Assessment of the South African sardine resource using data from 1984-2010: results at the posterior mode for a two stock hypothesis

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Abstract

The sardine assessment is extended to consider the presence of two (west and east) stocks separated at Cape Agulhas. Movement of recruits from west to east stocks is modelled. A Hockey Stick stock recruitment relationship, and the same median juvenile and adult natural mortality rates as for the single stock hypothesis are used. Two base case hypotheses are chosen: one estimates random effects about juvenile and adult natural mortality over time, while the other assumes time-invariant annual natural mortality. The resource abundance is near the historic average for the "west" stock, which is estimated to remain relatively constant over time in comparison to the "peak" in "east" stock 1+ biomass which is estimated to have occurred at the turn of the century. The "east" stock abundance is currently below the historic average. The proportion of recruits moving from year to year is not strongly correlated with high biomass or recruitment in the western/eastern stock that year or the preceding year.

Introduction

As part of the process of updating the assessment of the South African sardine resource, a two sardine stock hypothesis is to be tested. This hypothesis postulates a "west" stock distributed west of Cape Agulhas and an "east" stock distributed east of Cape Agulhas. Although initial testing of a two discrete stock hypothesis was considered to be not incompatible with the data (de Moor and Butterworth 2009), de Moor and Butterworth (2011a) have more recently shown that a two discrete stock hypothesis is implausible on the basis that it would imply only about one fifth of the recruits of the "east" stock is surveyed during the annual May hydroacoustic survey. de Moor and Butterworth (2011a) also gave initial results for a hypothesis of two stocks with movement from the "west" stock to the "east" stock in November as the recruits age to 1 year olds. These results are updated in this document.

Population Dynamics Model

The updated operating model for the South African sardine resource is detailed in Appendix A of de Moor and Butterworth (2011b) and the data used in this assessment are listed in de Moor *et al*. (2011). All key changes to the model described in de Moor and Butterworth (2011b) also apply to the model used for the two stock hypothesis. The particular difference when fitting the two-stock model to the data is that both abundance index and proportions-at-age/length data are divided west and east of Cape Agulhas, and the negative log likelihoods include terms for each of these spatially separate components. A glossary of terms used in this model is repeated from de Moor and Butterworth (2011b) in the Appendix of this document for ease of reference.

The median juvenile, $\overline{M}_j^S = 1.0$, and adult, $\overline{M}_{ad}^S = 0.8$, natural mortality and Hockey Stick stock recruitment relationship are assumed in line with that chosen for the base case single stock hypotheses. As for the single stock hypothesis, two base case hypotheses are considered:

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S^2_{HS}: base case hypothesis with random effects about juvenile and adult natural mortality over time

S^2_{cstM}: base case hypothesis with constant (time-invariant) natural mortality, i.e. no random effects

As hydroacoustic estimates of recruitment are available for the "east" stock from 1993 only, there is little information to accurately estimate movement of recruits from the "west" stock to the "east" stock in November as they reach age 1 prior to 1994. In the two base case hypotheses, the assumption is therefore made that there was no eastward movement of recruits between 1984 and 1993, i.e. $move_y = 0$ for $y = 1984,\ldots,1993$. Two alternatives are considered:

$S^2_{avgmove}$: As for S^2_{HS}, with $move_y = \frac{1}{17}\sum_{y'=1994}^{2010} move_{y'}$ for $y = 1984,\ldots,1993$

$S^2_{cstM\ avgmove}$: As for S^2_{cstM}, with $move_y = \frac{1}{17}\sum_{y'=1994}^{2010} move_{y'}$ for $y = 1984,\ldots,1993$

Results and Discussion

The S^2_{HS} and S^2_{cstM} population model fits to the time series of abundance estimates of November 1+ biomass are reasonable (Figure 1). The corresponding model fits to the time series of May recruitments are plotted in Figure 2. The residual for the "east" stock in 2001 is large (-6.8), but a larger than observed recruitment is required by the model as a non-negligible 0-year-old catch occurred to the east of Cape Agulhas before November 2001. As was the case for the single stock hypothesis, the model under-predicts recruitment to the "west" stock in May 2010 as it is unable to reconcile the conflicting data of an above average recruitment estimate in May 2010 with almost no increase in the November 1+ biomass estimate from 2009 to 2010. More than 50% of the "west" stock recruits are modelled to move to the "east" stock in November 1994, 1996 and 2000-2005.

Figures 4 and 5 show the model fits to the time series of survey and commercial proportion-at-age data, respectively. The model estimated survey and commercial selectivities at age are plotted in Figures 6 and 7, respectively. It is clear that the bounds of the uniform prior distribution are constraining the survey selectivities at ages 1, 2 and 5 (Table 1). However, given the design of the surveys, survey selectivity should not differ by age, and thus these bounds have been retained. As a consequence, however, there is a tendency for the model to over-predict proportions for the younger ages and under-predict for the older ages. The model consistently over-predicts proportions-at-age 2 and under-predicts proportions-at-age 5+ in the commercial catch data (Figure 4), and future work will seek to improve this. The below-par fit to these data is considered acceptable in the light of the low confidence placed in the ageing data.

Figure 8 shows the residuals from the fit to the survey proportion-at-length data while Figure 9 shows the residuals from the fit to the quarterly commercial proportion-at-length data. The model consistently over-predicts the commercial proportion in the minus lengthgroup of 12cm, and again future work will attempt to improve this.

The model estimate stock recruitment relationships are plotted in Figure 10. The "west" stock is estimated to be more productive than the "east" stock, with a maximum recruitment of 76 billion compared to 3 billion under S^2_{HS} (Table 1). The model estimated annual juvenile and adult natural mortality for S^2_{HS} is plotted in Figure 11 together with the estimated residuals. Some autocorrelation between these residuals is estimated by the model ($\rho = 0.43$), with the standard deviation in these residuals on the lower bound of the uniform prior distribution (Table 1). The historic annual harvest rates are plotted in Figure 12.

When migration of recruits from the "west" stock to the "east" stock was initially proposed, a suggestion was made that such migration may be linked to high biomass or recruitment in the "west" stock. Figure 13 plots the estimated proportion of "west" stock recruits migrating to the "east" stock in November against the model predicted "west" and "east" November 1+ biomass of the former year and the current year as well as against "west" stock May recruitment of the current year. Although some relationship is evident with higher proportions moving eastwards at higher abundances in some years, there are also years with high abundance where almost no migration occurs. The correlation coefficients for the linear relationships shown in Figure 13 are not that high (0.58, 0.09, 0.59, 0.66, 0.30). This feature is evident for movement expressed in absolute as well as in proportional terms, as can be seen when considering the recruit biomass or numbers which are modelled to move from the "west" stock to the "east" stock against the model predicted "west" or "east" stock November 1+ biomass and "west" stock May recruitment (Figure 14).

The model estimated loss to predation is given in Table 2.

Similarly to assessments for the single sardine stock hypothesis (de Moor and Butterworth 2011b), for many of the results presented in this document, a positive definite Hessian could not be obtained with ADMB.

Summary

This document has given the results at the posterior mode for a two stock hypothesis for the South African sardine resource. Two base case hypotheses have been chosen, one assuming a random effects model for juvenile and adult natural mortality, S^2_{HS}, and one assuming constant natural mortality, S^2_{cstM}. A Hockey stick stock recruitment relationship is assumed for these base case hypotheses. Under these base case hypotheses at the joint posterior mode, the "west" stock resource abundance is 0.6 million tons and the "east" stock resource abundance is 0.3 million tons in November 2010. The "west" stock abundance is near its long-term average, while the "east" stock abundance is below its long-term average of 0.74 million tons. Six out of the last seven years have resulted in below average recruitment for the "west" stock.

If using this hypothesis is to be used in simulation testing OMP-13, future migration from the “west” to “east” stocks will need to be modelled. This would be relatively simple if a strong relationship between “west” or “east” stock 1+ biomass or recruitment had been found. In that case the future 1+ biomass or recruitment would closely determine the amount of eastwards migration. In its current form, the model reflects only relatively weak relationships. Thus future movement modelled would have very high variability about such linear relationships, ranging from zero to near 100%. The implications of that are not immediately clear and will be evident only once projection simulations are conducted, but given this high variability, it is unlikely that any OMP could benefit in terms of performance by assuming some knowledge of the relationship.

References

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Table 1. Key model parameter values and model outputs estimated at the joint posterior mode. Values fixed on input are given in **bold**. Numbers are reported in billions and biomass in thousands of tonnes. $j=1$ denotes the "west" stock and $j=2$ denotes the "east" stock.

