown and the stock recruitment curves estimated using the assessments are also shown, with the curve from the previous assessment reproduced on plot (b) (dashed line)

Table 4: Key parameters and outputs at the joint posterior mode and the median of the marginal posterior distributions for the anchovy assessment. A comparison is made to the maximum likelihood estimate of some parameters from the previous assessment which considered data to May 2000 (De Oliveira 2003). Biomasses are given in thousands of tonnes and numbers in billions. Values in bold are fixed as input rather than estimated when fitting the assessment model to the data. No entry is given where a result is not applicable

Parameter		Previous assessment	Updated assessment		
		Maximising likelihood estimate	Joint posterior mode	Marginal posterior median	95% probability interval
Juvenile natural mortality	M^{A}_{ju}	**0.900**	**0.900**		
Adult natural mortality	M^{A}_{ad}	**0.900**	**0.900**		
Biases for November and recruit surveys	k^{A}_{N}	0.988	1.384	1.224	[0.934; 1.607]
	k^{A}_{r}	0.839	0.984	0.930	[0.668; 1.296]
Biases for proportions-at-age 1 in November surveys	k^{A}_{q}		1.268	1.160	[0.675; 1.855]
Stock-recruitment parameters	a^{A}	179.0	227.7	216.1	[146.1; 281.3]
	b^{A}	360	461	498	[335; 890]
	K^{A}	1 802	2 307	2 492	[1 676; 4 451]
	σ^{A}_{r}	0.685	0.740	0.883	[0.659; 1.276]
Current recruitment residual	ε^{A}_{2002}		0.877	0.789	[−0.040; 1.599]
Recruitment serial correlation	s^{A}_{cor}	0.324	0.565	0.474	[0.221; 0.622]
Current 1+ biomass	$\hat{B}^{A}_{2003,Nov}$		3 669	3 101	[2 006; 4 774]
Current depletion	$\hat{B}^{A}_{2003,Nov}/K^{A}$		1.261	1.234	[0.689; 1.973]
Average 1984–1999 1+ biomass*			1 023	1 169	[904; 1 502]

* This level is used as the threshold for defining risk, see Cunningham and Butterworth (2004)

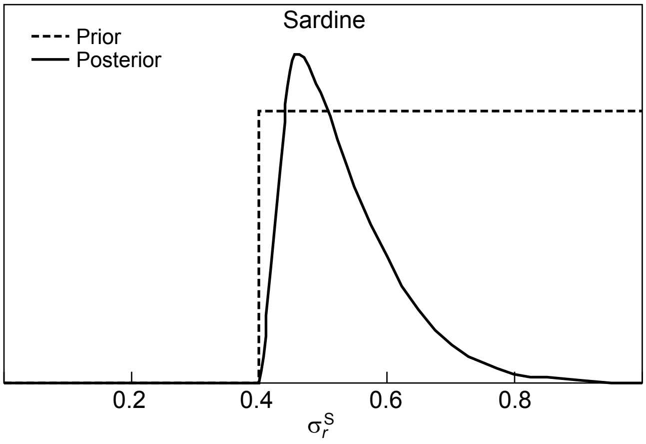

Figure 10: Prior and posterior pdf for the standard deviation of sardine recruitment residuals

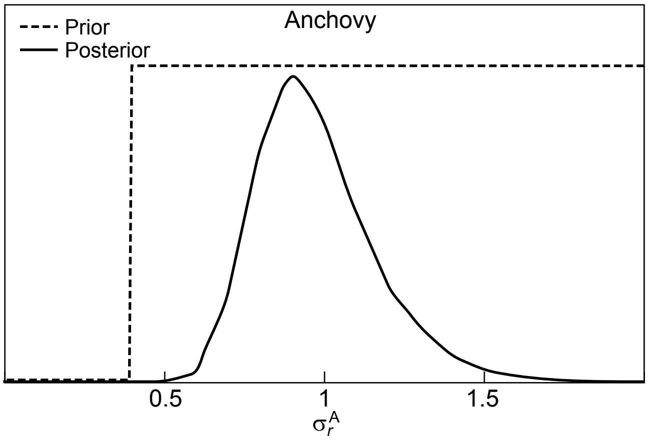

Figure 11: Prior and posterior pdf for the standard deviation of anchovy recruitment residuals

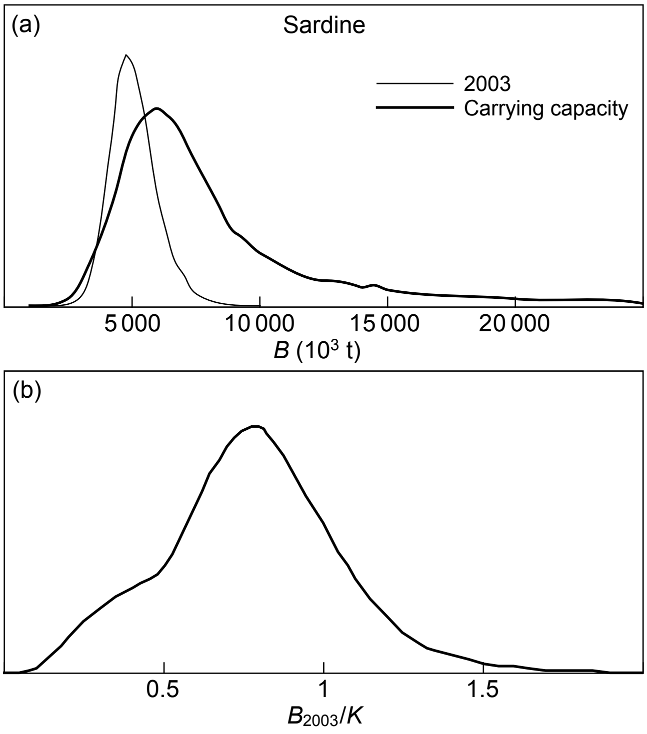

Figure 12: Posterior pdf for (a) the sardine 1+ biomass in 2003 compared to that for the estimated carrying capacity and (b) the sardine 1+ biomass in 2003 as a proportion of carrying capacity

