Agenda Item I.1.b
Attachment 2
April 2013

INITIAL ANALYSES RELATED TO EVALUATING PARAMETER VALUE CHOICES FOR PACIFIC SARDINE

Felipe Hurtado-Ferro and André Punt
School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020

EXCUTIVE SUMMARY

The risk assessment framework developed by the Pacific Sardine Harvest Parameters Workshop has been implemented. Analyses conducted to check that the behaviour of the framework is realistic have led to suggested changes to the specifications for the operating model. The harvest policy variants outlined during the Workshop have been more fully specified given the suggestion by the Workshop that CalCOFI_SST_an be the environmental variable which determines FRACTION (if FRACTION is to depend on an environmental variable). Initial results based on applying the 14 harvest policy variants to a base case scenario are presented, along with results based on applying a harvest policy variant which mimics the Amendment 13 OFL and HG control rules to a subset of the sensitivity tests identified by the Workshop.

INTRODUCTION

Amendment 8 to the Coastal Pelagic Species Fishery Management Plan (PFMC, 1998) established the following harvest control rule for Pacific sardine:

$$HG = (BIOMASS-CUTOFF) * FRACTION * DISTRIBUTION$$

where: HARVEST GUIDELINE is the target harvest level for each management year; BIOMASS is the annual population biomass estimate of sardine aged 1 and older; CUTOFF is 150,000 t, and is the threshold below which directed fishing is prohibited; FRACTION is/was a temperature-dependent exploitation fraction which ranges from 5% - 15%; DISTRIBUTION is the average proportion of the coastwide biomass in U.S. waters, estimated at 0.87. MAXCAT is the maximum allowable catch regardless of biomass. MAXCAT is 200,000 t for Pacific sardine.

PFMC (2013) developed an initial risk assessment framework to evaluate the performance of alternative Overfishing Limit and Harvest Guideline control rules. This initial framework was based on representing the northern subpopulation of Pacific sardine using a population dynamics model that considers the entire population from northern Baja California (Mexico) to northern Vancouver Island (Canada) as a single fully-mixed population which is fished by a single fleet. Except for one sensitivity test, and in common with the analyses on which Amendment 8 were based, the harvest by all fisheries is determined using a single harvest control rule (i.e., decision making in Mexico and Canada is not modelled explicitly).

This report first outlines suggested changes to the specifications for the analyses developed during the harvest parameters workshop based on the results of initial analyses. It then provides the results of projections under zero harvest to highlight the behaviour of the operating model, and to assist review bodies determine if the operating model is performing as anticipated. Next, analyses which estimate E_{MSY} (the fraction of the 1+ biomass which can be taken annually which maximises long-term yield) both when this fraction is independent of any environmental variable and when it depends on an environmental variable which is related to the environmental determinant of recruitment are provided. The next section of the report shows results for the control rule variant which mimics the HG control rule in Amendment 8 (“J” in Table 1) for some of the sensitivity scenarios identified by PFMC (2013), after which results are shown for all of the harvest control rule variants in Table 1 for a base-case set of simulations[1]. Finally, a set of possible next steps are outlined.

MODIFCATIONS TO THE OPERATING MODEL

Appendix A lists the specifications for the operating model. This operating model differs from that specified by PFMC (2013) in that the values for the parameters which specify how the square wave function which determines the environmental forcing of recruitment are updated. In addition, it differs because of some changes to how recruitment is related to spawning stock biomass, SSB[2]

Form of the stock-recruitment relationship

Appendix H of PFMC (2013) shows how the relationship of between log-recruitment and SSB and SST_CC_ann can be approximated. However, both the original relationship and the approximation have the undesirable property that recruitment will be non-zero as long as temperature is non-zero, irrespective of SSB, i.e. there is no way to collapse the stock, no matter how high fishing mortality becomes. It is recommended that a relationship between log(R/S) and SSB based on Table E6 of PFMC (2013) is used. This new recruitment model is a parametric approximation to a GAM fitted to spawning biomass and recruitment data from 1984 to 2008 and using SST_CC_ann as the environmental covariate. Equation A.2b consequently models recruitment using a modified Ricker stock-recruitment relationship, i.e.:

$$R_y = SSB_y \cdot \exp\left(\alpha + \beta \cdot SSB_y\right) e^{\varepsilon_y - \sigma_R^2/2}, \qquad (1)$$

where α and β are the parameters of the stock-recruitment relationship, SSB_y is spawning stock biomass in year y (age-2+ biomass), σ_R^2 is the extent of variation about the stock-recruitment relationship due to unmodelled white-noise processes[3]. Figure 1 compares the predicted recruitment from the GAM and the parametric approximation, with associated relative errors in Figures 2 and 3. Figure 4 compares the new stock-recruitment model and the original relationship. The full set of specifications are presented in Appendix A.

The original model specification used ERSST_ann to parameterize the underlying signal of the environmental variable. However, the recruitment model is now parameterized using the SST_CC_ann time series, which has different variability. Details of the revised parameterization are presented in Appendix B.

MODEL VALIDATION: PROJECTIONS UNDER ZERO CATCH

To validate the OM, projections under zero catch were conducted for seven scenarios:

(1) no process error or environmental impacts ($\phi = \sigma_R = \rho_R = 0$; “No error”),

(2) uncorrelated process error in recruitment, but no environmental impact ($\phi = \rho_R = 0$; “Rec. error only”),

---

[1] Results are not shown for all combinations of harvest control rule and scenario to keep the amount of output to a reasonable amount, and hence facilitate advice from the Council on next steps.

[2] Actually 2+ biomass (PFMC, 2013).

[3] The SSC was advised of this change during it 6-7 March 2013 meeting

(3) autocorrelated process error in recruitment, but no environmental impact ($\phi = 0$; Rec. error + AC"),

(4) no process error and a deterministic square wave environmental impact ($\sigma_R = \rho_R = \sigma_V = \rho_V = 0$; "Sq. Wave only"),

(5) uncorrelated process error in recruitment and a deterministic square wave environmental impact ($\rho_R = \sigma_V = \rho_V = 0$; "Sq. Wave w/error"),

(6) uncorrelated process error in recruitment and an uncorrelated stochastic square wave environmental impact($\rho_R = \rho_V = 0$; "All error"), and

(7) correlated process error in recruitment and a correlated stochastic square wave environmental impact("All error+AC"),

Figure 5 shows projections of the operating model 200 years into the future, displaying the 1+ biomass, recruitment and the environmental variable. The OM is capable of reproducing the observed values of SST_CC_ann, as well as high and low biomass levels. In the absence of fishing, the biomass does not drop to the levels observed during the mid-1960s to early-1980s. The 1+ biomass is equal to the deterministic unfished level on average even in presence of auto-correlated environmental forcing in the absence of an environmental impact. The average 1+ biomass under the "All error + AC" case is taken to be B_0 when applying control rules in which the CUTOFF parameter is a proportion of B_0.

SELECTING E_{MSY}

E_{MSY} ignoring the environmental effect

E_{MSY} is here defined as the exploitation rate that maximizes the mean catch for the "All error" scenario[4]. E_{MSY} was calculated under several recruitment and error specifications to understand the sensitivity of the results to error and assumptions (Figures 6 and 7). Two recruitment scenarios (simple Ricker model without environment forcing, and the log(R/S) model including environment forcing as described above), and two error scenarios (with and without error in recruitment and environment) were explored. No observation errors were considered when defining E_{MSY}. The OM was projected forward for 5,000 years (sufficient to reach equilibrium) and for a range of possible E_{MSY} values to estimate the deterministic E_{MSY} (i.e. no process error and a deterministic environmental effect). Stochastic E_{MSY} was estimated by projecting the OM forward for 100,000 years (100 simulations × 2,000 year), again to guarantee equilibrium. The resulting values for E_{MSY} are shown in Table 2. The resulting mean and median yield curves are shown in Figures 6 and 7. The value of E_{MSY} when it is taken to be a single fixed value is 0.18.

E_{MSY} accounting for an environmental effect

E_{MSY} is related to the environmental factor through the recruitment model; as temperature increases, E_{MSY} increases as well. Figure 8 illustrates this relationship. The operating model was projected forward (with no process or observation error) for 5,000 years (sufficient to reach equilibrium) and a range of possible E_{MSY} values while leaving temperature fixed to determine the relationship between E_{MSY} and temperature. Figure 9 shows the estimated relationship between E_{MSY} and temperature. This relationship was approximated using a polynomial equation (Figure 10). The cubic approximation was selected over quadratic and linear approximations using AIC (ΔAIC > 30).

---

[4] The value of E_{MSY} is 0.17 if expected yield is taken to be median rather than the mean of the distribution.

OFL, ABC and Harvest Guidelines

The OFL, ABC and the Harvest Guidelines are defined following the definitions in Amendment 13 (PFMC, 2010)[5]. Consistently with how OFLs have been calculated for the Pacific sardine, the OFL, defined as $OFL_y = E_{MSY}\left(I_y\right)\hat{B}_y^{1+}$ (eq. A5b), is bounded above by the E_{MSY} corresponding to the upper quartile of observed temperature. ABC is defined as OFL multiplied an uncertainty buffer (Table 3). The calculations of this report are based on the choice P*=0.4. The harvest guideline, HG, is defined as $HG_y = \mathrm{DISTRIBUTION}\times\mathrm{FRACTION}_y(B_y^{1+}-\mathrm{CUTOFF})$, where the FRACTION is given by the polynomial approximation of the relationship between E_{MSY} and temperature. DISTRIBUTION is set equal to 1 (Figure 10). The HG is bounded below by an E_{MIN} and above by MAXCATCH. Figures 11 and 12 show the relationships between 1+ biomass and catch (OFL, ABC, HG), and between SST and catch (OFL, ABC, HG), at different levels of SST and proportions of B_0 (Table 4). Figures 13 and 14 show the same relationships for the current specifications for setting OFL, ABC and HG (essentially variant J in Table 1, except that HG is bounded above by the ABC). B_0 is here defined as the **mean** biomass for scenario (7) of the projections with no catch[6].

RESULTS FOR A BASE-CASE OPERATING MODEL

The base-case operating model is defined in Table A4. Figure 16 shows the cumulative 1+ biomass and cumulative catch for the harvest policy variant which most closely resembles the current HG control rule (harvest policy "J" in Table 1) as well as those for the least (the setting catch to the OFL; harvest policy "OFL" in Table 1) and most (setting CUTOFF to 0.33B_0; harvest policy V4 in Table 1) conservative harvest policy variants. The catch for the OFL control rule is unbounded, whereas the catch for harvest policy variants J and V4 do not allow the catch to exceed 200,000t (MAXCAT).

Table 5 lists the values for the performance measures for all 14 harvest policy variants (see Section 4 of Appendix A for definitions of the performance measures), highlighting those harvest policy variants which perform best (green highlighted) and poorest (red highlighted) for each performance measure. No harvest policy variant is always in the "best" group, indicating that there are trade-offs amongst the management objectives which underlie the performance measures. Some of the key trade-offs are illustrated in Figure 17. Best performance occurs in the top left corner of the left panel of Figure 17 (high average catches and 1+ biomasses) and in the top left corner of the right panel of Figure 17 (high probability that the catch is larger than 50,000t and the 1+ biomass exceeds 400,000t). Some of the harvest policy variants (e.g. 3, "E_{MSY}") are "dominated" in Figure 17 (they achieve the same [or lower] average catch as another variant, but at lower average biomass). Harvest policy variant 3 leads to a high proportion of years with no catch (Figure 17, right panel) and 1+ biomass values below 400,000t (Figure 17, right panel).

The current harvest policy variant ("J" in Table 1, "6" in Figure 17), achieves amongst the lowest average catches, but performs best in terms of low catch variation and a low probability of the HG being zero (Table 5). This policy variant also leads to high variation in 1+ biomass.

---

[5] The OFL as defined in Amendment 13 includes the DISTRIBUTION parameter, but DISTRIBUTION is assumed to be 1.

[6] Note that this definition of B_0 is not the 'true B_0' of the stock, and is only used to define the CUTOFF parameter of the HG. The 'true' B_0 of the stock is not a static value and is related to the environment (Figure 15). Thus, the definition of B_0 being used here is not appropriate for defining an overfished threshold.

However, 1+ biomass remains about 400,000t with high probability (~95% of years). Selecting the range of exploitation rates on which to base the control rule as well as MAXCAT to maximize average catch (harvest policy variants "Alt3" and "Alt4" in Table 5) lead to larger catches than the current harvest policy variant, but the difference is small.

SENSTIVITY TO ALTERNATIVE SCENARIOS

Table 6 shows the values for the performance measures for harvest policy variant J, while the results of the sensitivity tests in the trade-off space are shown in Figure 18. A lower amplitude of the environmental signal results in lower probability of low catches and higher probability of high biomass (case S1), while the opposite is true for higher amplitudes of the environmental signal. Perhaps not surprisingly, variation in catch and biomass, as well as the probability of low (or zero) catches, is higher when the extent of recruitment variation is higher (case S6), and is lower when recruitment variation is lower (case S5). The probability of low (or zero) catches is markedly higher when the number of years of poor environmental conditions is increased (case S7). In contrast, longer periods of good and bad environmental conditions (case S8), or a smoother (i.e. sine) underlying environmental signal (case S9) are relatively inconsequential. The extent of the variation in the estimates of biomass (cases S3 and S4) is also relatively inconsequential.