Parameter	S^2_{HS}	S^2_{cstM}	$S^2_{avgmove}$	$S^2_{cstM\ avgmove}$
Objective function	278.13	279.91	287.71	325.0
$-\ln L^{Nov}$	47.09	48.22	55.80	58.11
$-\ln L^{rec}$	65.30	66.61	63.86	65.98
$-\ln L^{sur\ propa}$	3.22	3.28	3.33	3.39
$-\ln L^{com\ propa}$	2.83	2.85	3.04	2.68
$-\ln L^{coml\ propl \min}$	11.02	10.98	11.48	11.37
$-\ln L^{coml\ propl}$	162.99	162.92	162.54	162.91
$-\ln L^{sur\ propl \min}$	0.42	0.42	0.46	0.44
$-\ln L^{surl\ propl}$	6.46	6.46	6.49	6.45
$-\ln(priors)$	-21.20	12.70	-19.27	13.67
$\overline{M}^S_j$	**1.0**	**1.0**	**1.0**	**1.0**
$\overline{M}^S_{ad}$	**0.8**	**0.8**	**0.8**	**0.8**
$k^S_{j=1,N} = k^S_{ac}$	0.69	0.69	0.68	0.70
$k^S_{j=2,N} = k^S_{ac}$	0.69	0.69	0.68	0.70
k^S_{cov}	0.83	0.83	1.00	0.97
$k^S_{\mathrm{cov}E}$	0.52	0.53	0.15	0.22
$k^S_{j=1,r}$	0.57	0.57	0.68	0.68
$k^S_{j=2,r}$	0.30	0.31	0.10	0.15
$k^S_{j=1,r} / k^S_{j=1,N}$	0.83	0.83	1.00	0.97
$k^S_{j=2,r} / k^S_{j=2,N}$	0.43	0.44	0.15	0.21
$S^{survey}_{j,1}$	1.10	1.10	1.10	1.10
$S^{survey}_{j,2}$	0.90	0.90	0.90	0.90
$S^{survey}_{j,3}$	1.06	1.06	1.05	0.99
$S^{survey}_{j,4}$	**1.00**	**1.00**	**1.00**	**1.00**
$S^{survey}_{j,5+}$	1.10	1.10	1.10	1.10
$\left(\lambda^S_{j=1,N}\right)^2$	0.00	0.00	0.00	0.00
$\left(\lambda^S_{j=2,N}\right)^2$	0.00	0.00	0.00	0.20
$\left(\lambda^S_{j=1,r}\right)^2$	**0.00**	**0.00**	**0.00**	**0.00**
$\left(\lambda^S_{j=2,r}\right)^2$	**0.00**	**0.00**	**0.00**	**0.00**
σ_j	0.20	0.20	0.2	0.20
σ_{ad}	0.20	0.20	0.2	0.43
p	0.43	0.43	0.40	0.20

Table 1 (continued).

Parameter	S^2_{HS}	S^2_{cstM}	$S^2_{avgmove}$	$S^2_{cstM\ avgmove}$
$S_{q,1}$	0.04 from '84-'06, then 0.41 from '07-'10	0.05 from '84-'06, then 0.41 from '07-'10	0.06 from '84-'06, then 0.23 from '07-'10	0.05 from '84-'06, then 0.41 from '07-'10
$S_{q,2}$	1.65	1.71	0.92	1.86
S_3	1.55	1.60	0.87	1.58
S_4	**1.00**	**1.00**	**1.00**	**1.00**
S_{5+}	0.67 from '84-'06, then 0.07	0.87 from '84-'06, then 0.07	0.37 from '84-'06, then 0.17	1.00 from '84-'06, then 0.16
$N^S_{j=1,1983}$	2.74	2.49	2.60	2.33
$N^S_{j=2,1983}$	0.05	0.05	0.00	0.00
$\overline{B}^S_{j=1,Nov}$ [1]	455	465	373	324
$\overline{B}^S_{j=2,Nov}$	161	167	217	222
$K^S_{j=1}$	3379	3309	3627	2388
$K^S_{j=2}$	129	126	467	314
$a^S_{j=1}$	75.9	74.3	81.4	53.6
$a^S_{j=2}$	2.8	2.7	10.1	6.81
$b^S_{j=1}$	754	741	888	459
$b^S_{j=2}$	14	15.4	301	255
$\sigma^S_{j=1,r}$	0.40	0.40	0.40	0.40
$\sigma^S_{j=2,r}$	0.40	0.40	0.40	0.40
$\eta^S_{j=1,2009}$	0.81	0.89	0.92	0.72
$\eta^S_{j=2,2009}$	-0.16	-0.15	-0.20	-0.14
$s^S_{j=1,cor}$	-0.01	0.10	-0.05	0.01
$s^S_{j=2,cor}$	-0.28	-0.27	-0.34	-0.34
L_∞	20.5	20.5	20.6	20.6
κ	**0.56**	**0.56**	**0.56**	**0.56**
t_0	**-1.71**	**-1.71**	**-1.71**	**-1.71**
ϑ_1	0.29	0.29	0.27	0.28
ϑ_2	0.10	0.10	0.09	0.10
ϑ_3	0.06	0.06	0.06	0.06
ϑ_4	0.04	0.04	0.04	0.03
ϑ_{5+}	0.04	0.03	0.03	0.03

[1] OMP-04 and OMP-08 were developed using Risk defined as "the probability that 1+ sardine biomass falls below the average 1+ sardine biomass between November 1991 and November 1994 at least once during the projection period of 20 years".

Table 2. The annual estimated sardine loss to predation (in '000t), $P^{S}_{j,y}$ in Appendix D, compared to the annual sardine catch (in '000t).

Year	"West" stock					"East" stock				
	Catch	S^2_{HS}		S^2_{cstM}		Catch	S^2_{HS}		S^2_{cstM}	
		Loss to *M*	Catch: Loss to *M*	Loss to *M*	Catch: Loss to *M*		Loss to *M*	Catch: Loss to *M*	Loss to *M*	Catch: Loss to *M*
1984	27.2	110.8	0.25	100.2	0.27	0.0	2.3	0.00	2.4	0.00
1985	30.7	144.6	0.21	127.0	0.24	0.0	7.1	0.00	6.7	0.00
1986	30.6	170.7	0.18	143.1	0.21	0.0	11.2	0.00	10.1	0.00
1987	33.5	243.6	0.14	194.4	0.17	0.0	24.1	0.00	20.6	0.00
1988	36.3	216.7	0.17	188.7	0.19	0.0	34.5	0.00	31.7	0.00
1989	34.5	254.3	0.14	245.9	0.14	0.2	69.6	0.00	68.0	0.00
1990	56.9	293.5	0.19	296.3	0.19	0.5	95.0	0.01	94.9	0.01
1991	51.6	344.4	0.15	351.1	0.15	1.4	112.1	0.01	112.5	0.01
1992	52.6	413.8	0.13	410.8	0.13	2.5	124.4	0.02	121.9	0.02
1993	48.8	596.3	0.08	578.4	0.08	2.3	124.8	0.02	119.7	0.02
1994	90.5	706.7	0.13	702.6	0.13	4.4	126.4	0.03	123.8	0.04
1995	116.2	1029.6	0.11	1042.4	0.11	4.9	230.9	0.02	241.8	0.02
1996	100.3	858.9	0.12	930.3	0.11	7.5	230.1	0.03	244.2	0.03
1997	115.1	1479.1	0.08	1645.8	0.07	4.3	314.3	0.01	331.3	0.01
1998	129.1	1372.1	0.09	1517.8	0.09	4.2	371.9	0.01	397.4	0.01
1999	124.8	1688.1	0.07	1865.0	0.07	7.1	470.5	0.02	475.7	0.01
2000	129.2	1827.0	0.07	2010.1	0.06	6.0	779.6	0.01	769.3	0.01
2001	180.3	1910.9	0.09	2007.0	0.09	11.3	1042.0	0.01	956.3	0.01
2002	233.6	2376.5	0.10	2455.1	0.10	27.3	1564.5	0.02	1520.9	0.02
2003	229.0	2102.7	0.11	2076.9	0.11	61.0	1988.5	0.03	1881.3	0.03
2004	296.4	966.0	0.31	925.1	0.32	77.5	2109.1	0.04	2023.8	0.04
2005	91.7	442.8	0.21	434.9	0.21	155.0	1444.8	0.11	1411.9	0.11
2006	92.1	436.0	0.21	458.7	0.20	125.2	859.0	0.15	858.4	0.15
2007	58.3	310.5	0.19	332.9	0.18	81.2	453.7	0.18	466.8	0.17
2008	46.9	314.1	0.15	352.5	0.13	44.0	276.9	0.16	292.5	0.15
2009	60.2	419.3	0.14	453.5	0.13	34.1	207.1	0.16	208.2	0.16
2010	86.3	533.9	0.16	535.1	0.16	26.1	269.3	0.10	263.5	0.10

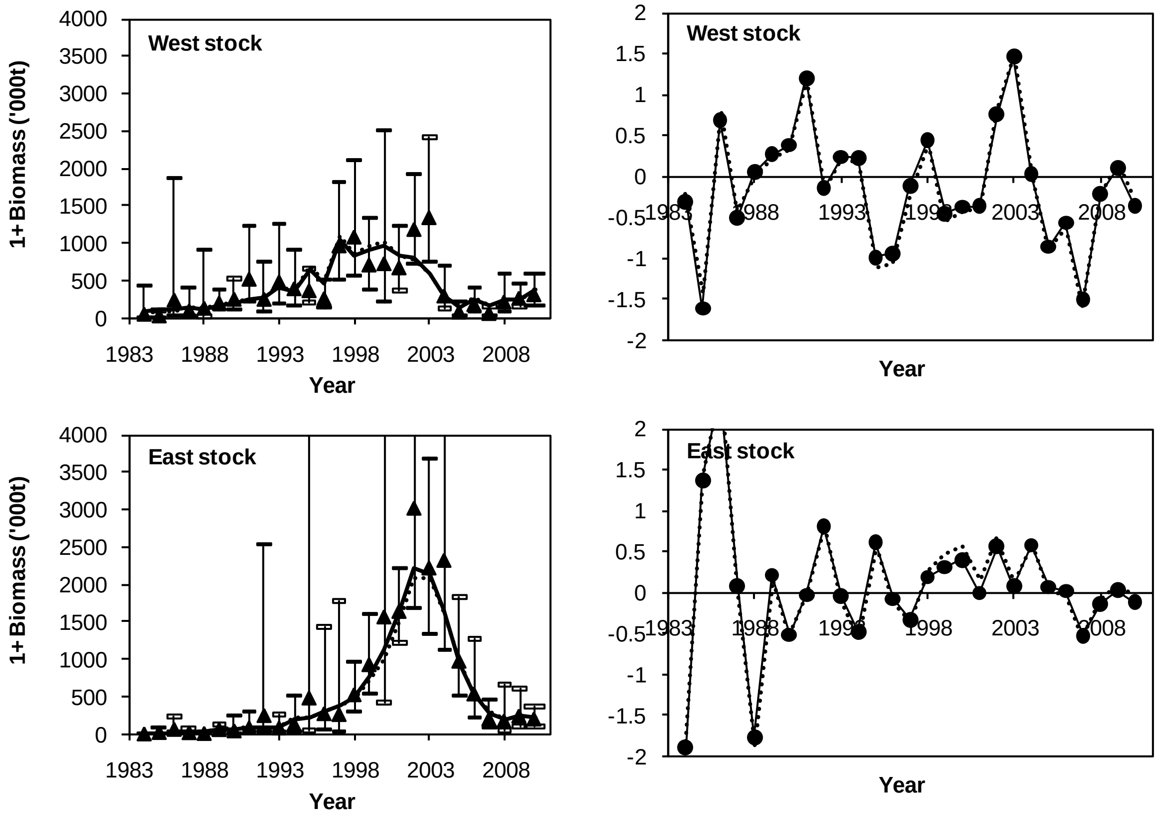

Figure 1. Acoustic survey estimated and model predicted November sardine 1+ biomass from 1984 to 2010 for S^2_{HS} (thick line, connecting filled circles in the right hand plot) and S^2_{cstM} (dotted lines). The observed indices are shown with 95% confidence intervals. The standardised residuals from the fits are given in the right hand plot.