can fluctuate down to low levels more frequently than previously thought. This new perception of the anchovy dynamics requires the risk to which the management of the anchovy fishery is tuned to be reconsidered.

Given the revised sardine stock-recruitment curve in Figure 8b, it is intriguing why the population was unable to recover from its depleted state sooner. If earlier management had been such that sardine catches had been restricted, median recruitment should have increased with time. However, the pelagic fishery was regulated by a global TAC encompassing eight species over a period commencing in 1971. This was replaced in 1983 by a combined sardine and anchovy TAC (with unlimited restrictions on the other pelagic species), and only in 1984 were separate TACs for sardine and anchovy implemented (De Oliveira et al. 1998). A gradual continued recovery of the sardine population occurred only after a separate TAC for sardine came into force. This probably evidences a failure of the combined species TAC approach. Although the dominant anchovy population that comprised most of the annual catch over that period was well managed, the lack of any effective restriction on the directed sardine catch from a depleted resource allowed the industry to focus on sardine as soon as any rise in its abundance became evident (e.g. in 1976 the sardine catch rose briefly to 176 000 t), thereby stalling any potential recovery to higher population abundance levels.

The sudden and substantial increase in recruitment in both sardine and anchovy at the turn of the century could be due to reasons other than the stock recruitment curves estimated in this paper. It has been postulated that there was a regime shift in the pelagic dynamics at the turn of the century, allowing for the rapid increase in sardine and anchovy recruitment and the simultaneous record levels of abundance of both species (e.g. Howard et al. 2007). This remains speculative at this stage as the data available for these analyses were not sufficient to test such a hypothesis.

It is important to document the updates to these assessments so that there is an accurate record of the historical analysis of the populations. This enables a better understanding of the dynamics of the populations and provides a basis for interpreting future trends. Another new feature in these assessments in comparison to previous assessments of the South African sardine and anchovy populations is their Bayesian basis. Samples from the simulated posterior distributions of key assessment model parameters and outputs are used as inputs to the simulation testing framework for the OMP used to manage the South African sardine and anchovy fisheries from 2004 to 2007 (Cunningham and Butterworth 2005a). In this manner, uncertainty is naturally and succinctly taken into account (Punt and Hilborn 1997).

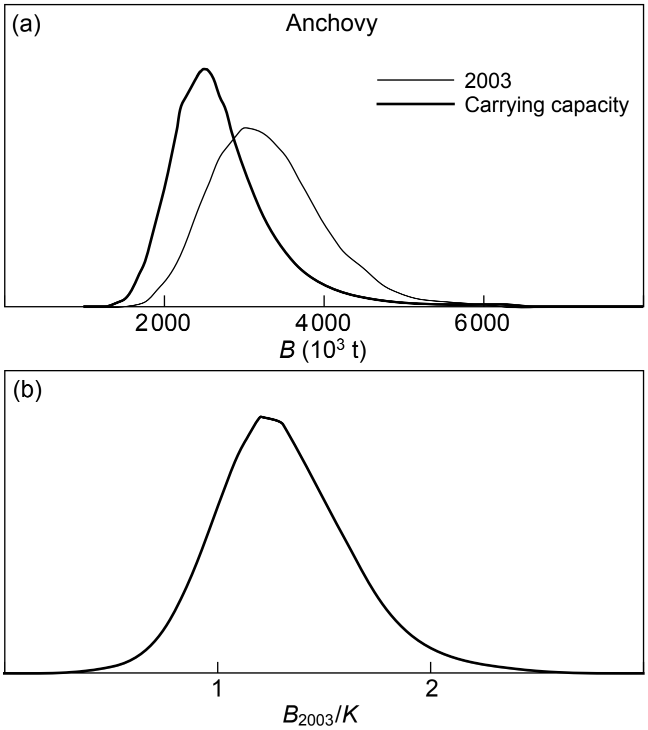

Figure 13: Posterior pdf for (a) the anchovy 1+ biomass in 2003 compared to that for the estimated carrying capacity and (b) the anchovy 1+ biomass in 2003 as a proportion of carrying capacity

Following these assessments, the sardine population suffered a number of years of below average recruitment and has subsequently declined appreciably from its peak abundance during the early years of this century (de Moor et al. 2008). The hydroacoustic surveys indicate that the anchovy population is still enjoying high abundance levels (de Moor et al. 2008). An update of these assessments has recently been carried out to contribute to a scheduled four-yearly revision of the OMP. These updated assessments will be published separately.