NEXT STEPS

The analyses of this report provide results for a subset of combinations of scenario and harvest policy variants for comparison. The next steps are:

- Completion of the sensitivity tests for the current harvest policy variant (supplementary material for the April Council meeting).
- Completion of the sensitivity tests for the remaining harvest policy variants (supplementary material for the April Council meeting).
- Validation that the performance measures selected by PFMC (2013) adequately cover the range of management objectives for which the type of risk assessment framework in Appendix A can address.
- Specification of additional sensitivity tests (e.g. combinations of factors in Table A4).
- Specification of additional harvest policy variants.
- Distribution of the code implementing the calculations.

ACKNOWLEDGEMENTS

Kevin Hill and Alec McCall (SWFSC, NOAA) are thanked for providing guidance regarding the evaluation of the harvest policy variants.

References

Hill, K.T., Crone, P.R., Lo, N.C.H., Demer, D.A., Zwolinski, J.P. and B.J. Macewicz. 2012. Assessment of the Pacific sardine resource in 2012 for U.S. management in 2013. Pacific Fishery Management Council, 7700 NE Ambassador Place, Portland, OR 97220, USA.

MacCall, A.D. 2002. Fishery-management and stock-rebuilding prospects under conditions of low frequency environmental variability and species interactions. Bulletin and Marine Science 70: 613–628

Murphy, G.I. 1966. Population biology of the Pacific sardine (*Sardinops caerulea*). *Proceedings of the California Academy of Sciences* 34: 1-84

PFMC. 1998. Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: the coastal pelagic species fishery management plan. Pacific Fishery Management Council, Portland, OR. (Appendix B: http://www.pcouncil.org/wp-content/uploads/a8apdxb.pdf)

PFMC. 2010. Measures for integrating new provisions of the Magnuson-Stevens Fishery Conservation and Management Act and National Standard 1 Guidelines into coastal pelagic species management. Amendment 13 to the Coastal Pelagic Species Fishery Management Plan. Partial Draft Environmental Assessment. Pacific Fishery Management Council, Portland, OR. (http://www.pcouncil.org/wp-content/uploads/F2a_ATT1_DRAFT_EA_JUNE2010BB.pdf)

PFMC. 2013. Report of the Pacific Sardine Harvest Parameters Workshop. Pacific Fishery Management Council, Portland, OR.

Ralston, S., Punt, A.E., Hamel, O.S., DeVore, J. and R.J. Conser. 2011. An approach to quantifying scientific uncertainty in stock assessment. *Fishery Bulletin* 109: 217-231.

Table 1. Harvest control rule variants. The numbers associated with each control rule variants are used in the figures. PFMC (2013) included a 15th variant, but this was equivalent to "HG Variant-1".

	Amendment 8 variants (the letters denote the variants in Amendment 8)				
Variant	**A (1)**	**F (2)**	**L (3)**	**M (4)**	**OFL (5)+**
FRACTION (%)	20	5-25*	E_{MSY}	DE_{MSY}	45
CUTOFF	50	100	0	0	$0.33B_0$
MAXCAT	400	400			
	Present HG (Option J) variants				
Variant	**HG (J) (6)**	**HG Variant-1 (7)**	**HG Variant-2 (8)**	**HG Variant-3 (9)**	**HG Variant-4 (10)**
FRACTION (%)	5-15*	5- E_{MSY} *	5- E_{MSY} *	5- E_{MSY} *	5- E_{MSY} *
CUTOFF	150	150	$0.10B_0$	$0.20B_0$	$0.33B_0$
MAXCAT	200	200	200		
	Other variants				
Variant	**Alt-1 (11)**	**Alt-2 (12)**	**Alt-3 (13)**	**Alt-4 (14)**	
FRACTION (%)	0-20*	5-2E_{MSY} *	Best Fit	Best Fit	
CUTOFF	$0.20B_0$	$0.20B_0$	Best Fit	Best Fit	
MAXCAT	200	200	200	-	

E_{MSY} – stochastic E_{MSY} (0.18)
DE_{MSY} – deterministic E_{MSY} (0.16)
* SST is in harvest control rule
\+ Not an Amendment 8 variant

Table 2. E_{MSY} under different recruitment and error assumptions. Assumptions with 'error' include error in recruitment and the environmental factor (if applicable).

Model specification	**E_{MSY} (mean)**	**E_{MSY} (median)**
No environment, no error	0.19	0.19
No environment, with error	0.21	0.21
With environment, no error	0.16	0.12
With environment and error*	0.18	0.17

*This is the stochastic E_{MSY}

Table 3. Uncertainty buffers for various *P** values for Pacific sardine.

P*	**Buffer (ABC/OFL)**
0.50	1.00000
0.45	0.95217
0.40	0.90592
0.30	0.81504
0.20	0.72020

Table 4. Values of biomass used in the harvest control rule variants (in ‘000 t).

Quantity	**Value**
B_0	1655
0.33 B_0	551.9
0.20 B_0	331.1
0.10 B_0	165.6

Table 5. Results of applying each of harvest control variants to a base-case scenario (see table A4 for specifications). The variants where the performance measure is within 5% of the best value is shaded in green and those for which the performance measure is within 5% of the poorest value is shaded in red.

Scenario	**A**	**F**	**L**	**M**	**OFL**	**HG-J**	**HG-V1**	**HG-V2**	**HG-V3**	**HG-V4**	**Alt1**	**Alt2**	**Alt3**	**Alt4**
Symbol	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
FRACTION (%)	20	5-25*	E_{MSY}	DE_{MSY}	45	5-15*	5-E_{MSY} *	5 E_{MSY} *	5-E_{MSY} *	5-E_{MSY} *	0-20*	5-2·E_{MSY} *	0.11-E_{MSY}†	E_{MSY}†
CUTOFF	50	100	0	0	0.33·B_0	150	150	0.10·B_0	0.20·B_0	0.33·B_0	0.20·B_0	0.20·B_0	50	50
MAXCAT	400	400				200	200	200			200	200	200	-
Performance_Measure														
Mean catch (‘000t)	148.9	150.9	123.9	135.4	291.7	109.9	113.7	113.2	144.9	105.8	110.8	112.5	117.9	118.4
SD catch (‘000t)	121.4	128.5	176.8	178.4	338.4	70.5	72.3	72.4	167.5	73.4	74.2	74.9	70.9	70.7
Mean B1+ (‘000t)	886.8	1089.8	449.7	549.0	903.6	1259.1	1239.5	1245.7	1215.5	1369.0	1300.4	1290.8	1190.4	1181.3
SD B1+ (‘000t)	836.7	788.2	607.5	665.2	609.9	875.8	872.7	872.0	744.9	857.2	862.7	861.4	878.8	880.7
Mean SSB † (‘000t)	641.2	810.0	295.3	368.4	625.2	978.4	959.7	965.4	922.6	1081.6	1015.5	1006.1	915.9	908.0
SD SSB (‘000t)	675.0	646.3	422.9	473.9	392.0	749.2	746.6	746.1	581.6	734.0	738.9	737.9	750.9	752.2
%B1+>400,000t	67.81	92.06	36.08	43.94	87.18	94.83	94.48	94.84	97.15	98.47	97.33	97.19	91.18	90.43
%No catch	0.89	2.37	5.79	2.80	36.11	2.65	2.68	2.84	7.01	16.33	7.37	6.88	2.23	2.24
%Catch<50,000t	25.90	30.09	48.87	41.83	46.22	30.43	30.15	30.60	37.28	43.78	35.85	35.61	26.90	26.48
Median catch (‘000t)	111.34	107.52	60.09	73.99	189.30	102.16	109.03	108.05	92.73	94.80	104.20	106.60	115.8	116.9
Median B1+ (‘000t)	652.0	891.3	219.4	317.3	751.6	1037.5	1013.8	1020.4	1039.9	1162.9	1081.2	1070.0	960.2	950.7
Median SSB (‘000t)	449.6	647.9	138.7	205.3	535.9	780.4	757.4	763.6	783.2	897.1	819.0	808.5	709.8	701.7
Mean Pop age	2.45	2.62	2.15	2.21	2.43	2.81	2.79	2.79	2.75	2.92	2.85	2.84	2.74	2.73
Mean Catch Age	1.58	1.66	1.37	1.41	0.97	1.79	1.77	1.78	1.67	1.62	1.75	1.74	1.75	1.74
Mean Yrs NoCatch	1.32	1.70	3.93	3.10	2.24	1.65	1.65	1.63	1.61	1.86	1.69	1.61	1.73	1.73
%HCR min	NA	NA	NA	NA	NA	11.93	11.93	11.93	11.93	11.93	1.70	11.93	33.40	NA
%HCR max	NA	NA	NA	NA	NA	52.27	42.20	42.20	42.20	42.20	35.77	0.00	42.20	NA
Mean Yrs HCR min	NA	NA	NA	NA	NA	2.64	2.64	2.64	2.64	2.64	1.66	2.64	4.83	NA
Mean Yrs HCR max	NA	NA	NA	NA	NA	7.47	6.01	6.01	6.01	6.01	5.14	0.00	6.01	NA

† – Combinations of FRACTION and CUTOFF, under 200 and 0 MAXCATCH, that lead to the largest mean catch (with zero catch years included), subject to the maximum exploitation rate not being larger than E_{MSY}.

Table 6. Results of applying harvest control variant J to a base-case scenario and ten of the sensitivity tests. Scenarios "Amp=0.5" and "Amp=2" refer to changing the amplitude of the environmental signal; scenarios "σ_B=0.268" and "σ_B=0.5" refer to changing the assumed extent of uncertainty associated with biomass estimation; scenarios "σ_R=0.9" and "σ_R=0.5" refer to changing the assumed extent of recruitment variability; scenarios "G=a2", "G=c", and "G=d" refer to the shape of the underlying environmental signal, G, as described in Figure A1.

Scenario	**HG-J**	**Amp = 0.5**	**Amp = 2**	**σ_B=0.268**	**σ_B=0.5**	**σ_R=0.5**	**σ_R=0.9**	**G=a2**	**G=c**	**G=d**
Symbol	**6**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Performance Measure										
Mean catch ('000t)	109.9	110.9	117.7	111.8	106.7	115.6	105.8	93.2	110.3	109.8
SD catch ('000t)	70.5	64.9	81.2	69.8	71.5	69.4	71.1	69.0	67.3	71.1
Mean B1+ ('000t)	1259.1	1195.8	1459.5	1252.9	1271.3	1278.9	1244.3	1093.4	1215.8	1255.4
SD B1+ ('000t)	875.8	719.5	1324.7	874.3	879.2	699.8	1030.5	773.6	780.0	876.4
Mean SSB † ('000t)	978.4	923.7	1150.2	971.8	991.4	990.5	969.5	851.5	941.4	975.6
SD SSB ('000t)	749.2	619.0	1129.3	747.5	753.0	584.4	891.9	655.1	668.3	747.7
%B1+>400,000t	94.8	97.34	82.62	94.92	94.65	98.63	91.07	92.60	96.24	94.06
%No catch	2.65	0.85	15.27	2.34	3.64	2.19	3.33	3.70	1.55	2.85
%Catch<50,000t	30.43	23.59	43.92	28.89	33.34	26.81	33.31	39.88	26.55	31.09
Median catch ('000t)	102.2	102.7	138.0	105.9	96.1	112.8	94.7	74.3	102.3	102.6
Median B1+ ('000t)	1037.5	1028.9	1068.1	1028.7	1053.9	1111.3	976.8	883.4	1028.7	1035.9
Median SSB ('000t)	780.4	770.1	805.9	772.7	795.8	839.9	731.3	672.8	771.3	777.7
Mean Pop age	2.81	2.74	3.01	2.80	2.82	2.72	2.87	2.82	2.76	2.80
Mean Catch Age	1.79	1.77	1.69	1.79	1.79	1.73	1.83	1.78	1.78	1.78
Mean_Yrs_NoCatch	1.65	1.36	2.83	1.70	1.52	1.69	1.67	1.66	1.55	1.69
%HCR min	11.93	6.06	30.56	11.93	11.93	11.93	11.93	16.09	8.32	12.39
%HCR max	52.27	53.25	50.68	52.27	52.27	52.27	52.27	40.32	52.90	51.99
Mean Yrs HCR min	2.64	2.00	5.38	2.64	2.64	2.64	2.64	2.68	2.34	2.72
Mean Yrs HCR max	7.47	5.33	19.52	7.47	7.47	7.47	7.47	5.56	6.08	7.87