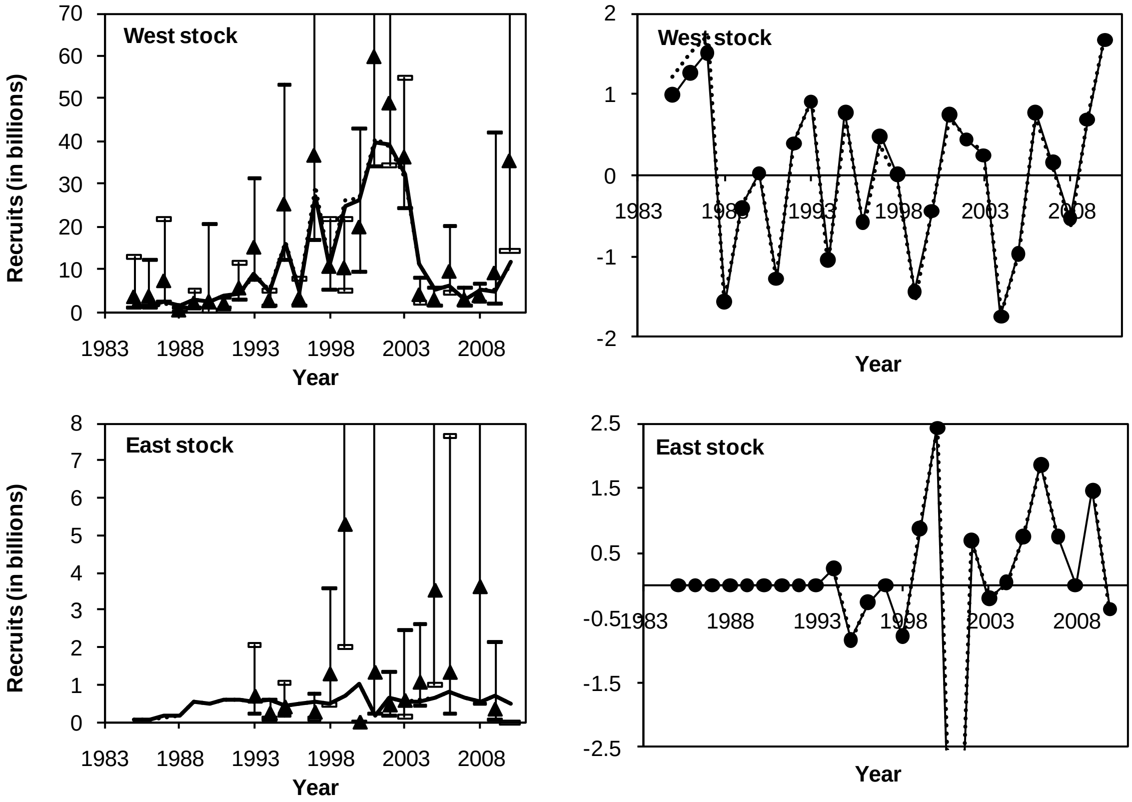

Figure 2. Acoustic survey estimated and model predicted sardine recruitment numbers from May 1985 to May 2010 for S^2_{HS} (thick line, connecting filled circles in the right hand plot) and S^2_{cstM} (dotted lines). The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

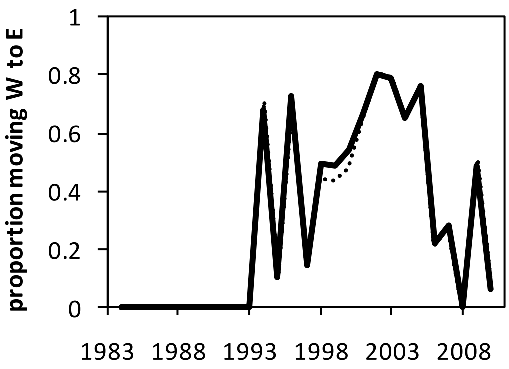

Figure 3. Model estimated proportion of recruits which move from the “west” stock to the “east” stock in November as they reach age 1 for S^2_{HS} (solid line) and S^2_{cstM} (dotted line).

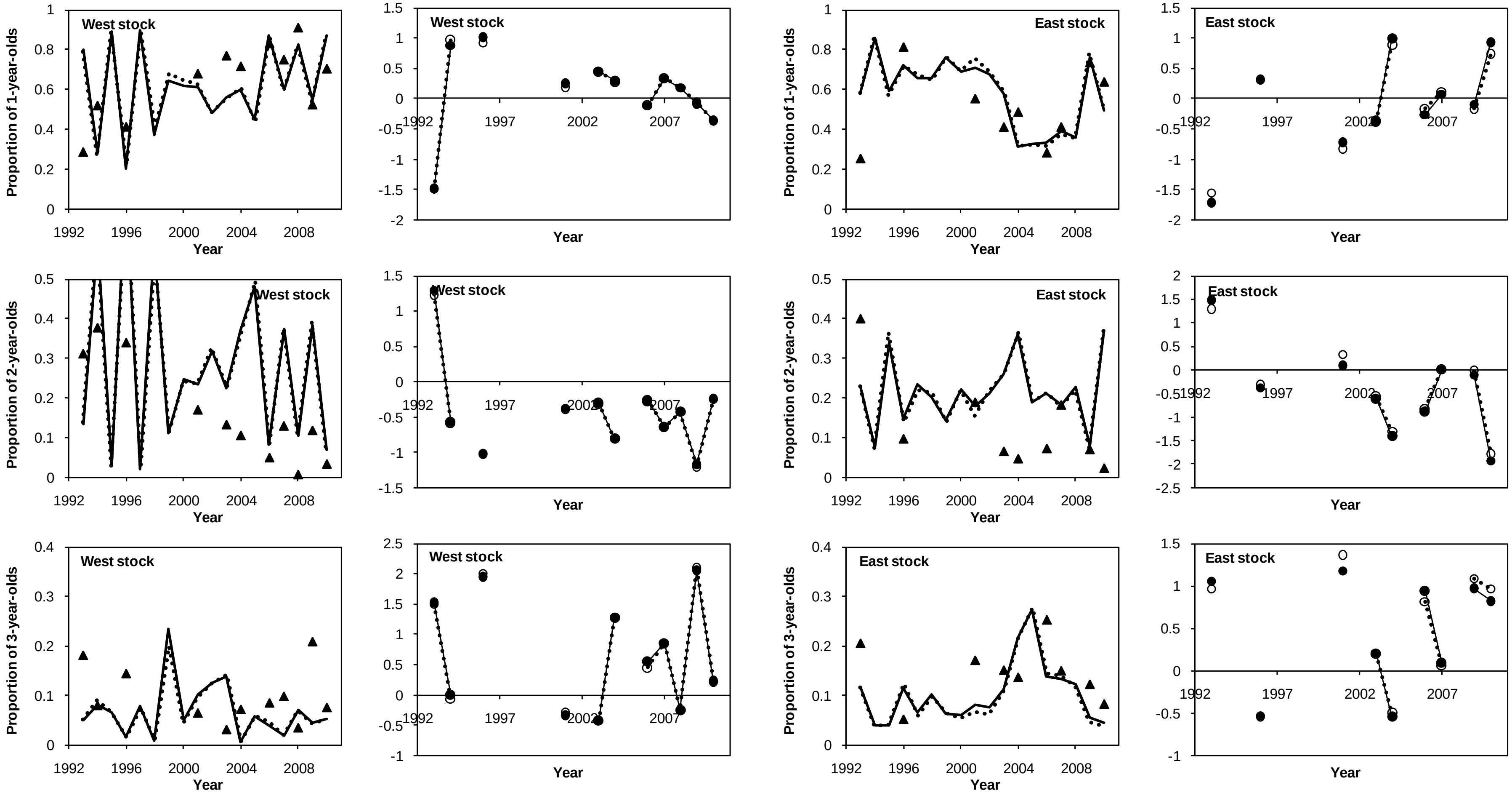

Figure 4. Acoustic survey estimated and model predicted sardine proportions-at-ages 1 (at the top) to 5+ (lowest plot) associated with the November surveys from 1993 to 2010 for S^2_{HS} (black, connecting filled circles in the right hand plot) and S^2_{cstM} (dotted, connecting open circles in the right hand plot). The west stock is plotted on the left and the east stock on the right. The residuals from the fits are given to the right of each fit.