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Appendix 1: Bayesian assessment model for the South African sardine population

Population dynamics

All sardine are assumed to have a birth date of 1 November, but become available to the fishery for the first time from 1 January. It is assumed that they die immediately after they reach five years of age and have spawned a final time (very few fish reach this age). Fishing is approximated as a pulse which is assumed to occur on 1 May. The numbers-at-age at 1 November are given by:

$$\hat{N}^{\mathrm{S}}_{y+1,1} = (\hat{N}^{\mathrm{S}}_{y,0}\mathrm{e}^{-M^{\mathrm{S}}_{\mathrm{ju}}/2} - C^{\mathrm{S}}_{y+1,0})\mathrm{e}^{-M^{\mathrm{S}}_{\mathrm{ju}}/2} \qquad y = 1979,\ldots,2002$$

$$\hat{N}^{\mathrm{S}}_{y+1,a+1} = (\hat{N}^{\mathrm{S}}_{y,a}\mathrm{e}^{-M^{\mathrm{S}}_{\mathrm{ad}}/2} - C^{\mathrm{S}}_{y+1,a})\mathrm{e}^{-M^{\mathrm{S}}_{\mathrm{ad}}/2}$$

$$y = 1980,\ a = 1;\ y = 1981,\ a = 1,2;\ y = 1982,\ a = 1,2,3;\ \text{and } y = 1983,\ldots,2002,\ a = 1,\ldots,4 \qquad \text{(App.1.1)}$$

where:

$\hat{N}^{\mathrm{S}}_{y,a}$ is the number (in billions) of sardine of age a at 1 November in year y;

$C^{\mathrm{S}}_{y,a}$ is the number (in billions) of sardine of age a caught from 1 November in year y−1 to 31 October in year y;

$M^{\mathrm{S}}_{\mathrm{ju}}$ is the rate of natural mortality (y^{-1}) of juvenile (age 0) sardine; and

$M^{\mathrm{S}}_{\mathrm{ad}}$ is the rate of natural mortality (y^{-1}) of adult (age 1+) sardine.

The 1+ biomass (in thousand tonnes) of sardine at 1 November in year y, associated with the November survey is:

$$\hat{B}^{\mathrm{S}}_{y,N} = \sum_{a=1}^{5} \hat{N}^{\mathrm{S}}_{y,a} w^{\mathrm{S}}_{y,a} \qquad y = 1984,\ldots,2003 \qquad \text{(App.1.2)}$$

where:

$w^{\mathrm{S}}_{y,a}$ is the mean mass (in grams) of sardine of age a sampled during the November survey of year y (Table App.1.1).

Sardine are assumed to mature and spawn when they turn one year old (Armstrong et al. 1989), so that $\hat{B}^{\mathrm{S}}_{y,N}$ also corresponds to the spawner biomass. Recruitment at the beginning of November is assumed to fluctuate lognormally about a hockey-stick stock-recruitment curve:

$$\hat{N}^{\mathrm{S}}_{y,0} = \begin{cases} a^{\mathrm{S}}_{79-83}\mathrm{e}^{\varepsilon^{\mathrm{S}}_y} & ,\ \text{if } \hat{B}^{\mathrm{S}}_{y,N} \geq b^{\mathrm{S}} \\ \dfrac{a^{\mathrm{S}}_{79-83}}{b^{\mathrm{S}}}\hat{B}^{\mathrm{S}}_{y,N}\mathrm{e}^{\varepsilon^{\mathrm{S}}_y} & ,\ \text{if } \hat{B}^{\mathrm{S}}_{y,N} < b^{\mathrm{S}} \end{cases} \qquad y = 1979,\ldots,1983$$

$$\hat{N}^{\mathrm{S}}_{y,0} = \begin{cases} a^{\mathrm{S}}\mathrm{e}^{\varepsilon^{\mathrm{S}}_y} & ,\ \text{if } \hat{B}^{\mathrm{S}}_{y,N} \geq b^{\mathrm{S}} \\ \dfrac{a^{\mathrm{S}}}{b^{\mathrm{S}}}\hat{B}^{\mathrm{S}}_{y,N}\mathrm{e}^{\varepsilon^{\mathrm{S}}_y} & ,\ \text{if } \hat{B}^{\mathrm{S}}_{y,N} < b^{\mathrm{S}} \end{cases} \qquad y = 1984,\ldots,2002 \qquad \text{(App.1.3)}$$

where:

a^{S} is the maximum deterministic sardine recruitment (in billions);

a^{S}_{79-83} is the maximum deterministic sardine recruitment (in billions) applicable over the period 1979–1983 only;

b^{S} is the sardine spawner biomass below which median recruitment declines linearly with this biomass; and

$\varepsilon^{\mathrm{S}}_y$ is the annual lognormal deviation of sardine recruitment.

Initial experimentation in the model showed that appreciably better fits to the data were obtained by allowing a change in the value of maximum deterministic recruitment after 1983.

Assuming pulse fishing of juveniles midway between 1 January and the start of the recruit survey, the number (in billions) of juvenile sardine at the time of the recruit survey in year y is:

$$\hat{N}^{\mathrm{S}}_{y,r} = (\hat{N}^{\mathrm{S}}_{y,0}\mathrm{e}^{-\left[2+0.5(4+t^{\mathrm{S}}_y)\right]M^{\mathrm{S}}_{\mathrm{ju}}/12} - C^{\mathrm{S}}_{y,0\mathrm{bs}})\mathrm{e}^{-0.5(4+t^{\mathrm{S}}_y)M^{\mathrm{S}}_{\mathrm{ju}}/12} \qquad y = 1984,\ldots,2003 \qquad \text{(App.1.4)}$$

where:

$C^{\mathrm{S}}_{y,0\mathrm{bs}}$ is the number (in billions) of juvenile sardine caught between 1 January and the day before the start of the recruit survey in year y (Table App.1.2); and

t^{S}_y is the time lapsed (in months) between 1 May and the start of the recruit survey in year y (Table App.1.2).