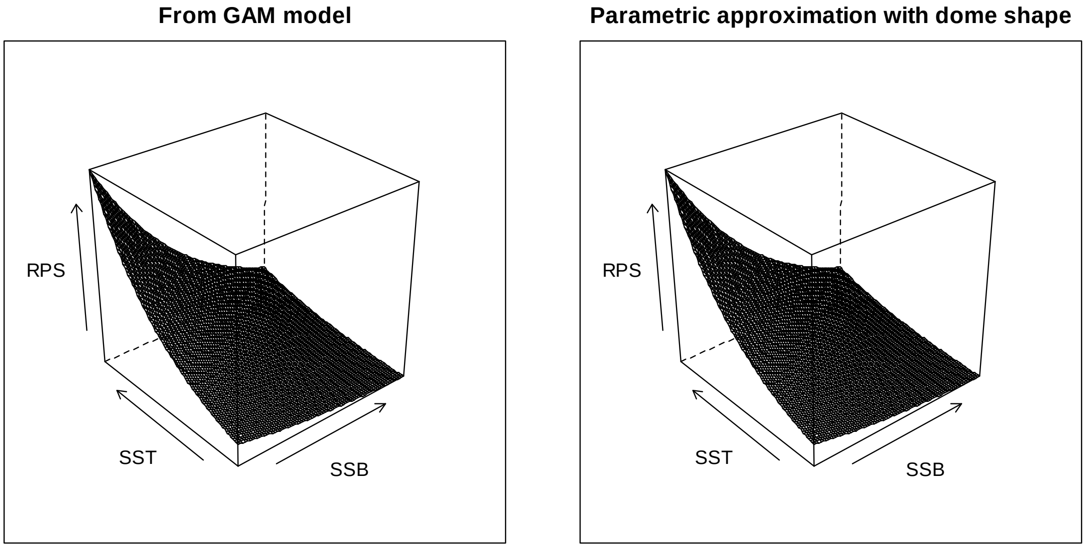

Figure 1. Predicted recruitments from the log(R/S) GAM model (left) and from the parametric approximation (right) to this model for a range of spawning biomass and SST levels.

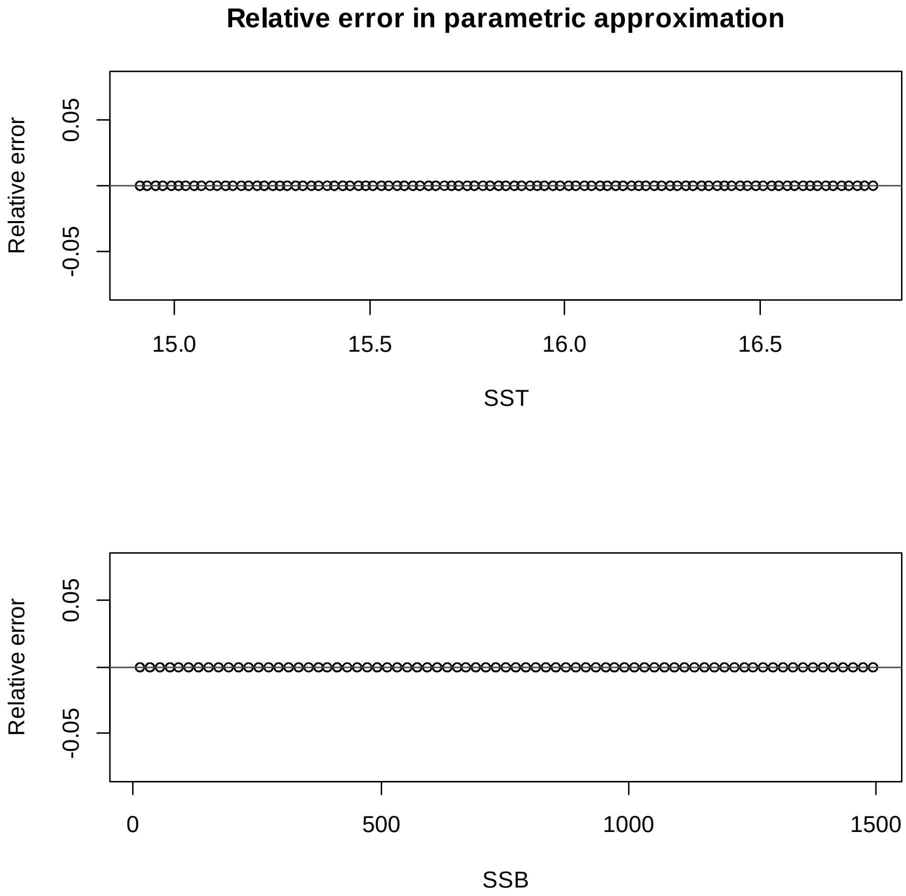

Figure 2. Relative error in approximating predictions from the log(R/S) GAM model for Pacific sardine using the back-transformed linear model. Relative error is $e = (\hat{R} - \tilde{R}) / \hat{R}$ where $\widehat{R}$ is a prediction from the log(R/S) GAM model and $\tilde{R}$ is the approximation. Results shown are for a random sample (N=1,000) of spawning biomass and SST points.

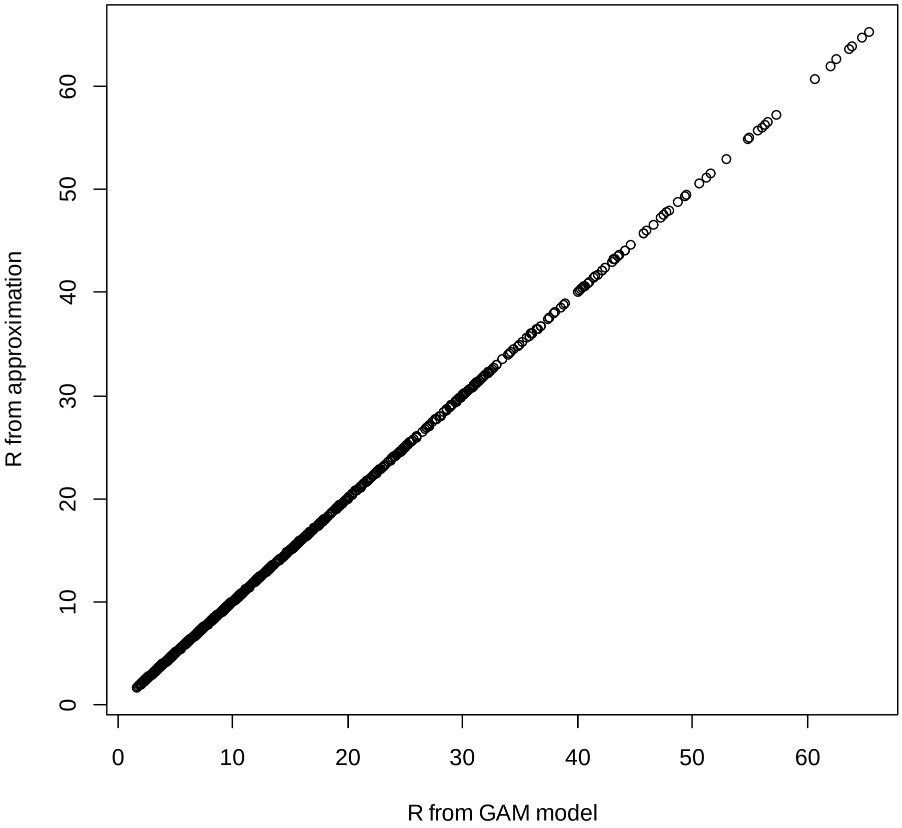

Figure 3. Correspondence between predicted values from the log(R/S) GAM model and the parametric approximation function. Results shown are for a random sample (N=1,000) of spawning biomass and SST points.

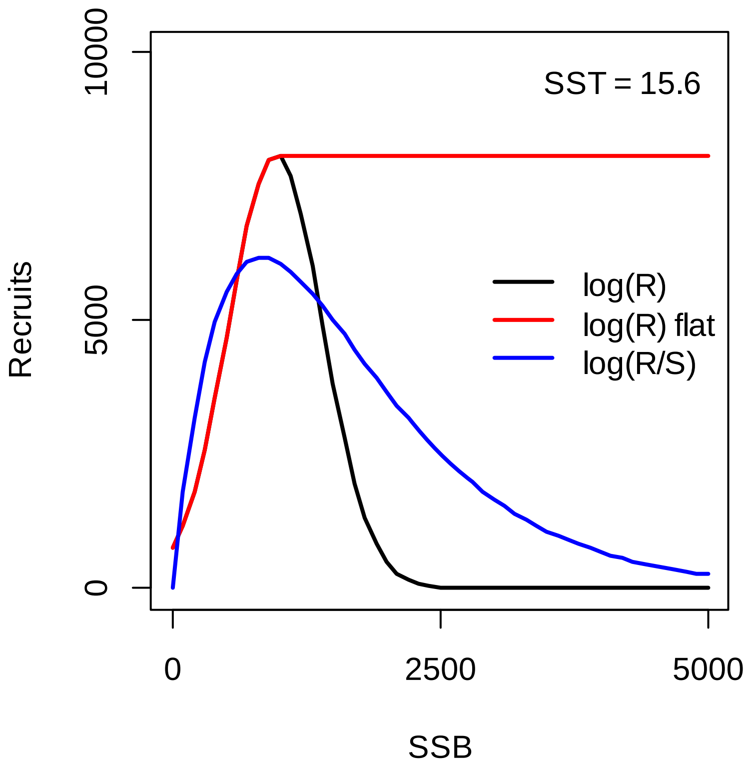

Figure 4. The original [log(R)] and the new [log(R/S)] relationships at SST = 15.6°C (i.e. the mean temperature of the SST_CC_ann time series). Note that the two curves based on log(R) do not go to zero when SSB = 0.

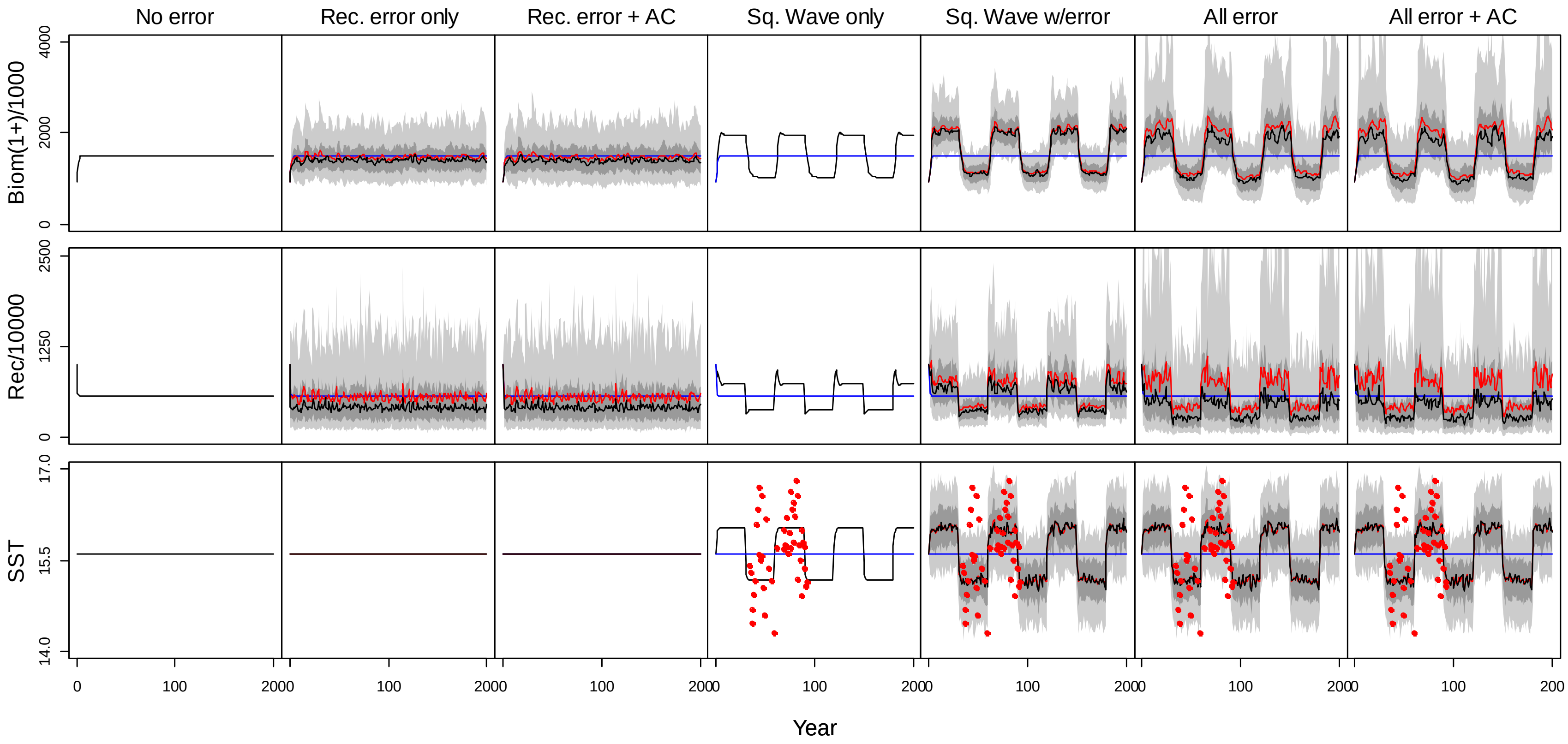

Figure 5. Projections under zero fishing mortality using the SST_CC_ann data. The black line represents the median of 100 simulations, the red line indicates the mean, and the blue line reproduces the result of the no error case. Light and dark gray represent the 95% and 50% quantiles respectively. Red points represent observed SST_CC_ann data (aligned for ease of visualization).