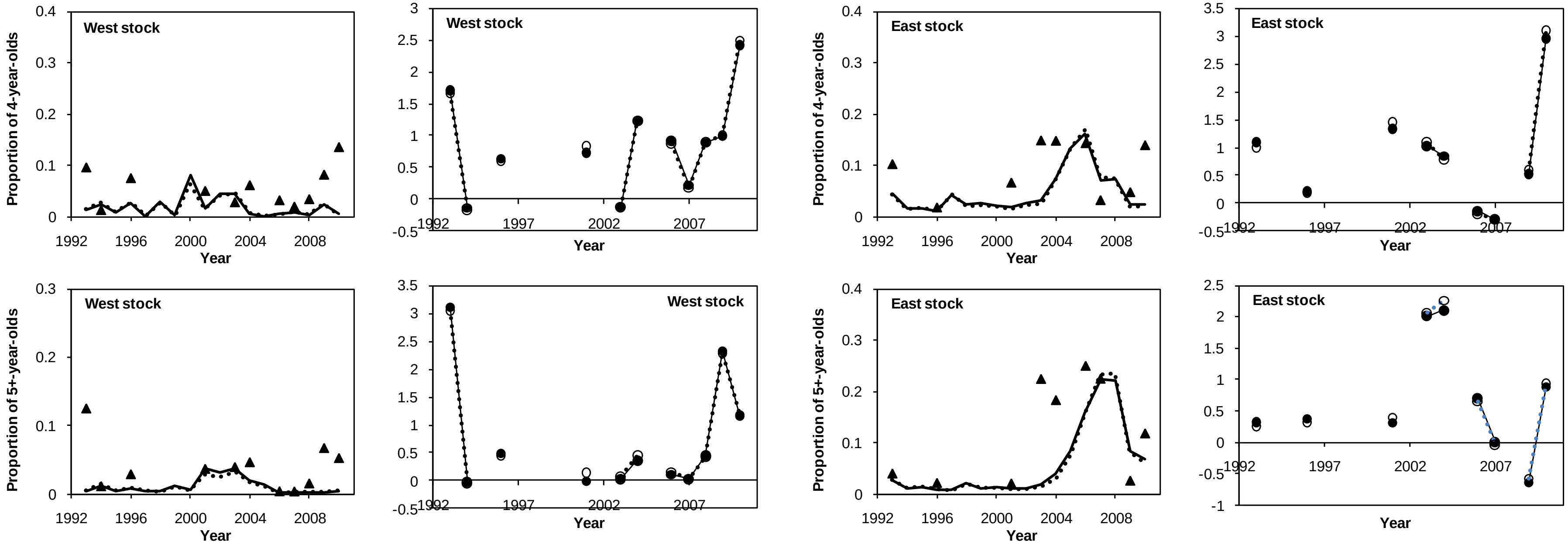

Figure 4 (continued).

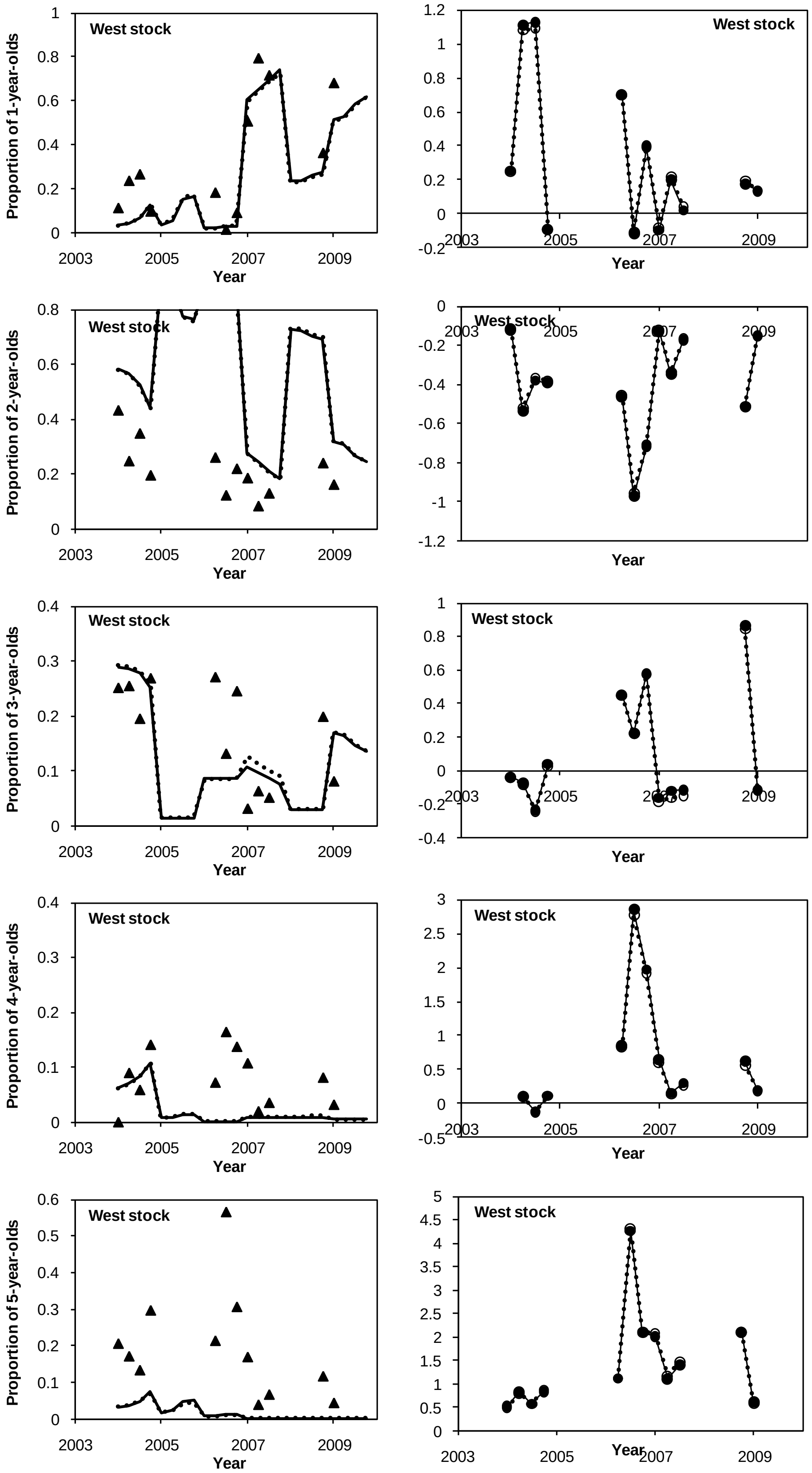

Figure 5. Acoustic survey estimated and model predicted sardine proportions-at-ages 1 (at the top) to 5+ (lowest plot) associated with the quarterly commercial catches from 2004 to 2009 for S^2_{HS} (black, connecting filled circles in the right hand plots) and S^2_{cstM} (dotted, connecting open circles in the right hand plots). The residuals from the fits are given in the right hand plots.

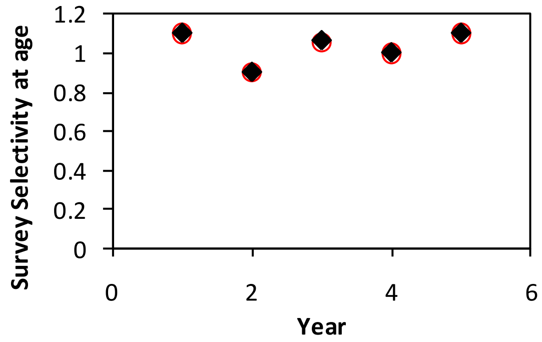

Figure 6. The model estimated November survey selectivity at age for S^2_{HS} (black filled diamonds) and S^2_{cstM} (red open circles).

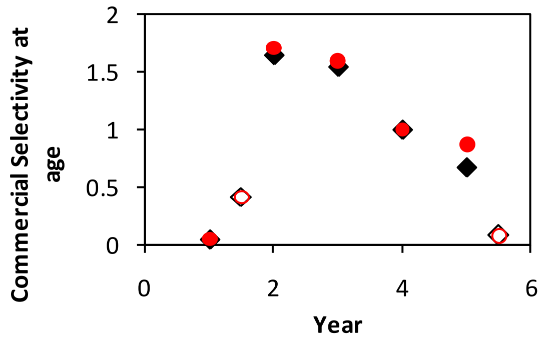

Figure 7. The model estimated commercial selectivity at age for S^2_{HS} (black diamonds) and S^2_{cstM} (red circles). The open indices represent the selectivity at ages 1 and 5+ estimated from 2007 to 2010, while the solid indices for these ages represent the selectivity from 1984 to 2006.