The proportion of sardine of age a at 1 November in year y, associated with the November survey is:

$$\hat{p}^{\mathrm{S}}_{y,a} = \frac{\hat{N}^{\mathrm{S}}_{y,a}}{\sum_{a=1}^{5}\hat{N}^{\mathrm{S}}_{y,a}} \qquad y = 1984,\ldots,2003,\ a = 1,\ldots,5 \qquad \text{(App.1.5)}$$

Likelihood

The survey observations are assumed to be lognormally distributed. The negative log-likelihood function is given as follows:

$$\begin{aligned} -\ln L = {} & \tfrac{1}{2}\sum_{y=1984}^{2003}\left\{ \frac{(\ln B^{\mathrm{S}}_{y,N} - \ln(k^{\mathrm{S}}_N \hat{B}^{\mathrm{S}}_{y,N}))^2}{(\sigma^{\mathrm{S}}_{y,N})^2 + (\lambda^{\mathrm{S}}_N)^2} + \ln\left[2\pi((\sigma^{\mathrm{S}}_{y,N})^2 + (\lambda^{\mathrm{S}}_N)^2)\right] \right\} \\ & + \tfrac{1}{2}\sum_{y=1985(y\neq 88,89,90)}^{2003}\left\{ \frac{(\ln N^{\mathrm{S}}_{y,r} - \ln(k^{\mathrm{S}}_r \hat{N}^{\mathrm{S}}_{y,r}))^2}{(\sigma^{\mathrm{S}}_{y,r})^2 + (\lambda^{\mathrm{S}}_r)^2} + \ln\left[2\pi((\sigma^{\mathrm{S}}_{y,r})^2 + (\lambda^{\mathrm{S}}_r)^2)\right] \right\} \\ & + \tfrac{1}{2}\sum_{y=1988}^{1999}\sum_{a=1}^{5}\left\{ \frac{n_y p^{\mathrm{S}}_{y,a}(\ln p^{\mathrm{S}}_{y,a} - \ln(k^{\mathrm{S}}_{p,a}\hat{p}^{\mathrm{S}}_{y,a}))^2}{(\sigma^{\mathrm{S}}_p)^2} + \ln\left[2\pi(\sigma^{\mathrm{S}}_p)^2/(n_y p^{\mathrm{S}}_{y,a})\right] \right\} \end{aligned} \qquad \text{(App.1.6)}$$

where:

$B^{\mathrm{S}}_{y,N}$ is the acoustic survey estimate of 1+ sardine biomass (in thousand tonnes) from the November survey in year y (see Table 1), with associated CV $\sigma^{\mathrm{S}}_{y,N}$ and constant of proportionality (multiplicative bias) k^{S}_N;

$N_{y,r}^{S}$	is the acoustic survey estimate of sardine recruitment (in billions) from the recruit survey in year y (see Table 1), with associated CV $\sigma_{y,r}^{S}$ and constant of proportionality k_r^{S};
$p_{y,a}^{S}$	is an estimate of the proportion (by number) of sardine of age a in the November survey of year y (Table App.1.1), with constant of proportionality $k_{p,a}^{S}$;
n_y	is the number of fish from the November survey trawls in year y used to compile the age–length key for calculating $p_{y,a}^{S}$ (Table App.1.1);
$(\lambda_{N/r}^{S})^2$	is the additional variance (over and above the survey sampling CV $\sigma_{y,N/r}^{S}$ that reflects survey inter-transect variance) associated with the November/recruit surveys; and
$(\sigma_p^{S})^2$	is the overall variance-related parameter for the log-transformed proportion-at-age observations, $p_{y,a}^{s}$ [note variance = $(\sigma_p^{S})^2/(n_y p_{y,a}^{S})$].

The third term in Equation App.1.6 was structured so that undue importance was not given to observations that were based on only a few samples (Geromont and Butterworth 1999).

Model parameters

Natural mortality was fixed at the same values used in the previous assessment (De Oliveira 2003). The multiplicative bias associated with the November survey biomass was approximated by its median value (Figure 2). These fixed values, together with the prior distributions for the estimated parameters, are listed in Table App.1.3.

Further outputs

Of key importance when considering future management options for this population are the parameters on which recruitment and risk depend, such as recruitment serial correlation:

$$s_{\text{cor}}^{S} = \frac{\sum_{y=1984}^{2002} \varepsilon_y^{S} \varepsilon_{y+1}^{S}}{\sqrt{\left(\sum_{y=1984}^{2002} {\varepsilon_y^{S}}^2\right)\left(\sum_{y=1984}^{2002} {\varepsilon_{y+1}^{S}}^2\right)}} \qquad \text{(App.1.7)}$$

and the 2003 standardised recruitment residual value:

$$\eta_{2003}^{S} = \frac{\varepsilon_{2003}^{S}}{\sigma_r^{S}} \qquad \text{(App.1.8)}$$

where:

σ_r^{S} is the standard deviation of the recruitment residuals.