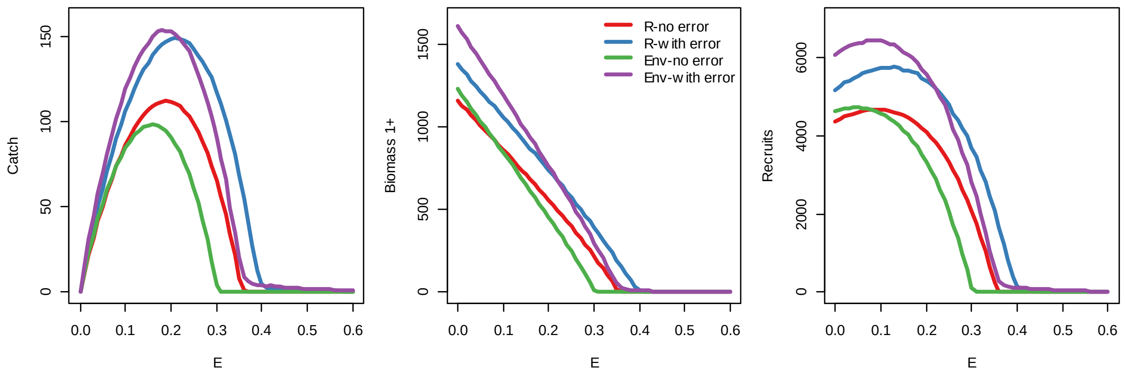

Figure 6. Mean yield, biomass and recruitment versus the exploitation rate in a constant exploitation rate harvest control rule, for projections under different scenarios of recruitment and error.

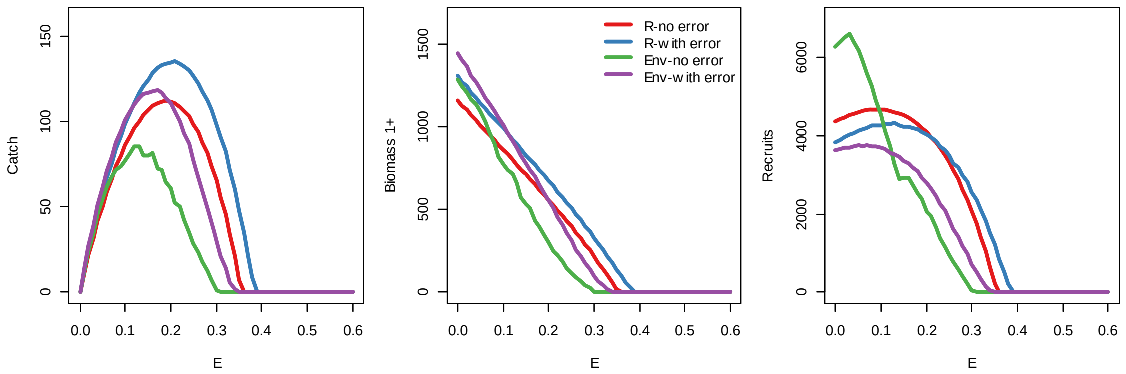

Figure 7. Median yield, biomass and recruitment curves versus the exploitation rate in a constant exploitation rate harvest control rule, for projections under different scenarios of recruitment and error.

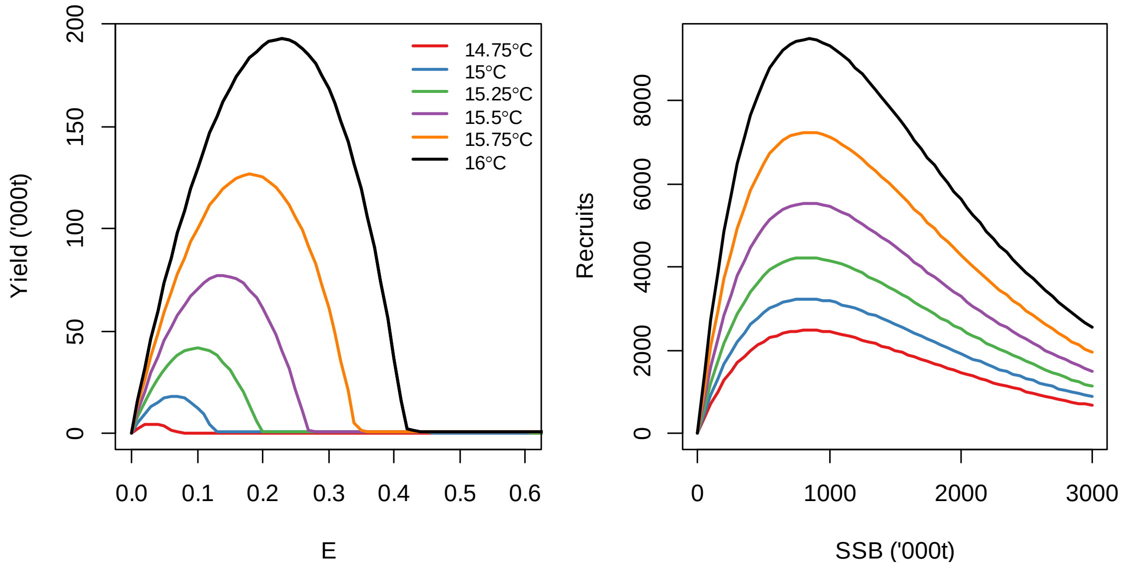

Figure 8. Yield functions (yield versus exploitation rate) for different fixed values for SST (left) and the stock-recruitment relationships for those values for SST (right).

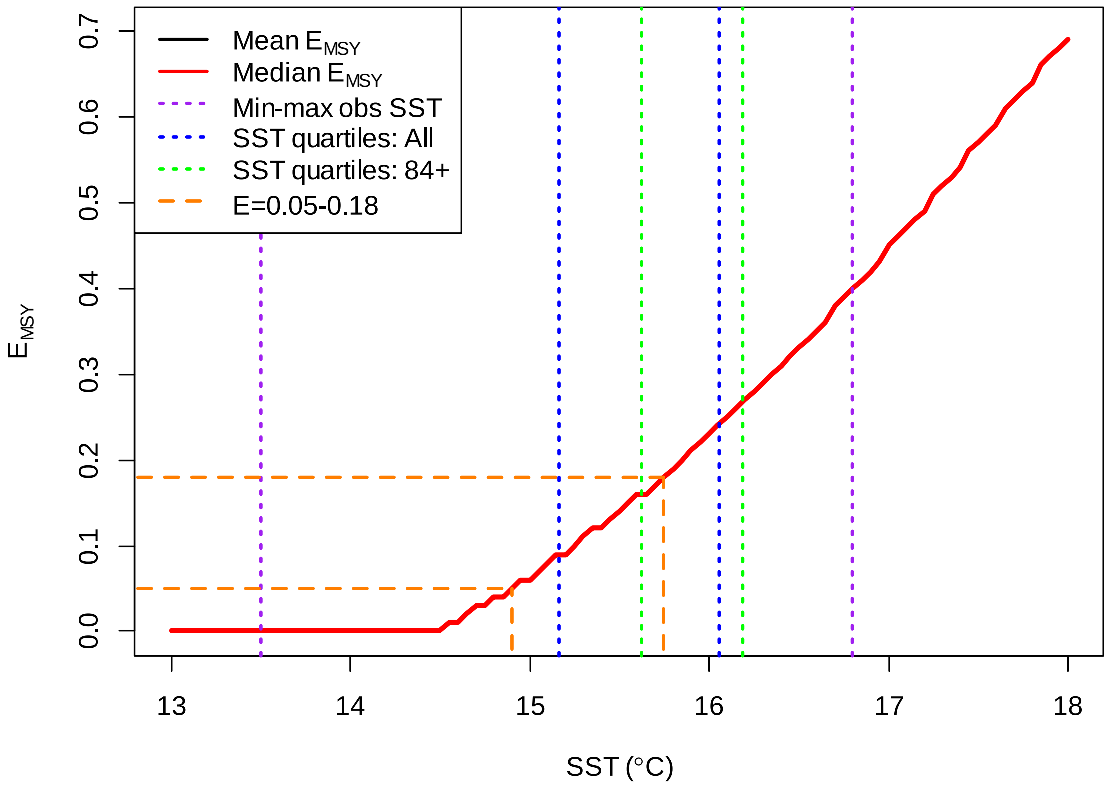

Figure 9. Relationship between SST and E_{MSY}, showing quartiles of observed SST in the SST_CC_ann time series.

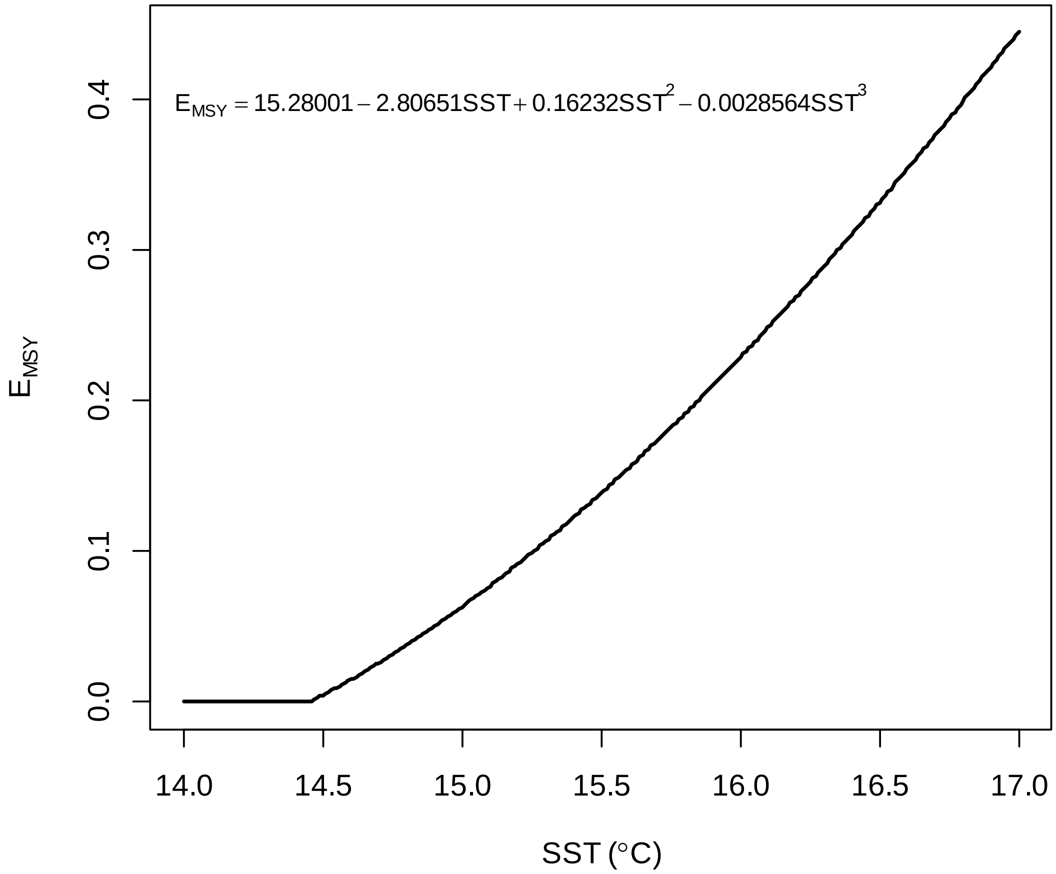

Figure 10. Polynomial approximation to the relationship between SST and E_{MSY}.