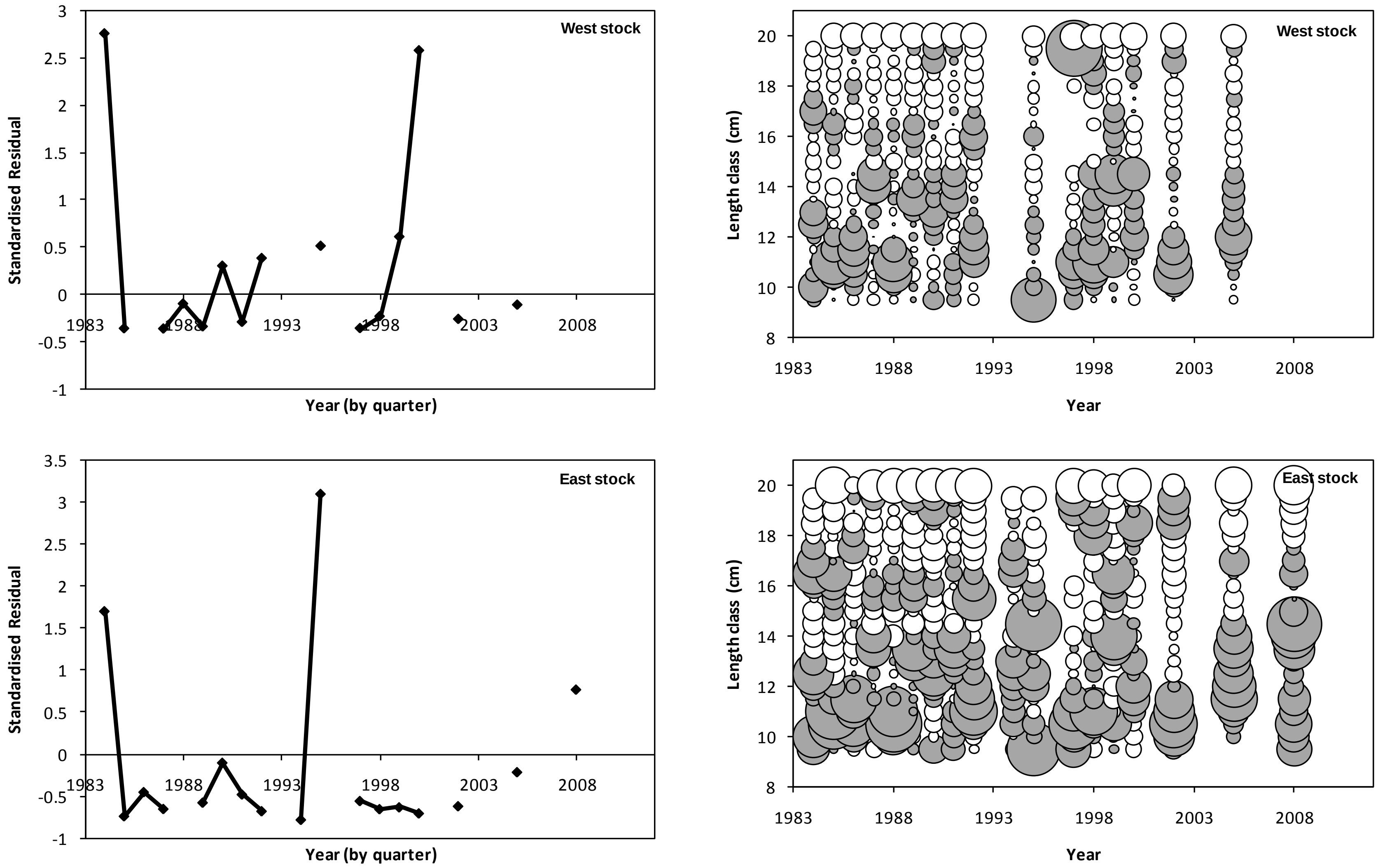

Figure 8a. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions for S^2_{HS}. The left panels show the residuals for the minus length class (9cm) and the right panels show the residuals for the remaining length classes.

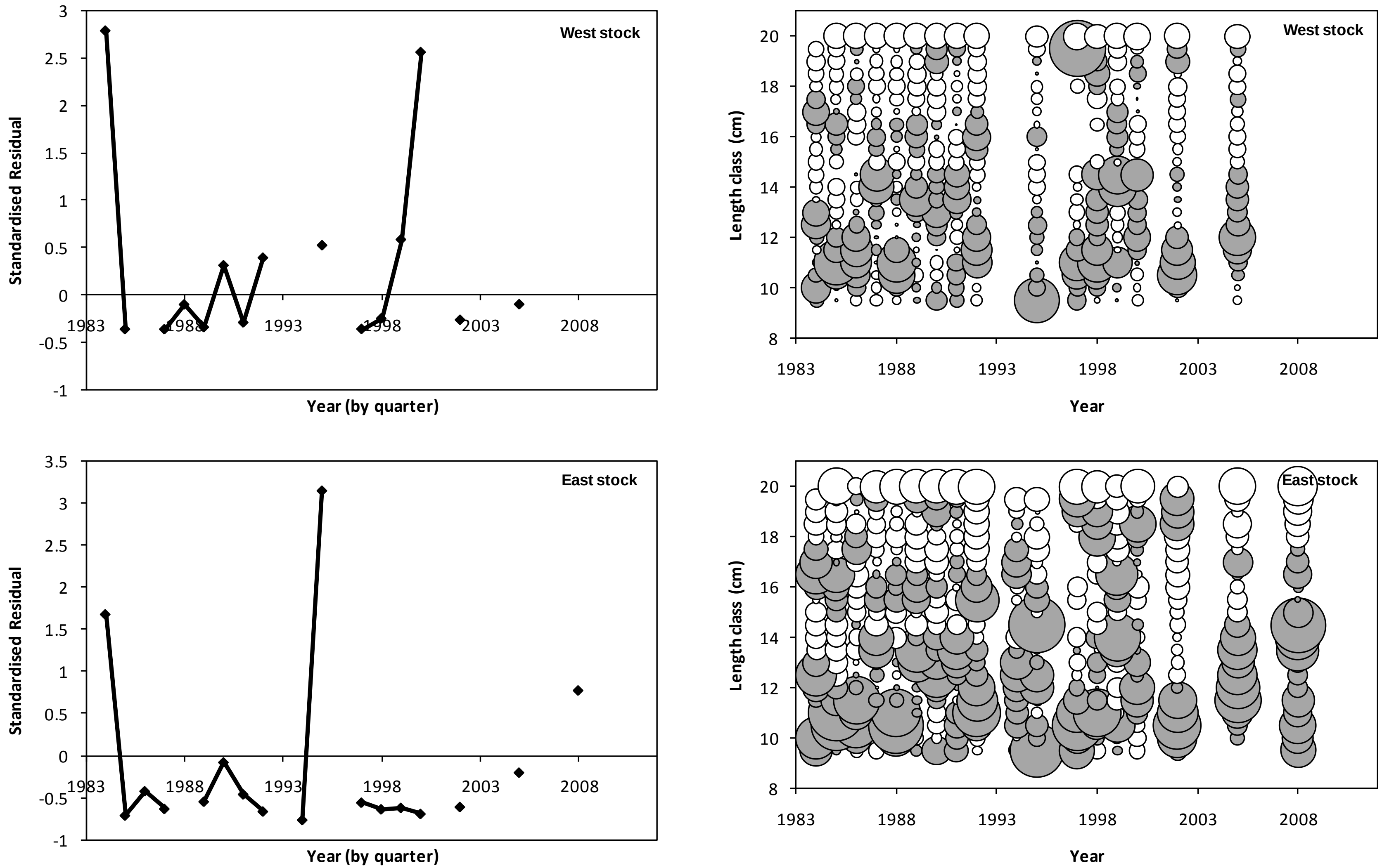

Figure 8b. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions for S^2_{cstM}. The left panels show the residuals for the minus length class (9cm) and the right panels show the residuals for the remaining length classes.

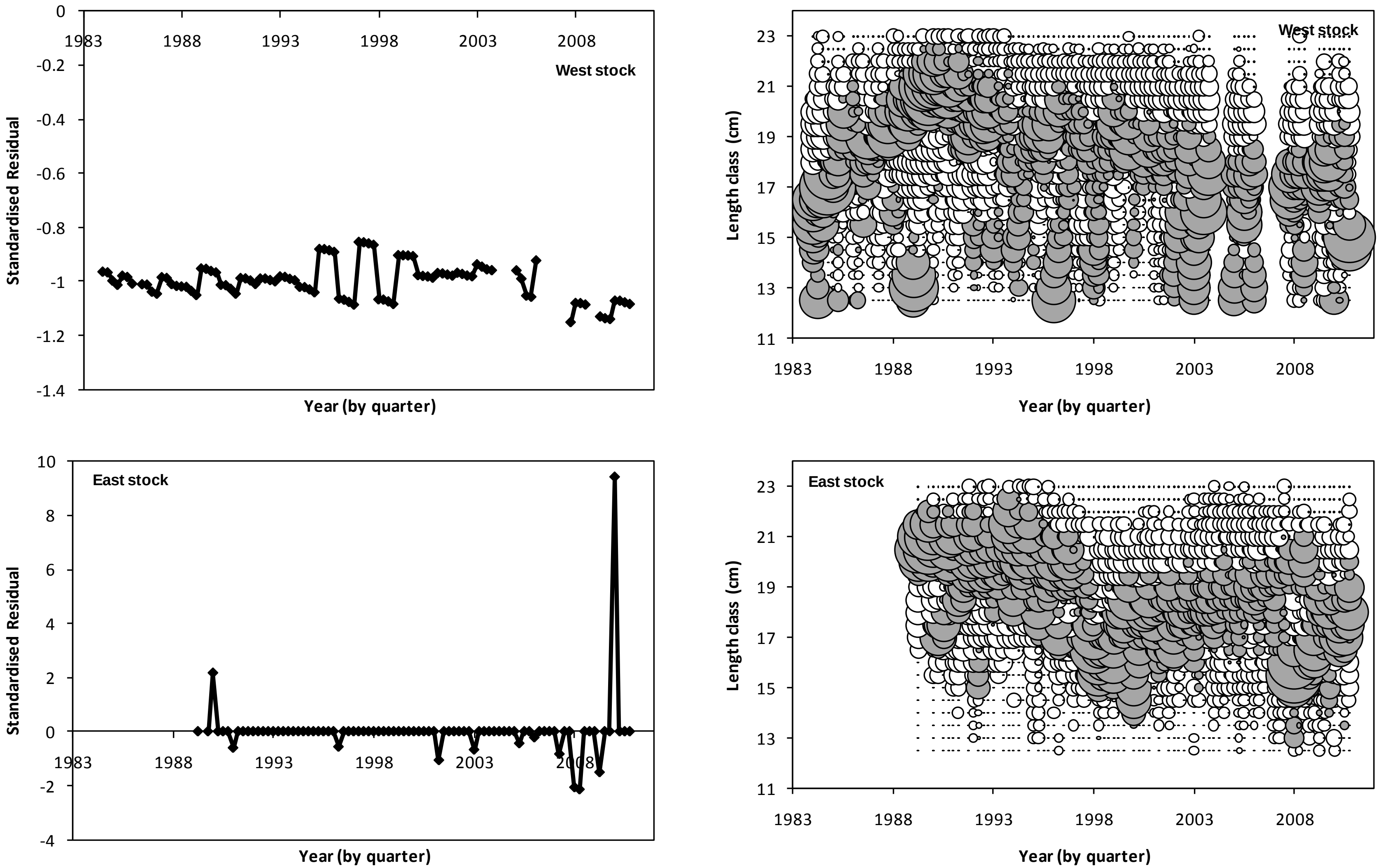

Figure 9a. Residuals from the fit of the model predicted proportions-at-length in the commercial catch to the observed proportions for S^2_{HS}. The left panels show the residuals for the minus length class (12cm) and the right panels show the residuals for the remaining length classes.