Finally, the carrying capacity K^{S} (essentially the $\hat{B}_{y,N}^{S}$ value where the replacement line and the function describing expected recruitment intersect) is given by:

$$K^{S} = a^{S} e^{\frac{1}{2}\left({\sigma_r^{S}}^2\right)} \left[\sum_{a=1}^{5} \bar{w}_a^{S} e^{-M_{\text{ju}}^{S} - (a-1)M_{\text{ad}}^{S}}\right] \qquad \text{(App.1.9)}$$

where:

$\bar{w}_a^{S}$ is the average of $w_{y,a}^{S}$ defined above (Table App.1.1).

Table App.1.1: Mean masses-at-age (in grams), $w_{y,a}^{S}$, measured during the November 1+ biomass survey, together with proportions-at-age estimates from the November survey, $p_{y,a}^{S}$, and the sample size, n_y, (number of fish) used to compile age–length keys underlying these estimates. For years in which the masses-at-age are not available (i.e. 1984–1987), the average masses-at-age, $\bar{w}_a^{S}$, are used

Year	$w_{y,1}^{S}$	$w_{y,2}^{S}$	$w_{y,3}^{S}$	$w_{y,4}^{S}$	$w_{y,5}^{S}$	$p_{y,1}^{S}$	$p_{y,2}^{S}$	$p_{y,3}^{S}$	$p_{y,4}^{S}$	$p_{y,5}^{S}$	n_y
1988	31.57	66.56	85.94	106.01	94.56	0.7748	0.1462	0.0640	0.0139	0.0011	153
1989	37.81	76.28	91.34	99.33	100.42	0.6183	0.2524	0.0375	0.0649	0.0269	202
1990	46.59	78.43	88.60	103.46	118.83	0.3616	0.3633	0.1313	0.0827	0.0611	225
1991	29.87	75.05	95.27	109.79	131.43	0.7390	0.1113	0.1022	0.0358	0.0118	668
1992	27.12	49.64	79.07	89.46	109.13	0.7132	0.1861	0.0582	0.0299	0.0126	604
1993	34.56	69.26	78.09	98.32	111.92	0.6002	0.0977	0.2307	0.0277	0.0437	583
1994	45.87	78.22	91.79	102.83	118.93	0.2319	0.3399	0.2717	0.1199	0.0366	623
1995	21.89	66.12	87.70	97.07	117.47	0.6452	0.1291	0.1112	0.0532	0.0613	861
1996	31.65	54.78	81.82	90.58	107.15	0.4023	0.4243	0.1238	0.0296	0.0200	335
1997	28.72	64.66	73.57	83.88	93.43	0.3908	0.1546	0.2494	0.1534	0.0518	342
1998	28.10	70.50	87.49	92.99	116.73	0.7429	0.1234	0.0568	0.0508	0.0261	722
1999	48.18	84.94	97.77	110.78	118.33	0.6919	0.1614	0.1089	0.0296	0.0082	575
2000	43.74	80.27	99.62	108.88	122.26	–	–	–	–	–	–
2001	24.47	68.50	82.20	89.07	97.92	–	–	–	–	–	–
2002	35.39	72.13	79.30	85.59	95.75	–	–	–	–	–	–
2003	37.20	65.13	74.60	81.77	91.80	–	–	–	–	–	–
Average	34.54	70.03	85.89	96.86	109.13	–	–	–	–	–	–

Table App.1.2: The time (in months) of the recruit survey after 1 May, t^{S}_{y}, and the recruit catch (in billions) taken prior to the commencement of the recruit survey, $C^{\mathrm{S}}_{y,0\mathrm{bs}}$

Year	t^{S}_{y}	$C^{\mathrm{S}}_{y,0\mathrm{bs}}$
1985	0.613	0.859
1986	1.300	0.837
1987	2.613	0.373
1988	1.867	0.397
1989	1.233	0.646
1990	0.161	0.387
1991	0.194	0.402
1992	0.387	0.323
1993	0.645	0.324
1994	0.129	0.554
1995	1.300	0.918
1996	1.133	0.703
1997	0.516	0.052
1998	0.613	0.829
1999	0.290	0.161
2000	0.452	0.597
2001	0.129	0.172
2002	0.129	0.418
2003	0.419	0.870

Table App.1.3: The fixed values or prior distributions of sardine model parameters

Parameter		Fixed value
$M^{\mathrm{S}}_{\mathrm{ju}}$	Juvenile natural mortality	1.0
$M^{\mathrm{S}}_{\mathrm{ad}}$	Adult natural mortality	0.4
k^{S}_{N}	Multiplicative bias associated with the November survey biomass	0.72
		Prior distribution
ε^{s}_{y}, y= 1979,...,2002	Recruitment residuals[1]	$N(0, {\sigma^{\mathrm{S}}_{r}}^{2} = 0.4^{2} + (\lambda^{\mathrm{S}}_{0})^{2})$
k^{S}_{r}	Multiplicative bias associated with the May survey recruitment estimate	$\log N(1.1, 0.7^{2})$[2]
$k^{\mathrm{S}}_{p,a}$, a = 1,...,5	Multiplicative bias associated with the November proportions-at-age	$\log N(1,1)$
$(\lambda^{\mathrm{S}}_{N})^{2}$	Additional variance associated with the November survey biomass estimate	$U(0,1)$
$(\lambda^{\mathrm{S}}_{r})^{2}$	Additional variance associated with the May survey recruitment estimate	$U(0,10\,000)$
$(\lambda^{\mathrm{S}}_{0})^{2}$	Additional variance associated with the recruitment residuals	$U(0,10\,000)$
σ^{S}_{p}	Variance-related parameter for November proportions-at-age	$\log N(3, 0.7^{2})$
a^{S}	Maximum deterministic recruitment	$\log N(100, 1^{2})$
$a^{\mathrm{S}}_{79\text{–}83}$	Maximum deterministic recruitment over the period 1979–1983	$N\left(\frac{1}{6}\sum_{y=1984}^{1989}\hat{N}^{\mathrm{S}}_{y,0}, 1^{2}\right)$
$b^{\mathrm{S}}/K^{\mathrm{S}}$	Spawner biomass below which median recruitment declines linearly, expressed as a proportion of carrying capacity	$U(0,1)$