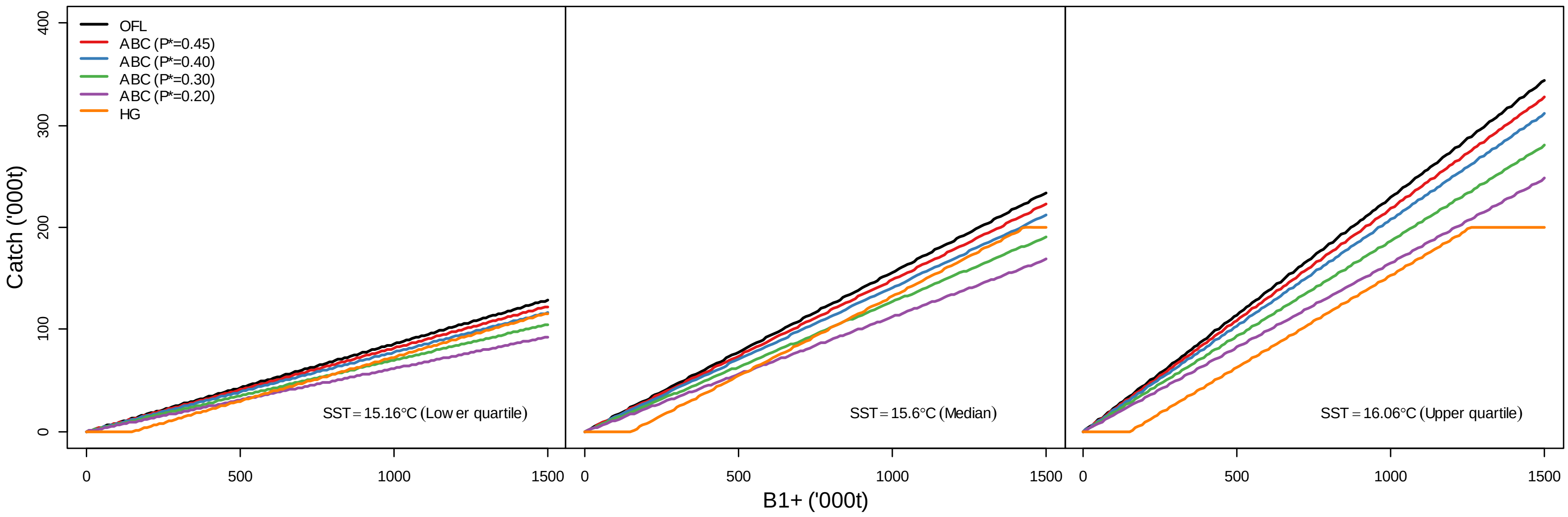

Figure 11. Relationships between 1+ biomass and catch (OFL, ABC, HG) for the upper, middle, and lower quartile of SSTs. The values for CUTOFF and MAXCAT are set to 150,000 t and 200,000 t respectively. Note that the HG would be constrained by the ABC if the HG was larger than the ABC (this does not occur for a P* of 0.4 but would for a P* of 0.2).

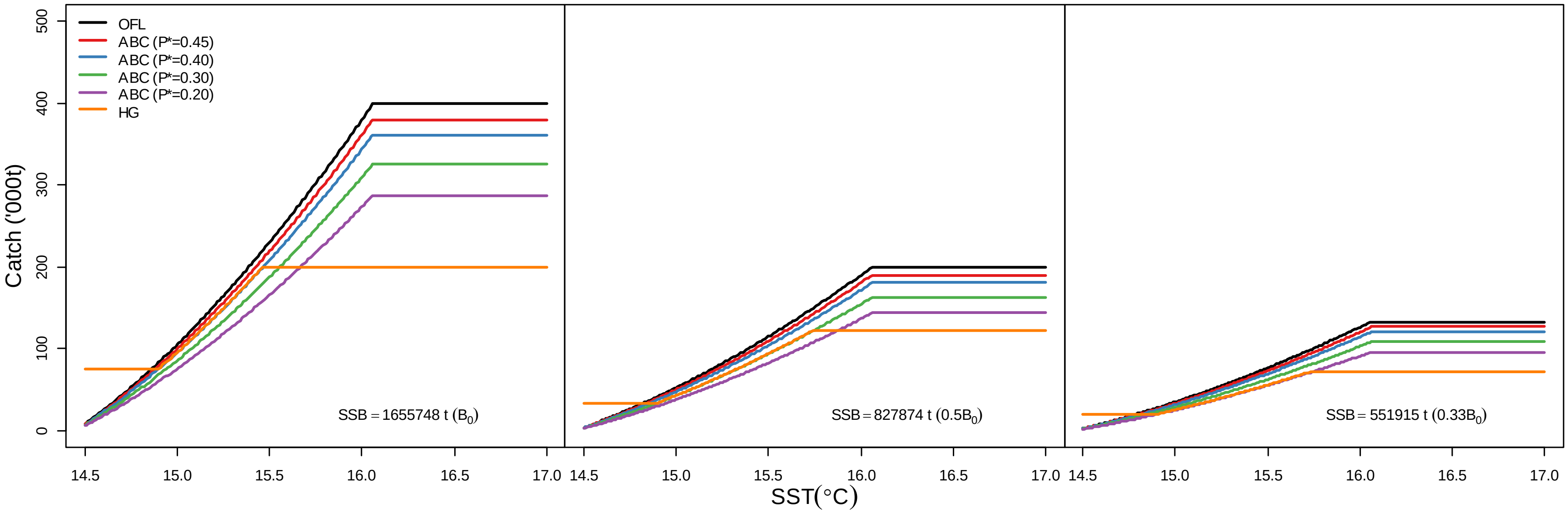

Figure 12. Relationships between SST and catch (OFL, ABC, HG) when the 1+ biomass from the assessment equals various fractions of B_0 (B_0, $0.5B_0$ and $0.33B_0$). CUTOFF and MAXCAT are set to 150,000 t and 200,000 t respectively. Note that the HG would be constrained by the ABC if the HG was larger than the ABC.

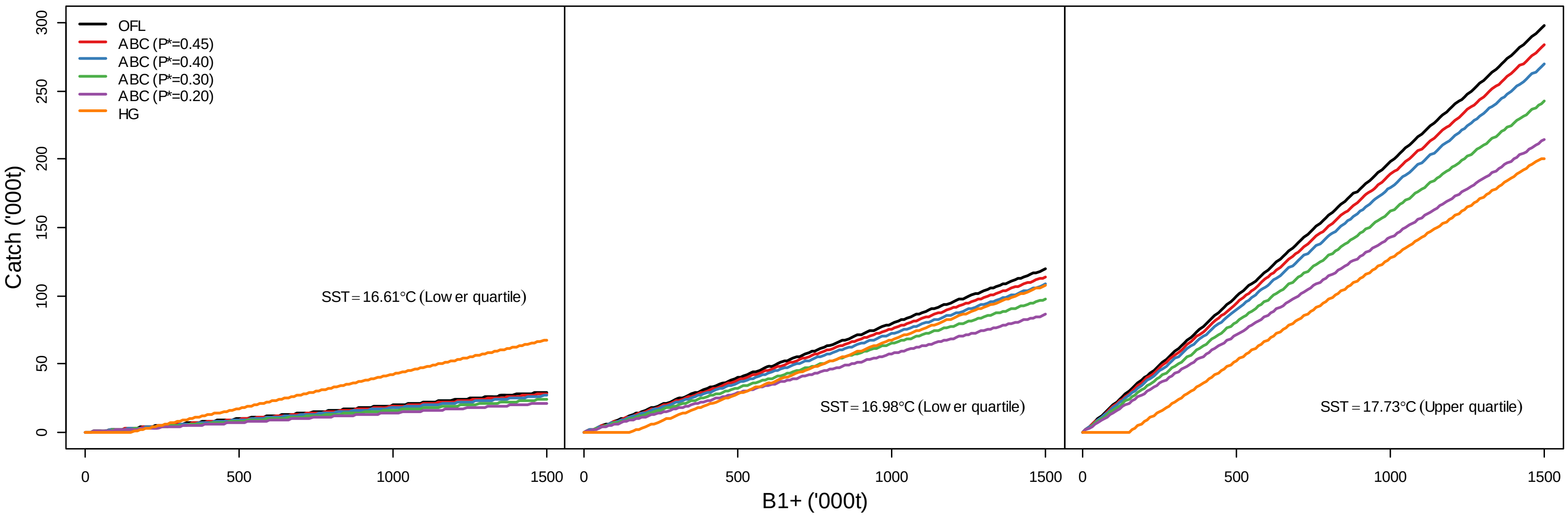

Figure 13. Relationships between 1+ biomass and catch (OFL, ABC, HG) for the upper, middle, and lower quartile of SSTs under the CURRENT harvest control rules. The values for CUTOFF and MAXCAT are set to 150,000 t and 200,000 t respectively. Note that the HG would be constrained by the ABC if the HG was larger than the ABC.

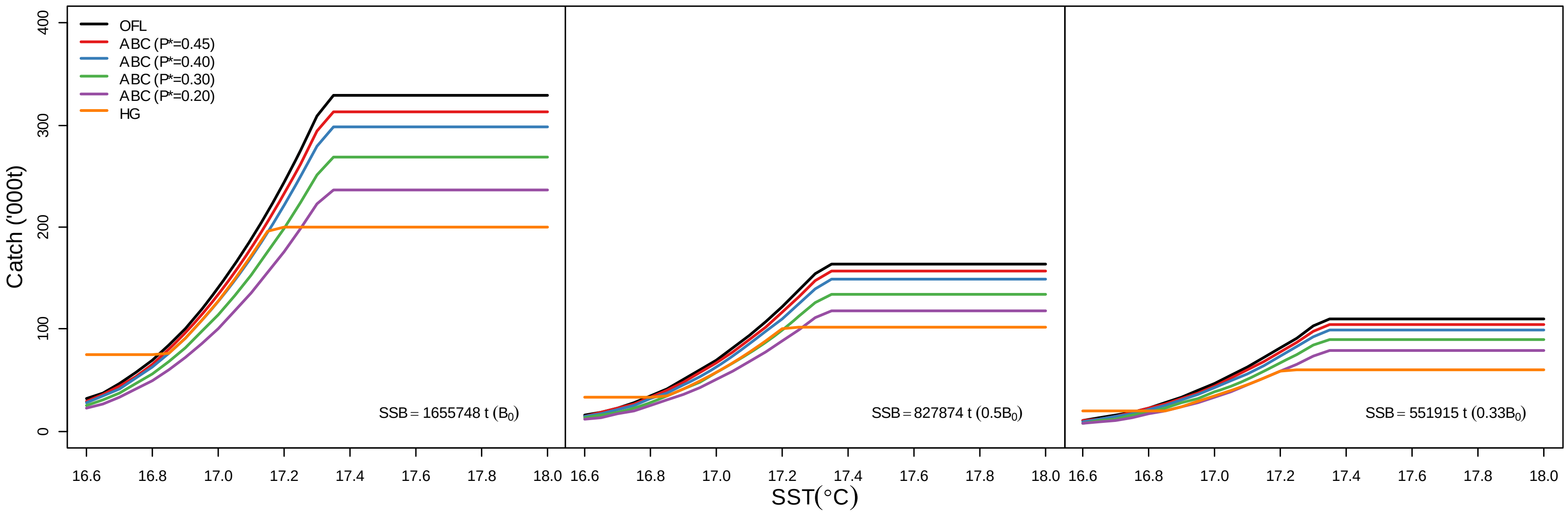

Figure 14. Relationships between SST and catch (OFL, ABC, HG) for different levels of CUTOFF the 1+ biomass from the assessment equals various fractions of B_0 (B_0, $0.5B_0$ and $0.33B_0$) under the CURRENT management. MAXCAT is set to 200,000 t in the trials. Note that the HG would be constrained by the ABC if the HG was larger than the ABC.

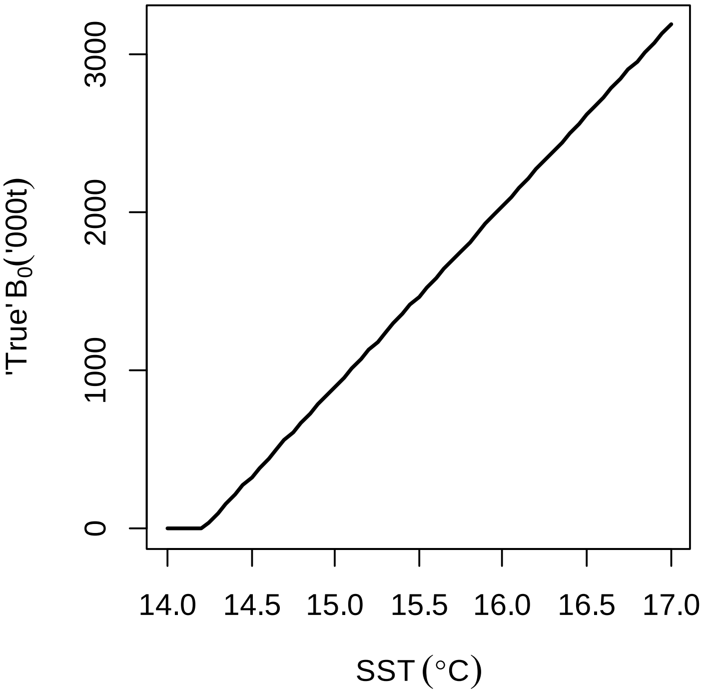

Figure 15. Relationship between SST and the operating model unfished equilibrium population size, B_0.