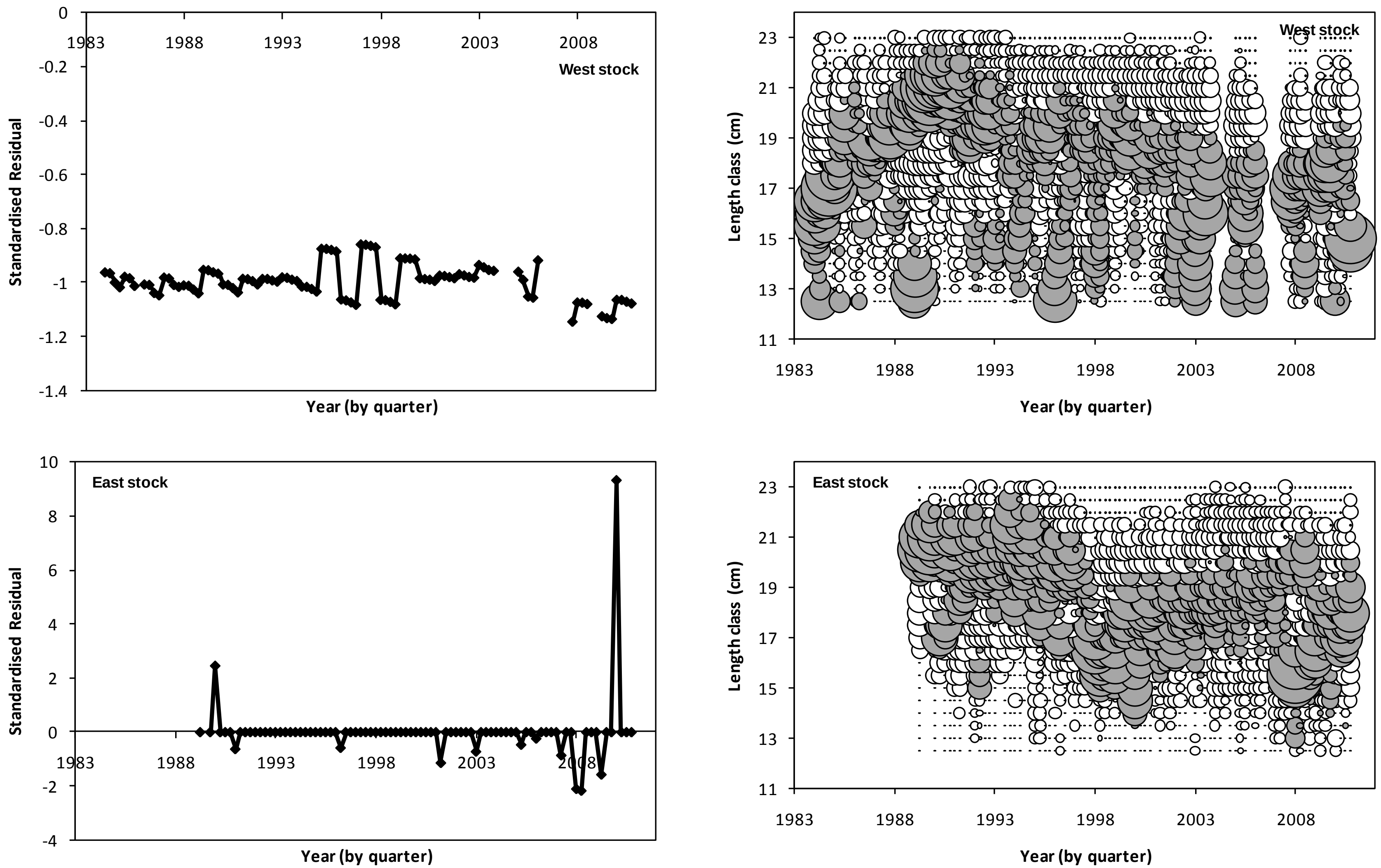

Figure 9b. Residuals from the fit of the model predicted proportions-at-length in the commercial catch to the observed proportions for S^2_{cstM}. The left panels show the residuals for the minus length class (12cm) and the right panels show the residuals for the remaining length classes.

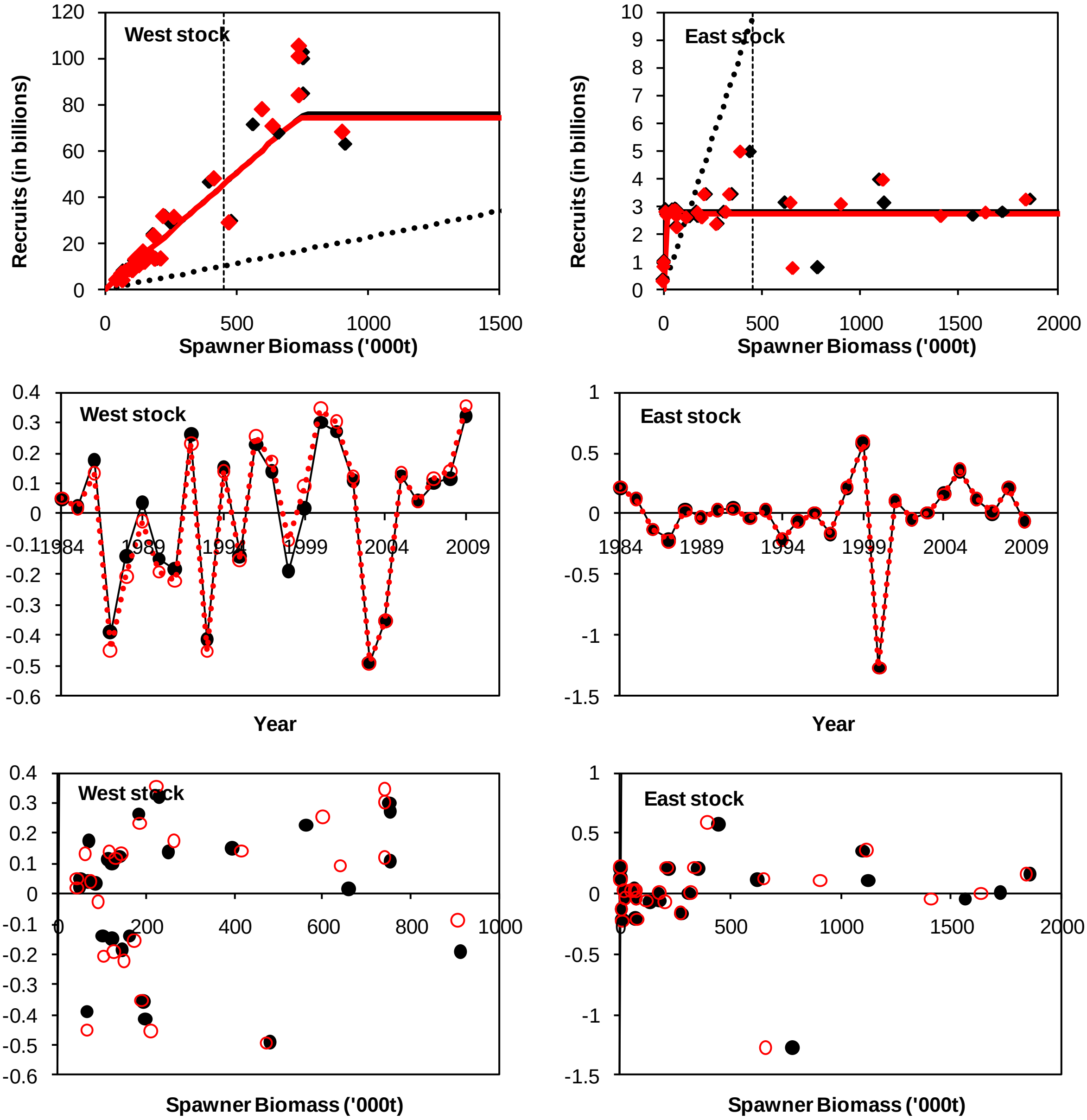

Figure 10. Model predicted anchovy recruitment (in November) plotted against spawner biomass from November 1984 to November 2009 for S_{HS} (black, filled symbols) and S_{cstM} (red, open symbols) with the Hockey stick stock recruitment relationship. The vertical thin dashed line indicates the average 1991 to 1994 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.