[1] The fixed minimum variance was introduced to avoid the overall variance being estimated to be unrealistically small

[2] Here the convention is used that in $x \sim \log N(m, \sigma^{2})$, m denotes the median of x and σ^{2} denotes the variance of the logarithm of x

Appendix 2: Bayesian assessment model for the South African anchovy population

Population dynamics

All anchovy are assumed to have a birth date of 1 November, but become available to the fishery for the first time from 1 January. It is assumed that they die immediately after they reach four years of age and have spawned a final time (very few fish reach this age). Fishing is approximated as a pulse which is assumed to occur on 1 February for 1-year-olds and 1 June for 0-year-olds. The numbers-at-age at 1 November are given by:

$$\hat{N}^{\text{A}}_{y+1,1} = (\hat{N}^{\text{A}}_{y,0}\text{e}^{-7M^{\text{A}}_{\text{ju}}/12} - C^{\text{A}}_{y+1,0})\text{e}^{-5M^{\text{A}}_{\text{ju}}/12} \qquad y = 1980,...,2002$$

$$\hat{N}^{\text{A}}_{y+1,2} = (\hat{N}^{\text{A}}_{y,1}\text{e}^{-M^{\text{A}}_{\text{ad}}/4} - C^{\text{A}}_{y+1,1})\text{e}^{-3M^{\text{A}}_{\text{ad}}/4} \qquad y = 1981,...,2002$$

$$\hat{N}^{\text{A}}_{y+1,a+1} = \hat{N}^{\text{A}}_{y,a}\text{e}^{-M^{\text{A}}_{\text{ad}}} \qquad \begin{array}{r} y = 1982,\ a = 2 \\ y = 1983,...,2002,\ a = 2,3 \end{array} \qquad \text{(App.2.1)}$$

where:

$\hat{N}^{\text{A}}_{y,a}$ is the number (in billions) of anchovy of age a at 1 November in year y;

$C^{\text{A}}_{y,a}$ 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}_{ju} is the natural mortality (y^{-1}) of juvenile (age 0) anchovy; and

M^{A}_{ad} is the natural mortality (y^{-1}) of adult (age 1+) anchovy.

The 1+ biomass (in thousand tonnes) of anchovy at 1 November in year y, associated with the November survey is:

$$\hat{B}^{\text{A}}_{y,N} = \sum_{a=1}^{4} \hat{N}^{\text{A}}_{y,a} w^{\text{A}}_{y,a} \qquad y = 1984,...,2003 \qquad \text{(App.2.2)}$$

where:

$w^{\text{A}}_{y,a}$ is the mean mass (in grams) of anchovy of age a sampled during the November survey of year y (Table App.2.1).

Anchovy are assumed to mature and spawn when they turn one year old (Melo 1992), so that $\hat{B}^{\text{A}}_{y,N}$ also corresponds to the spawner biomass. Recruitment at the beginning of November is assumed to fluctuate lognormally about a hockey-stick stock-recruitment curve:

$$\hat{N}^{\text{A}}_{y,0} = \begin{cases} a^{\text{A}}\text{e}^{\varepsilon^{\text{A}}_{y}} & \text{if} \quad \hat{B}^{\text{A}}_{y,N} \geq b^{\text{A}} \\ \dfrac{a^{\text{A}}}{b^{\text{A}}}\hat{B}^{\text{A}}_{y,N}\text{e}^{\varepsilon^{\text{A}}_{y}} & \text{if} \quad \hat{B}^{\text{A}}_{y,N} < b^{\text{A}} \end{cases} \qquad y = 1980,...,2002 \quad \text{(App.2.3)}$$

where:

a^{A} is the maximum deterministic anchovy recruitment (in billions);

b^{A} is the anchovy spawner biomass below which median recruitment declines linearly with this biomass; and

$\varepsilon^{\text{A}}_{y}$ is the annual lognormal deviation of anchovy recruitment.

Assuming pulse fishing of juveniles midway between 1 April (the first time juvenile anchovy become available to the fishery) and the start of the recruit survey, the number (in billions) of juvenile anchovy at the time of the recruit survey in year y is:

$$\hat{N}^{\text{A}}_{y,r} = (\hat{N}^{\text{A}}_{y,0}\text{e}^{-[5+0.5(1+t^{\text{A}}_{y})]M^{\text{A}}_{\text{ju}}/12} - C^{\text{A}}_{y,0\text{bs}})\text{e}^{-0.5(1+t^{\text{A}}_{y})M^{\text{A}}_{\text{ju}}/12} \qquad y = 1984,...,2003 \quad \text{(App.2.4)}$$

where:

$C^{\text{A}}_{y,0\text{bs}}$ is the number (in billions) of juvenile anchovy caught between 1 April and the day before the start of the recruit survey in year y (Table App.2.1); and

t^{A}_{y} is the time lapsed (in months) between 1 May and the start of the recruit survey in year y (Table App.2.1).