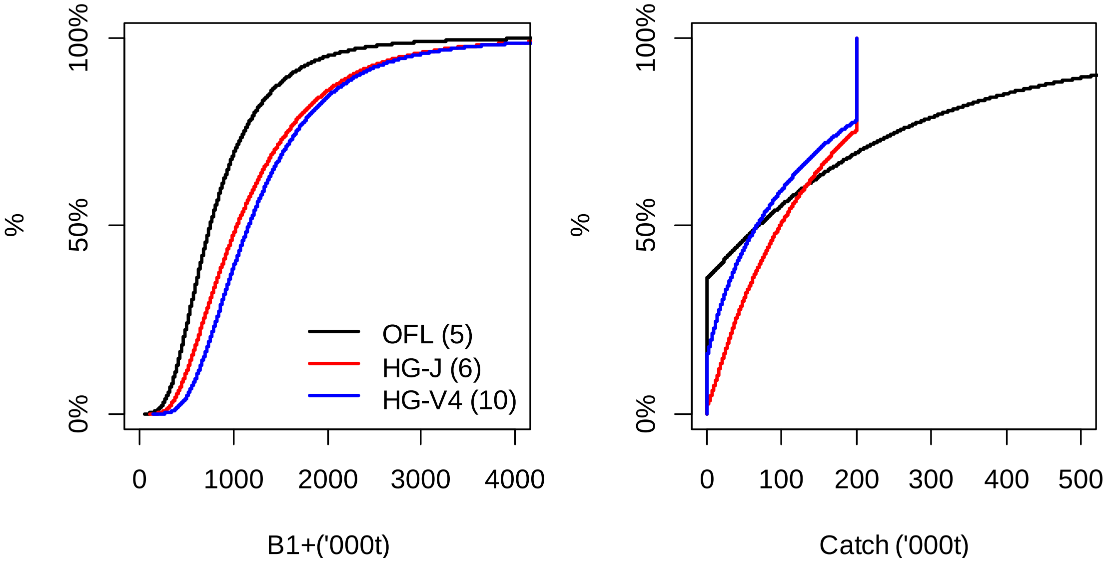

Figure 16. Cumulative distributions for mean biomass (1+) and mean catch for three harvest control variants.

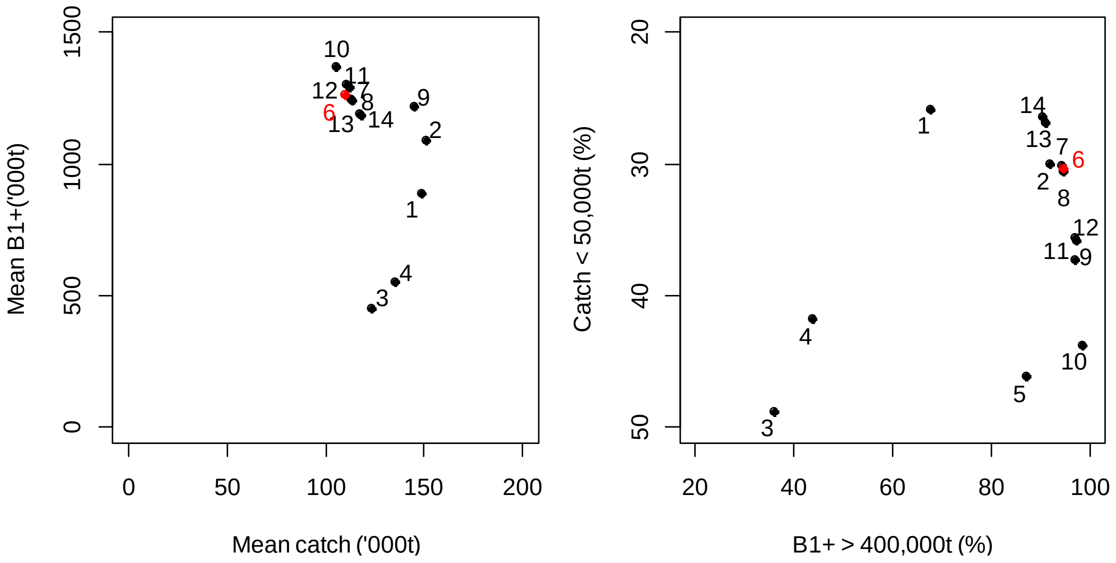

Figure 17. Trade-offs plots (mean annual catch when the catch is non-zero vs 1+ biomass [left]; and the probability of a catch < 50,000t vs. the probability of 1+ biomass exceeding 400,000t [right]) for the base-case scenario. The numbers denote the values used to refer to the harvest control rule variants in Table 1.

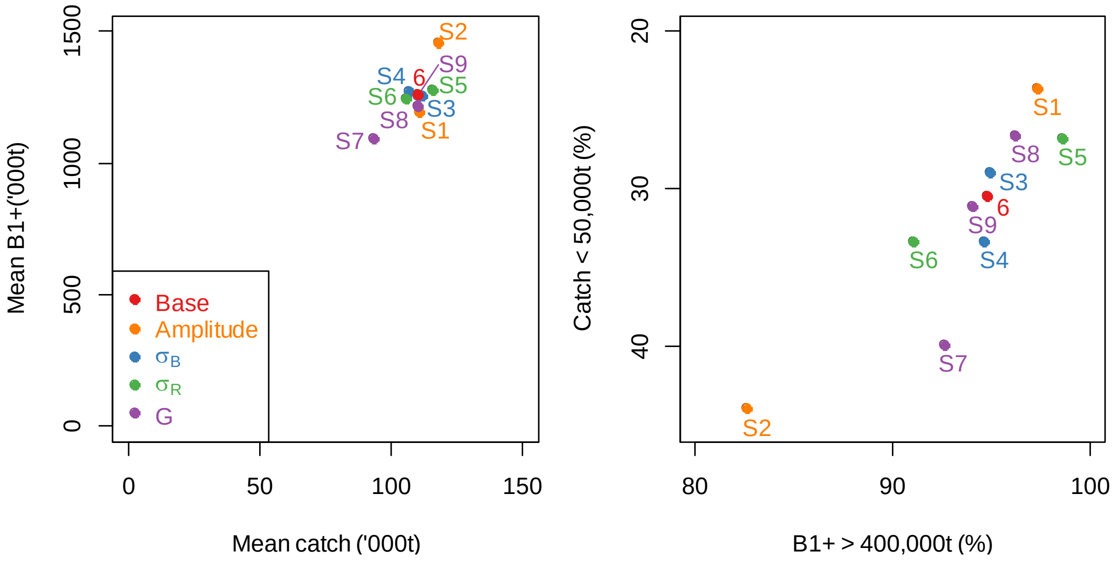

Figure 18. Trade-offs plots (mean annual catch when the catch is non-zero vs 1+ biomass [left]; and the probability of a catch < 50,000t vs. the probability of 1+ biomass exceeding 400,000t [right]) for the various selectivity scenarios. The numbers denote the values used to refer to the sensitivity scenarios in Table 6.

Appendix A. Revised Specifications for Calculations to Evaluate Control Rules for Pacific Sardine

1. Basic dynamics

The operating model is age-structured, and recruitment is related to an environmental covariate (or driven on the assumption that recruitment is cyclic). The basic population dynamics are governed by the equation:

$$N_{y+1,a}=\begin{cases} R_{y+1} & \text{if } a=0 \\ N_{y,a-1}e^{-M-S_{y,a-1}F_y} & \text{if } 1\le a<x \\ N_{y,x-1}e^{-M-S_{y,x-1}F_y}+N_{y,x}e^{-M-S_{y,x}F_y} & \text{if } a=x \end{cases} \tag{A.1}$$

where $N_{y,a}$ is the number of animals of age a at the start of year y, M is the rate of natural mortality (assumed to be 0.4yr^{-1} for consistency with the stock assessment[7]), $S_{y,a}$ is the selectivity of fishery on animals of age a during year y, F_y is the fully-selected fishing mortality during year y, and x is the maximum (plus-group) age.

Several fisheries (e.g. Ensenada, Southern California, Central California, Oregon, Washington, and Canada) operate on Pacific sardine. Rather than trying to model how the catch limit for the Pacific sardine fishery is allocated amongst those fisheries, selectivity-at-age is computed as a fishing mortality-weighted average selectivity from the most recent assessment (Table A.1).

Recruitment is governed by a stock-recruitment relationship with deviations which are autocorrelated and subject to a cyclic pattern.

$$R_y=f\left(SSB_y\right)e^{\varepsilon_y-\sigma_R^2/2} \tag{A.2a}$$

$$f\left(SSB_y\right)=SSB_y\exp\left(\alpha+\beta SSB_y+\phi V_y\right) \tag{A.2b}$$

$$\varepsilon_y=\rho_R\varepsilon_{y-1}+\sqrt{1-\rho_R^2}\eta_y \tag{A.2c}$$

$$\eta_y\sim N(0;\sigma_R^2); \tag{A.2d}$$

where $f(SSB_y)$ is the stock-recruitment relationship, α and β are the parameters of the stock-recruitment relationship (Table A.2), SSB_y is spawning stock biomass in year y (age 2+ biomass), σ_R^2 is the extent of variation about the stock-recruitment relationship due to unmodelled white-noise processes, ρ_R determines the extent of auto-correlation in the deviations about the stock-recruitment due to white noise processes, ϕ determines the extent of the link to the environmental variable, and V_y is the value of the environmental variable in future year y. V_y will be assumed to be cyclic and temporally auto-correlated, i.e.

$$V_y=\rho_V V_{y-1}+(1-\rho_V)G_y+\sqrt{1-\rho_V^2}\,\nu_y \tag{A.3a}$$

---

[7] Sensitivity should be conducted to this assumption in future work, but this requires rerunning the stock assessment and repeating the stock-recruitment analyses.

$$G_y = -\psi \frac{\sin(2\pi(y-\bar{y})/p)}{|\sin(2\pi(y-\bar{y})/p)|} \tag{A.3b}$$

$$\nu_y \sim N\left(0;\sigma_v^2\right) \tag{A.3c}$$

where ρ_V is the extent of auto-correlation in the environmental variable, ν_y is the deviation in the environmental variable about its expected value, G_y is the underlying signal in the environmental variable (Figure A.1), ψ is the amplitude of the underlying signal, $\bar{y}$ is a reference year, and *p* is the period of the wave.

The catch during (future) year *y* will be determined using the equation:

$$C_y = \sum_{a=0}^{x} \tfrac{w_{y,a+1/2} S_{y,a} F_y}{M + S_{y,a} F_y} N_{y,a} (1 - e^{-M - S_{y,a} F_y}) \tag{A.4}$$

where $w_{y,a+1/2}$ is weight-at-age in the middle of year *y*. The catch includes age-0 fish even through the HCRs are based on estimates of the biomass of fish of age 1 and older (see below).

The initial numbers-at-age will be taken from the 2012 stock assessment (Hill *et al.*, 2012; Model X6e), along with the values of the parameters determining fecundity-at-age and weight-at-age (Table A.3).

2. Potential control rules

2.1 OFL control rule

One possible OFL control rule is:

$$OFL_y = E_{MSY}\, \hat{B}_y^{1+} \tag{A.5a}$$

where B_y^{1+} is the estimate of 1+ biomass at the start of fishing season, and E_{MSY} is the proxy for F_{MSY}. Given the structure of Equation A.5a, here F_{MSY} is an exploitation rate, E_{MSY}, rather than a fishing mortality. This structure is consistent with the way the current OFL and HG control rules were developed (PFMC 199) and also avoids the need to generate estimates of the population age-structure at the start of year *y* (the error structure for which could be complicated).

Selection of a value for E_{MSY} in equation A.5a will be based on projecting the operating model forward for 20 replicates of 1000 years for a range of values for E_{MSY} assuming that B_y^{1+} is log-normally distributed about the true 1+ biomass. E_{MSY} will be computed for various choices for V_y to allow a relationship between F_{MSY} and V_y to be determined, i.e. :

$$OFL_y = E_{MSY}(I_y)\, \hat{B}_y^{1+} \tag{A.5b}$$

where I_y allows for error in the measuring the "true" value of the environmental variable[8], i.e. E_{MSY} would not be based on V_y but rather an estimate of V_y which is subject to error, i.e.:

---

[8] It is best not to think of SST or any other real-world measurement as being *V*. The real *V* is probably unmeasurable (it may be most related to some property of the flow of the California Current), and the best we can do is to use a proxy for it, such as SST. For that reason there is error associated with the connection between *V* and *I*.

$$I_y = V_y + \varsigma_y \; ; \; \varsigma_y \sim N(0, \sigma_\varsigma^2) \qquad \text{(A.6)}$$

where σ_ς determines the extent of measurement error.