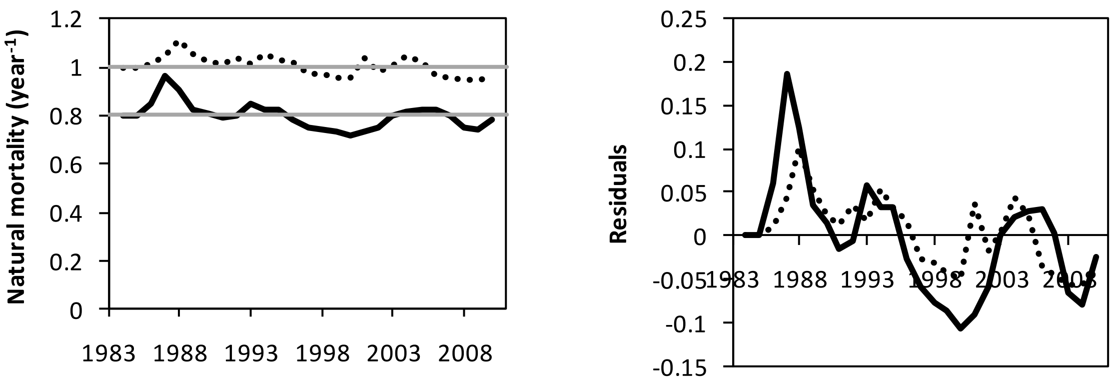

Figure 11. Model estimated annual juvenile (dotted) and adult (solid) natural mortality for S_{HS}. The random effect estimates are plotted in the right hand panel.

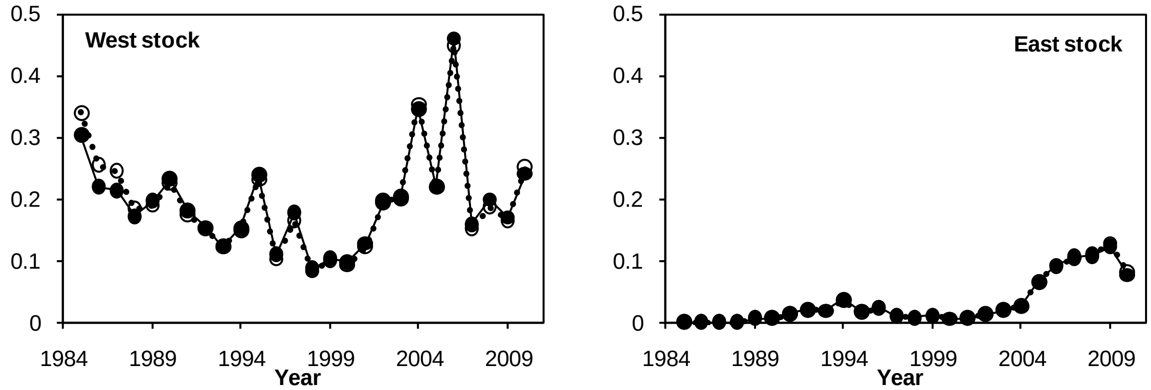

Figure 12. The historic harvest proportion (catch by mass to 1+ biomass) for sardine for S_{HS} (black, connecting filled circles) and S_{cstM} (dotted connecting open circles).

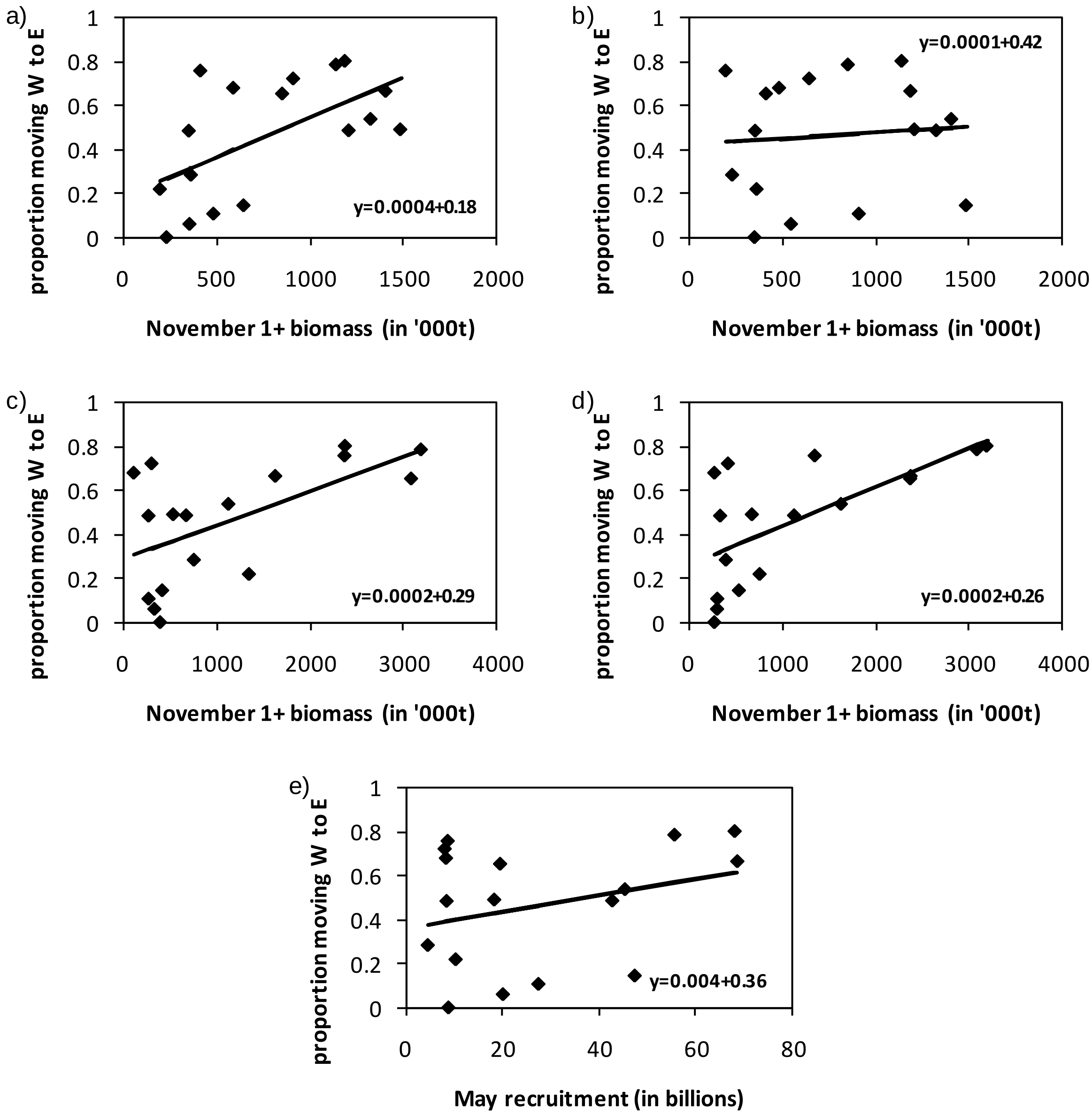

Figure 13. The model predicted proportion of "west" stock recruits which migrate to the "east" stock at the beginning of November plotted against a) "west" stock November 1+ biomass of the previous year, b) "west" stock November 1+ biomass of the current year, c) "east" stock November 1+ biomass of the previous year, d) "east" stock November 1+ biomass of the current year and e) "west" stock recruitment of the current year, for S^2_{HS}. The straight line regressions between the two sets of data in each plot are also shown, with correlation coefficients of a) 0.58, b) 0.09, c) 0.59, d) 0.66 and e) 0.30 and residual standard deviations of a) 0.23, b) 0.28, c) 0.23, d) 0.21 and e) 0.27.

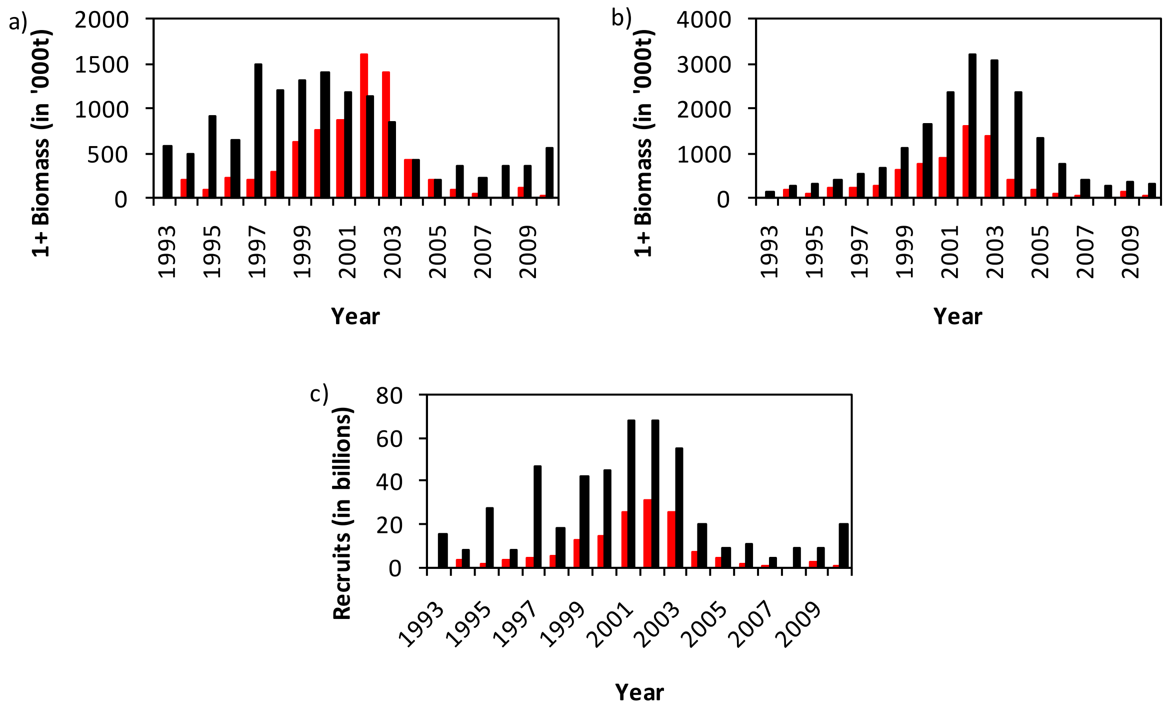

Figure 14. The model predicted biomass/numbers of "west" stock recruits which migrate to the "east" stock at the beginning of November (red/lighter shaded bars) plotted with a) "west" stock November 1+ biomass, b) "east" stock November 1+ biomass, and c) "west" stock May recruitment (black shaded bars) of the current year for S^2_{HS}.