The proportion of 1-year-old anchovy at 1 November in year y, associated with the November survey is:

$$\hat{p}^{\text{A}}_{y,1} = \frac{\hat{N}^{\text{A}}_{y,1}}{\sum_{a=1}^{4}\hat{N}^{\text{A}}_{y,a}} \qquad y = 1984,...,2003 \qquad \text{(App.2.5)}$$

Likelihood

The survey observations are assumed to be lognormally distributed. The proportions of 1-year-olds are first logit-transformed before being used in the likelihood. The negative log-likelihood function is given as follows:

$$\begin{aligned} -\ln L = {} & \tfrac{1}{2}\sum_{y=1984}^{2003}\left\{\begin{array}{l} \dfrac{(\ln B^{\text{A}}_{y,N} - \ln(k^{\text{A}}_{N}\hat{B}^{\text{A}}_{y,N}))^2}{(\sigma^{\text{A}}_{y,N})^2 + (\lambda^{\text{A}}_{N})^2} \\ + \ln\left[2\pi((\sigma^{\text{A}}_{y,N})^2 + (\lambda^{\text{A}}_{N})^2)\right] \end{array}\right\} \\ & + \tfrac{1}{2}\sum_{y=1984}^{1990}\left\{\dfrac{(\ln B^{\text{A}}_{y,\text{egg}} - \ln(k^{\text{A}}_{g}\hat{B}^{\text{A}}_{y,N}))^2}{(\sigma^{\text{A}}_{y,\text{egg}})^2} + \ln\left[2\pi(\sigma^{\text{A}}_{y,\text{egg}})^2\right]\right\} \\ & + \tfrac{1}{2}\sum_{y=1985}^{2003}\left\{\begin{array}{l} \dfrac{(\ln N^{\text{A}}_{y,r} - \ln(k^{\text{A}}_{r}\hat{N}^{\text{A}}_{y,r}))^2}{(\sigma^{\text{A}}_{y,r})^2 + (\lambda^{\text{A}}_{r})^2} \\ + \ln\left[2\pi((\sigma^{\text{A}}_{y,r})^2 + (\lambda^{\text{A}}_{r})^2)\right] \end{array}\right\} \\ & + \tfrac{1}{2}\sum_{y=1988}^{2000}\left\{\begin{array}{l} \dfrac{(\ln q^{\text{A}}_{y,1} - \ln k^{\text{A}}_{q}\hat{q}^{\text{A}}_{y,1})^2}{(\sigma^{\text{A}}_{q})^2 + (\lambda^{\text{A}}_{p})^2} \\ + \ln\left[2\pi((\sigma^{\text{A}}_{q})^2 + (\lambda^{\text{A}}_{p})^2)\right] \end{array}\right\} \end{aligned} \qquad \text{(App.2.6)}$$

where:

$$\hat{q}^{\text{A}}_{y,1} = \frac{1-\hat{p}^{\text{A}}_{y,1}}{\hat{p}^{\text{A}}_{y,1}}, \quad q^{\text{A}}_{y,1} = \frac{1-p^{\text{A}}_{y,1}}{p^{\text{A}}_{y,1}}$$

and

$B^{\text{A}}_{y,N}$ is the acoustic survey estimate of 1+ anchovy biomass (in thousand tonnes) from the November survey in year y (see Table 1), with associated CV $\sigma^{\text{A}}_{y,N}$ and constant of proportionality (multiplicative bias) k^{A}_{N};

$B^A_{y,\mathrm{egg}}$ is the egg survey estimate of anchovy spawner biomass (in thousand tonnes) from the November survey in year y (see Table 1), with associated CV $\sigma^A_{y,\mathrm{egg}}$ and constant of proportionality k^A_g;

$N^A_{y,r}$ is the acoustic survey estimate of anchovy recruitment (in billions) from the recruit survey in year y (see Table 1), with associated CV $\sigma^A_{y,r}$ and constant of proportionality k^A_r;

$p^A_{y,1}$ is an estimate of the proportion (by number) of 1-year-old anchovy in the November survey of year y (Table App.2.1) and constant of proportionality k^A_q;

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

$(\sigma^A_q)^2$ is a minimum variance associated with the proportion of 1-year-olds in the likelihood; and

$(\lambda^A_q)^2$ is the additional variance (over and above $(\sigma^A_q)^2$) associated with the final term in the likelihood.

Model parameters

Natural mortality was fixed at the same values used in the previous assessment (De Oliveira 2003). The egg survey estimates of biomass were assumed to be absolute (De Oliveira 2003). These and other fixed values, together with the prior distributions for the estimated parameters, are listed in Table App.2.2.