2.2 Potential Harvest Guideline control rules

The general form of the harvest guideline (HG) control rule is:

$$HG_y = \text{DISTRIBUTION}\, x\, \text{FRACTION}_y (B_y^{1+} - \text{CUTOFF}) \qquad \text{(A.8)}$$

where HG_y is the harvest guideline for year *y*, DISTRIBUTION is the proportion of the stock in US waters, FRACTION$_y$ is the proportion of the stock above the cutoff which is taken in all fisheries during year *y*, and CUTOFF is the biomass level below which no directed fishing is permitted. Given that the purpose of this analysis is to analyse stockwide harvest, DISTRIBUTION will be set to 1 (except for one of the sensitivity runs). The value of harvest guideline is constrained to be less than the ABC (the OFL multiplied by a buffer based on a P* of 0.4, which consistent with the way the Council have selected the ABC for the 2012 and 2013 fisheries) and the maximum catch (MAXCAT). FRACTION will depend on the environmental variable for some of the variants.

3. Candidate analyses and performance measures

There are many factors (apart from the parameters of the OFL and HG control rules; Table 1) which could be varied to explore the robustness of candidate control rule variants. Note that the catch is always assumed to be at least 2,000t to cover catches in the live bait fishery. Table A.4 lists a range of factors along with reference values (in bold underline), and values which will be considered in tests of sensitivity. The performance measures will be:

- Average catch (abbreviation “Mean catch”)
- Standard deviation of catch (abbreviation “SD catch”)
- Mean biomass (SSB and 1+ biomass) (abbreviations “Mean B1+” and “Mean SSB”)
- Standard deviation (SSB and 1+ biomass) (abbreviations “SD B1+” and “SD SSB”)
- Percentage (1+) biomass > 400,000t (abbreviation “%B1+>400,000t”)
- Percentage of years with no catch (or catch below a threshold value) (abbreviations “% No catch” and “%Catch < 50,000t”)
- Median catch (abbreviation “Median catch”)
- Median biomass (SSB and 1+ biomass) (abbreviations “Median B1+” and “Median SSB”)
- Cumulative distribution for catch
- Cumulative distribution for biomass
- Average number of consecutive years with zero catch (abbreviation “Mean Yrs No Catch”)
- How often the HCR sets FRACTION to its minimum value (abbreviation “%HCR min”)
- How often the HCR sets FRACTION to its maximum value (abbreviation “%HCR max”)
- Average number of consecutive years FRACTION equals its minimum value (abbreviation “Mean Yrs HCR min”)
- Average number of consecutive years FRACTION equals its maximum value (abbreviation “Mean Yrs HCR max”)

- Mean age of the population (abbreviation “Mean Pop Age”)
- Mean age of the catch (abbreviation “Mean Catch Age”)

4. Sensitivity analyses

4.1 Multiple fleets

For this sensitivity test, the OFL and HG are computed based on a value for DISTRIBUTION of 0.87, the catch by Canada will be computed using the Pacific Northwest selectivity pattern and a fully-selected fishing mortality of 0.1y^{-1}, the catch by Mexico will be computed using the MexCal selectivity pattern and a fully-selected fishing mortality of 0.2yr^{-1}, i.e. the fully-selected fishing mortality for the US fishery is computed as:

$$C_y = \sum_{a=0}^{x} \frac{w_{y,a+1/2} S_{y,a} F_y}{Z_{y,a}} N_{y,a}(1-e^{-Z_{y,a}}) \tag{A.7}$$

where $Z_{y,a} = M + S_{y,a}F_y + S_a^{\text{MexCal}}0.2 + S_a^{\text{PNW}}0.1$

4.2 Time-varying selectivity

For this sensitivity test, the age-specific selectivity pattern is given by:

$$S_{y,a} = J_y S_{y,a}^{\text{MexCal}} + (1-J_y) S_a^{\text{PNW}} \tag{A.8a}$$

where $J_y = \max(0, \min(1, a + bV_y))$ and a and b are selected so that $J_{1985} = 0$ and $J_{2011} / (1-J_{2011})$ matches the ratio of the fully-selected *F*s for the MexCal area to the PNW. The selectivity-at-age for the MexCal fleet is:

$$S_{y,a}^{\text{MexCal}} = L_y S_a^{\text{MexCal-1}} + (1-L_y) S_a^{\text{MexCal-2}} \tag{A.8b}$$

where $L_y = \max(0, \min(1, c + dV_y))$ and c and d are selected so that $L_{1996} = 1$ and $L_{2006} = 0$. $S_a^{\text{MexCal-1}}$ is the *F*-weighted selectivity-at-age (between seasons) for the MexCal area for 1993-1999 and $S_a^{\text{MexCal-2}}$ is the *F*-weighted selectivity-at-age (between seasons) for the MexCal area for 2000-2011 (Table A.5).

4.3 Time-varying weight-at-age

The weight-at-age for year *y* is:

$$w_{y,a} = Q_y w_a^{1981-1993} + (1-Q_y) w_a^{2000-2011} \tag{A.9}$$

Where $Q_y = \max(0, \min(1, e + fV_y))$ and e and f are selected so that $Q_{1987} = 1$ and $Q_{2006} = 0$. The weight-at-age used when computing 1+ biomass for use in the HCR will be set to the average weight-at-age.

Table App.A.1. Fleet-average selectivity (computed using the output of model X6e of Hill *et al*. [2012]). Results are shown for 2011, 2007-2011, and 2002-2011.

Year Range	Age (yr)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2011	0.263	1.000	1.000	0.669	0.471	0.390	0.358	0.345	0.339	0.335	0.333	0.332	0.332	0.331	0.331	0.331
2007-11	0.245	0.962	1.000	0.713	0.539	0.468	0.440	0.428	0.423	0.420	0.418	0.417	0.417	0.417	0.416	0.416
2002-11	0.218	0.918	1.000	0.741	0.578	0.511	0.485	0.475	0.470	0.467	0.466	0.465	0.464	0.464	0.464	0.464

Table App.A.2. Parameter values for the recruitment model

Parameter	Value
α	-13.788
β	-0.001198
ϕ	1.076

Table App.A.3. Vector of weights-at-age

Year Range	Age (yr)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1981-90	0.014	0.081	0.134	0.160	0.172	0.177	0.179	0.179	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180
1991-2010	0.015	0.067	0.130	0.163	0.178	0.184	0.187	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188

Table App.A.4. Possible factors that could be varied during simulations to evaluate candidate OFL and HG control rules. The baseline values for the factors are indicated in bold-underline font. Analyses will be conducted for all combinations of factors. Values for sensitivity are indicated by square brackets

Factor	Values	Justification / reference
Recruitment variation, σ_R^*	0.5, **0.538**, 0.9	Hill *et al.* (2012) [base level]
Auto-correlation in recruitment deviations, ρ_R	**0.091**	Based on the objective 2a analyses of
Assessment SE(log), σ_B	[0.268], **0.36**, 0.5	0.268: Hill *et al.* (2012) 0.36: Ralston *et al.* (2011)
Auto-correlation in assessment error, ρ_B	**0.5**, 0.707	
Future correlation between M and V_y	**None** [0.4 yr^{-1} when $\Delta V>0$; 0.8 yr^{-1} when $\Delta V<0$]	Murphy (1966) [alternative]
Variance of the measurement error associated with the environmental index, σ_ς	**0.374**	Adjunct A
Nature of the environmental variable	**A. Square Wave with period of 60 years (equal periods of high and low values)** B. As for A but with unequal periods of high and low values C. [As for A but the reduction in V occurs gradually] D. [Sine wave with period of 60 years (equal periods of high and low values)] E. [As for A except the period is 100 years]	See Figure 1
Auto-correlation in the environmental variable, ρ_v	**0.337**	Adjunct B
Variance of the environmental variable about its expectation, σ_v	**0.477**	Adjunct B
Amplitude of the underlying environmental signal, ψ	**0.434**; [0.5 Best estimate; 2 Best estimate]	Adjunct B
Scaling parameter, ϕ	**1.076**	
Center of wave	**1975**	Hurtado-Ferro *et al*. (Primary Document 1)
Selectivity	**Set to average values** [Time-varying]	
Hyper-stability of biomass estimates	**None** $[\hat{B}_y^{1+} \propto (B_y^{1+})^{0.5}]$	

Table App.A.5. Selectivities-at-age for sensitivity analyses (computed using the output of model X6e of Hill *et al*. [2012]).

	Age (yr)															
Pattern	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$S^{MexCal-1}$	0.084	0.563	0.71	0.532	0.352	0.241	0.18	0.147	0.129	0.118	0.112	0.108	0.106	0.105	0.104	0.103
$S^{MexCal-2}$	0.145	0.683	0.59	0.303	0.151	0.09	0.066	0.056	0.051	0.048	0.047	0.046	0.045	0.045	0.045	0.044
S^{PNW} (2011)	0.001	0.076	0.371	0.683	0.852	0.924	0.954	0.967	0.974	0.977	0.98	0.981	0.982	0.982	0.982	0.983
S^{PNW} (2007-11)	0.001	0.076	0.371	0.683	0.852	0.924	0.954	0.967	0.974	0.977	0.98	0.981	0.982	0.982	0.982	0.983

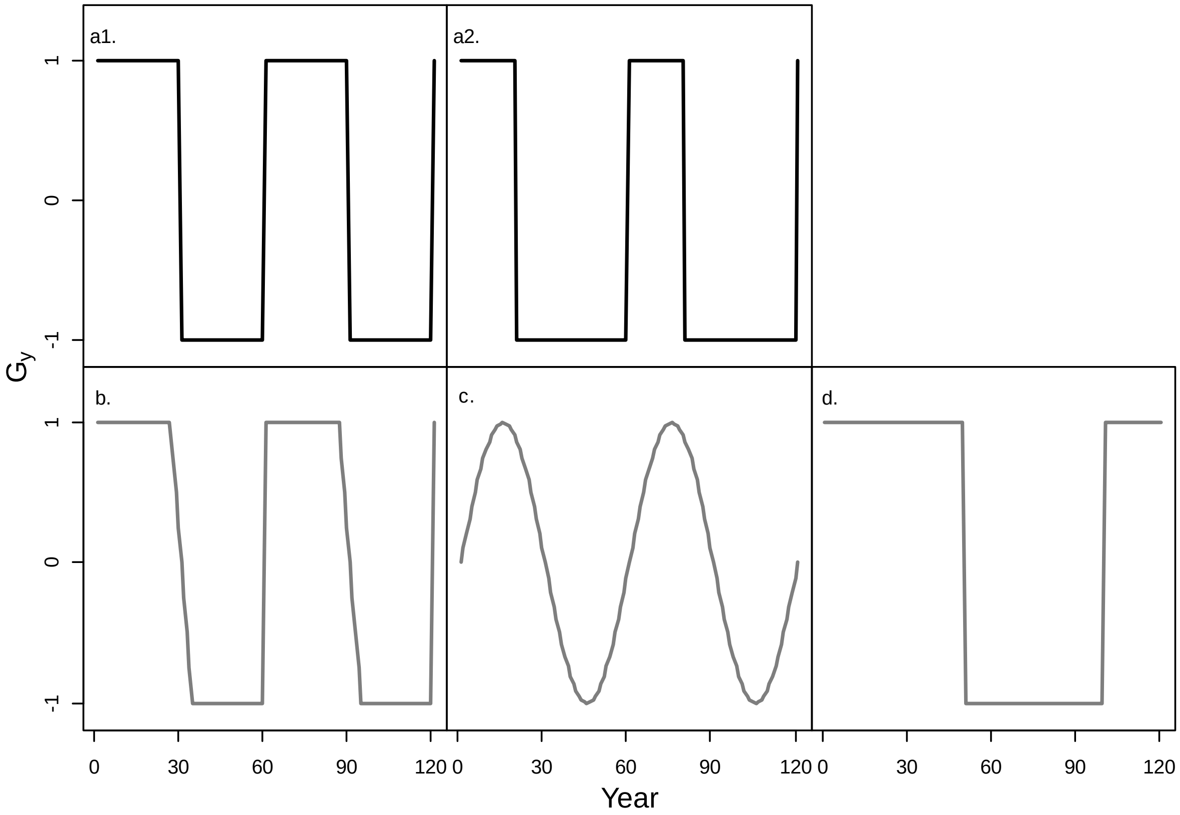

Figure App.A.1. Defined shapes for the environmental signal G_y. a1) and a2) are the base cases; b), c) and d) are sensitivity tests.

Appendix B. Update to fitting environmental data to the chosen model

The Pacific sardine harvest control rule parameters workshop decided that the values for the parameters of the environmental model in the sardine OM would be estimated by fitting it to the ERSST_ann data, since the ERSST_ann time-series is long and likely more reliable than the SST_CC_ann time series (which was used to fit the stock-recruitment relationship). The methods and parameter estimates are described in Adjunct B of Appendix J of PFMC (2013) for the analyses based on the ERSST_ann time series. However, ERSST_ann was not an ideal choice to model the environmental variable because (1) the biomass cycles observed in projections were not of the desired amplitude, with the lowest simulated biomasses being around 1,000,000 t in the absence of harvest; and (2) the OM unable to reproduce the observed SST data.