Appendix: Glossary of parameters used in this document

Annual numbers and biomass:

$N^S_{j,y,a}$ - model predicted number (in billions) of sardine of age a at the beginning of November in year y of stock j

$B^S_{j,y}$ - model predicted biomass (in thousand tonnes) of adult sardine of stock j at the beginning of November in year y, associated with the November survey

$SSB^S_{j,y}$ - model predicted spawning stock biomass (in thousand tonnes) of stock j at the beginning of November in year y

$w^S_{j,y,a}$ - mean mass (in grams) of sardine of age a of stock j sampled during the November survey of year y

$N^S_{j,y,r}$ - model predicted number (in billions) of juvenile sardine of stock j at the time of the recruit survey in year y

t^S_y - time lapsed (in months) between 1 May and the start of the recruit survey in year y

$move_y$ - proportion of west stock recruits which migrate to the east stock at the beginning of November of year y

Natural mortality:

$M^S_{a,y}$ - rate of natural mortality (in year^{-1}) of sardine of age a in year y

$\overline{M}^S_{ju}$ - median juvenile rate of natural mortality (in year^{-1})

$\overline{M}^S_{ad}$ - median adult rate of natural mortality (in year^{-1})

ε^{ad}_y - annual residuals about adult natural mortality

η^{ad}_y - normally distributed error used in calculating ε^{ad}_y

σ_{ad} - standard deviation in the annual residuals about adult natural mortality

σ_j - standard deviation in the annual residuals about juvenile natural mortality

p - annual autocorrelation coefficient in annual residuals about adult natural mortality

Catch:

$C^S_{j,y,a,q}$ - model predicted umber (in billions) of sardine of age a of stock j caught during quarter q of year y

$C^{RLF}_{j,y,m,l}$ - number of fish in length class l landed in month m of year y of stock j (the ‘raised length frequency’)

$lcut_{y,m}$ - cut off length for recruits in month m of year y

$C^{bycatch}_{j,y,q,a}$ - the number of fish of age $a \geq 1$ from the anchovy-directed fishery in quarter q of year y

$S_{j,y,q,a}$ - commercial selectivity at age a during quarter q of year y of stock j

$F_{j,y,q}$ - fished proportion in quarter q of year y for a fully selected age class a of stock j, by the directed and redeye bycatch fisheries

$\tilde{C}^{S}_{j,y,0bs}$ - number (in billions) of juvenile sardine of stock j caught between 1 May and the day before the start of the recruit survey

Proportions at age:

$p^{S}_{j,y,a}$ - model predicted proportion-at-age a of stock j in the November survey of year y

$S^{survey}_{j,a}$ - survey selectivity at age a in the November survey for stock j

$p^{com,S}_{j,y,q,a}$ - model predicted proportion-at-age a of stock j in the directed and redeye bycatch commercial catch of quarter q of year y

Recruitment:

a^{S}_{j} - maximum recruitment of stock j (in billions)

b^{S}_{j} - spawner biomass above which there should be no recruitment failure risk in the hockey stick model for stock j

c^{S} - constant recruitment (distribution median) during the "peak" years of 2000 to 2004

$\varepsilon^{S}_{j,y}$ - annual lognormal deviation of sardine recruitment.

$\sigma^{S}_{j,r}$ - standard deviation in the residuals (lognormal deviation) about the stock recruitment curve of stock j

$\sigma^{S}_{r,peak}$ - standard deviation in the residuals (lognormal deviation) about the stock recruitment curve during peak years in the single stock hypothesis

Proportions at length and growth curve:

$p^{S}_{j,y,l}$ - model predicted proportion-at-length l of stock j associated with the November survey in year y

$A^{sur}_{j,a,l}$ - proportion of sardine of age a of stock j that fall in the length group l in November

$p^{coml,S}_{j,y,q,l}$ - model predicted proportion-at-length l of stock j in the directed and redeye bycatch commercial catch of quarter q of year y

$A^{com}_{j,q,a,l}$ - proportion of sardine of age a of stock j that fall in the length group l in quarter q

$L_{j,\infty}$ - maximum length of sardine of stock j

κ_j - annual growth rate of sardine of stock j

$t_{0,j}$ - age at which the growth rate is zero of sardine of stock j

$\vartheta_{j,a}$ - standard deviation about the mean length for age a of sardine of stock j

Likelihoods:

$-\ln L^{Nov}$ - contribution to the negative log likelihood from the model fit to the November 1+ biomass data

$-\ln L^{rec}$ - contribution to the negative log likelihood from the model fit to the May recruit data

$-\ln L^{sur\ propa}$ - contribution to the negative log likelihood from the model fit to the November survey proportion-at-age data

$-\ln L^{com\ propa}$ - contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-age data

$-\ln L^{sur\ propl\min}$ - contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data for the minus length class only

$-\ln L^{sur\ propl}$ - contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data for the minus length class only

$-\ln L^{com\ propl\min}$ - contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data for the minus length class only

$-\ln L^{com\ propl}$ - contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data for the remaining length classes

$\hat{B}^S_{j,y}$ - acoustic survey estimate (in thousands of tonnes) of adult sardine biomass of stock j from the November survey in year y

$\sigma^S_{j,y,Nov}$ - survey sampling CV associated with $\hat{B}^S_{j,y}$ that reflects survey inter-transect variance

$k^S_{j,N}$ - constant of proportionality (multiplicative bias) associated with the November survey of stock j

k^S_{ac} - multiplicative bias associated with the acoustic survey

$\hat{N}^S_{j,y,r}$ - acoustic survey estimate (in billions) of sardine recruitment numbers of stock j from the recruit survey in year y

$\sigma^S_{j,y,rec}$ - survey sampling CV associated with $\hat{N}^S_{j,y,r}$ that reflects survey inter-transect variance

$k^S_{j,r}$ - constant of proportionality (multiplicative bias) associated with the recruit survey of stock j

k^S_{cov} - multiplicative bias associated with the coverage of the recruits by the recruit survey in comparison to the 1+ biomass by the November survey

$k_{\text{cov}E}^{S}$ - multiplicative bias associated with the coverage of the east stock recruits by the recruit survey in comparison to the west stock recruits during the same survey

ϕ_{ac}^{S} - the CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually;

$(\lambda_{j,N/r}^{S})^2$ - additional variance (over and above $\sigma_{y,Nov/rec}^{S}$ and ϕ_{ac}^{S}) associated with the November/recruit surveys of stock j

$\hat{p}_{j,y,a}^{S}$ - estimate of the proportion (by number) of sardine of age a in stock j in the November survey of year y

$n_{s,y}$ - number of fish from the November survey trawls in year y used to compile the age-length key for calculating $\hat{p}_{j,y,a}^{S}$

$(\sigma_{p}^{S})^2$ - overall variance-related parameter for the log-transformed survey proportion-at-age observations, $\hat{p}_{j,y,a}^{S}$ [note variance = $(\sigma_{p}^{S})^2/(n_y\,\hat{p}_{j,y,a}^{S})$]

ys - years for which ALKs are available to calculate proportion-at-age in the November survey (‘93, ‘94, ’96, ’01, ’03, ’04, ’06-’10);

w_{propa}^{survey} - weighting applied to the survey proportion-at-age data

$\hat{p}_{y,q,a}^{com,S}$ - estimate of the proportion (by number) of single-stock or “west stock” sardine of age a in the commercial catch of quarter q of year y

$n_{y,q}^{com}$ - number of fish from the commercial trawls in quarter q of year y used to compile the age-length key for calculating $\hat{p}_{y,q,a}^{com,S}$

$(\sigma_{com}^{S})^2$ - overall variance-related parameter for the log-transformed commercial proportion-at-age observations, $\hat{p}_{y,q,a}^{com,S}$ [note variance = $(\sigma_{com}^{S})^2/(n_{y,q}^{com}\,\hat{p}_{y,q,a}^{com,S})$]

yc/qc - years/quarters for which ALKs are available to calculate quarterly proportions-at-age in the commercial catch (’04 Q1-4, ’06 Q2-4, ’07 Q1-3, ’08 Q4, ’09 Q1);

w_{propa}^{com} - weighting applied to the commercial proportion-at-age data

$\hat{p}_{j,y,q,l}^{coml,S}$ - observed proportion (by number) of the directed and redeye bycatch commercial catch in length group l of during quarter q of year y;

$w_{propl\min}^{com}$ - weighting applied to the commercial proportion at length data for the minus length class

w_{propl}^{com} - weighting applied to the remaining commercial proportion at length data

$\sigma^S_{coml\,\min}$ - variance-related parameter for the log-transformed commercial proportion-at-length data of the minus length class

σ^S_{coml} - variance-related parameter for the log-transformed commercial proportion-at-length data

<u>Other:</u>

F_{init} - rate of fishing mortality assumed in the initial year

$s^S_{j,cor}$ - recruitment serial correlation for stock j

$\eta^S_{j,2009}$ - standardised recruitment residual value for 2009 for stock j

K^S_j - carrying capacity for stock j

K^S_{peak} - carrying capacity during peak years (only for single stock hypothesis)

$\overline{w}^S_{j,a}$ - mean mass (in grams) of sardine of age *a* from stock j sampled during each November survey, averaged over all November surveys for which an estimate of mean mass-at-age is available