Further outputs

Of key importance when considering future management options for this population are the parameters on which recruitment and risk depend, such as recruitment serial correlation:

$$s^A_{\mathrm{cor}} = \frac{\sum_{y=1984}^{2002} \varepsilon^A_y \varepsilon^A_{y+1}}{\sqrt{\left(\sum_{y=1984}^{2002} {\varepsilon^A_y}^2\right)\left(\sum_{y=1984}^{2002} {\varepsilon^A_{y+1}}^2\right)}} \qquad \text{(App.2.7)}$$

and the 2003 standardised recruitment residual value:

$$\eta^A_{2003} = \frac{\varepsilon^A_{2003}}{\sigma^A_r} \qquad \text{(App.2.8)}$$

where:

σ^A_r is the standard deviation of the recruitment residuals.

The carrying capacity, K^A, is defined as follows:

$$K^A = a^A e^{\frac{1}{2}({\sigma^A_r}^2)} \left[\sum_{a=1}^{4} \bar{w}^A_a e^{-M^A_{\mathrm{ju}}-(a-1)M^A_{\mathrm{ad}}}\right] \qquad \text{(App.2.9)}$$

where:

$\bar{w}^A_a$ is the average of $w^A_{y,a}$ defined above (Table App.2.1).

Table App.2.1: The time (in months) of the recruit survey after 1 May, t^A_y, the recruit catch (in billions) taken prior to the commencement of the recruit survey, $C^A_{y,0bs}$, and the mean masses-at-age (in grams), $w^A_{y,a}$, measured during the November 1+ biomass survey. For years in which these masses-at-age are not available (i.e. 1984–1987), the average masses-at-age, $\bar{w}^A_a$, are used. The estimated proportions (by number) of 1-year-old anchovy in the November survey, $p^A_{y,1}$, are also given

Year	t^A_y	$C^A_{y,0bs}$	$w^A_{y,1}$	$w^A_{y,2}$	$w^A_{y,3}$	$w^A_{y,4}$	$p^A_{y,1}$
1984			–	–	–	–	–
1985	0.613	15.664	–	–	–	–	–
1986	1.300	23.080	–	–	–	–	–
1987	2.613	18.616	–	–	–	–	–
1988	1.867	14.858	10.25	13.17	15.43	16.89	0.640
1989	1.233	17.634	12.53	14.44	15.46	15.69	0.350
1990	0.700	27.722	8.01	12.43	14.95	16.45	0.766
1991	0.194	7.710	8.43	12.31	14.33	15.46	0.727
1992	0.387	13.152	8.25	12.91	13.98	17.32	0.588
1993	0.645	4.764	9.32	13.52	14.25	15.51	0.429
1994	0.129	4.495	10.96	14.87	16.01	15.79	0.453
1995	1.300	9.877	8.94	13.88	17.01	16.60	0.884
1996	1.133	3.425	8.92	16.11	17.60	17.52	0.530
1997	0.516	0.163	13.60	20.09	23.23	22.76	0.467
1998	0.613	6.085	9.66	17.86	20.88	19.90	0.468
1999	0.290	1.724	9.73	15.04	18.25	18.01	0.629
2000	0.452	7.172	8.24	12.43	14.81	15.68	0.756
2001	0.129	5.353	7.23	11.86	14.91	17.00	–
2002	0.129	3.502	8.08	12.09	13.71	15.15	–
2003	0.419	3.591	8.49	11.93	14.27	16.95	–
Average			9.41	14.05	16.19	17.08	

Table App.2.2: The fixed values or prior distributions of anchovy model parameters

Parameter		Fixed value
$M^{\mathrm{A}}_{\mathrm{ju}}$	Juvenile natural mortality	0.9
$M^{\mathrm{A}}_{\mathrm{ad}}$	Adult natural mortality	0.9
$(\sigma^{\mathrm{A}}_{q})^2$	Minimum variance associated with the proportion of 1-year-olds in the likelihood	0.4^2
$(\lambda^{\mathrm{A}}_{N})^2$	Additional variance associated with the November survey biomass estimate	0
k^{A}_{g}	Multiplicative bias associated with the egg survey estimates	1
b^{A}	Spawner biomass below which median recruitment declines linearly	$0.2K^{\mathrm{A}}$
$\varepsilon^{\mathrm{A}}_{1980}$	Recruitment residual[1]	$-\sum_{y=1981}^{2002} \varepsilon^{\mathrm{A}}_{y}$
		Prior distribution
$\varepsilon^{\mathrm{A}}_{y}$, y = 1981,...,2002	Recruitment residuals[2]	$N(0, {\sigma^{\mathrm{A}}_{r}}^2 = 0.4^2 + (\lambda^{\mathrm{A}}_{0})^2)$
k^{A}_{N}	Multiplicative bias associated with the November survey biomass estimate	log $N(1,0.5^2)$
k^{A}_{r}	Multiplicative bias associated with the May survey recruitment estimate	log $N(1,0.5^2)$
k^{A}_{q}	Multiplicative bias associated with the November proportion-at-age 1	log $N(1,0.5^2)$
$(\lambda^{\mathrm{A}}_{r})^2$	Additional variance associated with the May survey recruitment estimate	$U(0,10\,000)$
$(\lambda^{\mathrm{A}}_{p})^2$	Additional variance associated with the November proportion-at-age 1	$U(0,10\,000)$
$(\lambda^{\mathrm{A}}_{0})^2$	Additional variance associated with the recruitment residuals	$U(0,10\,000)$
a^{A}	Maximum deterministic recruitment	log $(a) \sim U(0,8)$

[1] This forces the overall average deviations to sum to zero

[2] The fixed minimum variance was introduced to avoid the overall variance being estimated to be unrealistically small