The parameters for the environmental variable were re-estimated by applying the methods described in Adjunct B of Appendix J of PFMC (2013) to the SST_CC_ann time series. The estimates of amplitude and σ_V based on the SST_CC_ann data are larger than those based on the ERSST_ann data, while the estimate of ρ_V is smaller. The revised parameter estimates are shown in Table App.B.1, while Table App.B.2 shows the results from the fit to the ERSST_ann data (repeated from Adjunct B for convenience). Figures App.A.1 and App.A.2 show the fits and residuals for the SST_CC_an data.

Using the parameter values in Table App.B.1 improves model performance in terms of the problems described above, but also introduces a new problem: the high value of σ_V. The SST_CC_an temperatures during 1957, 1958, 1959, 1963, and 1995 were high even though these years correspond to the ‘cold period’ (i.e. pre-1975). Three of these years (1957, 1965, and 1966) coincided with El Nino events, and removing these years could lead to an improved OM. The results removing the 3 El Nino outliers are shown in Table App.B.3, and Figures App.B.3 and App.B.4. The results removing all five unusual years are given in Table App.B.4, and Figures App.B.5 and App.B.6.

Table App.B.1. Estimated parameters and AIC for each model fit for SST_CC_ann data.

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.288	0.613	-	5.0
SQ with AC	0.293	0.601	0.214	5.1
Sin	0.340	0.626	-	6.9

Table App.B.2. Estimated parameters and AIC for each model fit for ERSST_ann data.

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.181	0.393	-	-64.4
SQ with AC	0.193	0.364	0.372	-74.6
Sin	0.222	0.404	-	-60

Table App.B.3. Parameters removing the thee El Nino years

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.353	0.582	-	0.500
SQ with AC	0.362	0.564	0.302	-0.312
Sin	0.449	0.592	-	1.959

Table App.B.4. Parameters removing all five unusual years

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.428	0.494	-	-12.832
SQ with AC	0.434	0.477	0.337	-13.744
Sin	0.592	0.488	-	-13.811

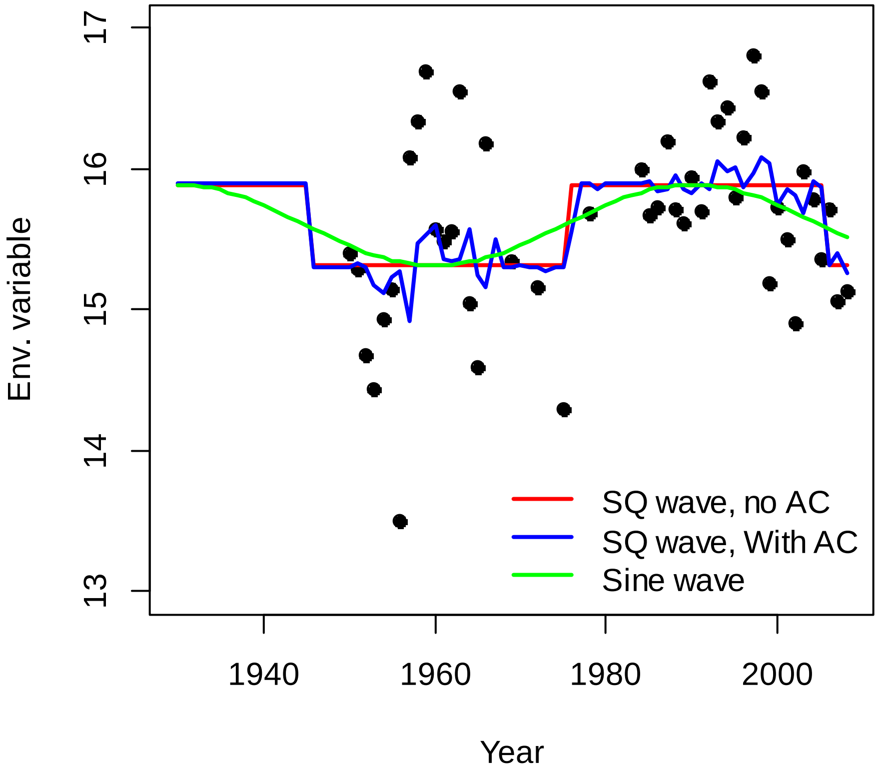

Figure App.B.1. Fits of each model to the SST_CC_ann data

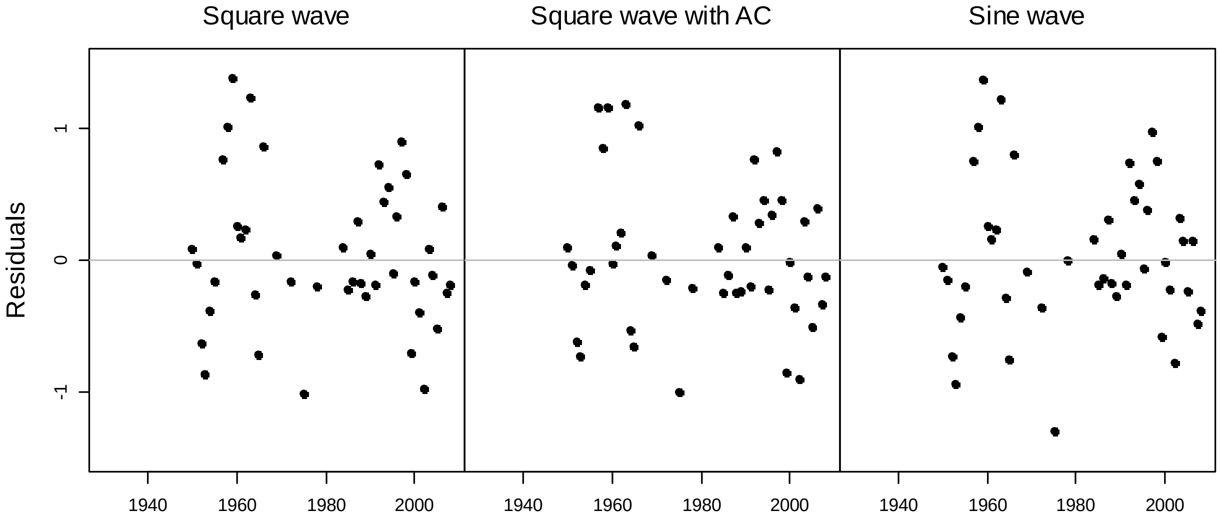

Figure App.B.2. Residual plot for the three models

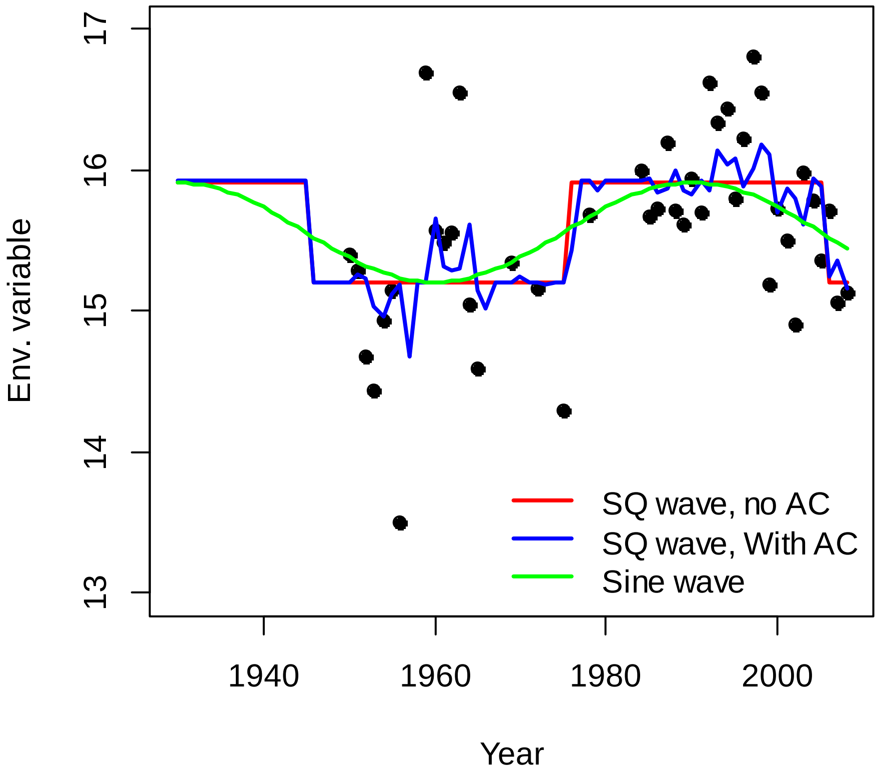

Figure App.B.3. Fits of each model to the SST_CC_ann data removing the three El Nino years

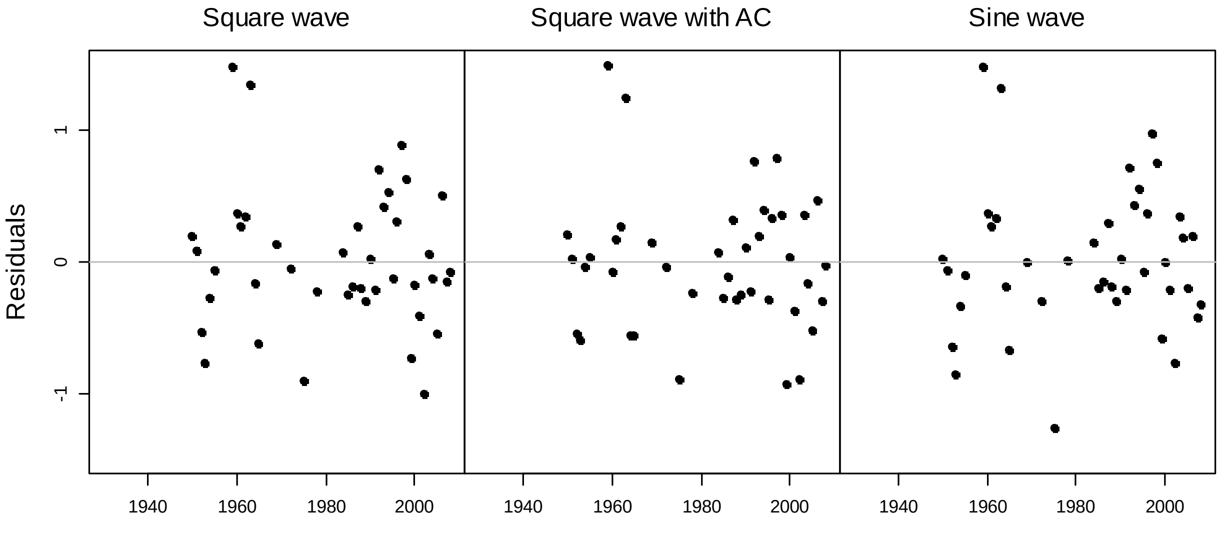

Figure App.B.4. Residual plot for the three models removing the three El Nino years

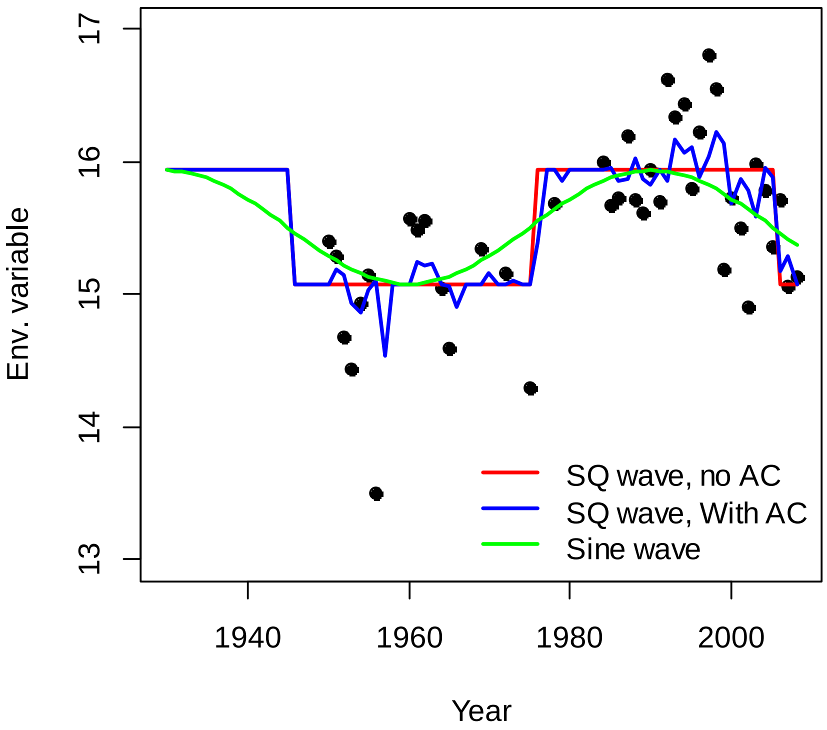

Figure App.B.5. Fits of each model to the SST_CC_ann data removing all five unusual years

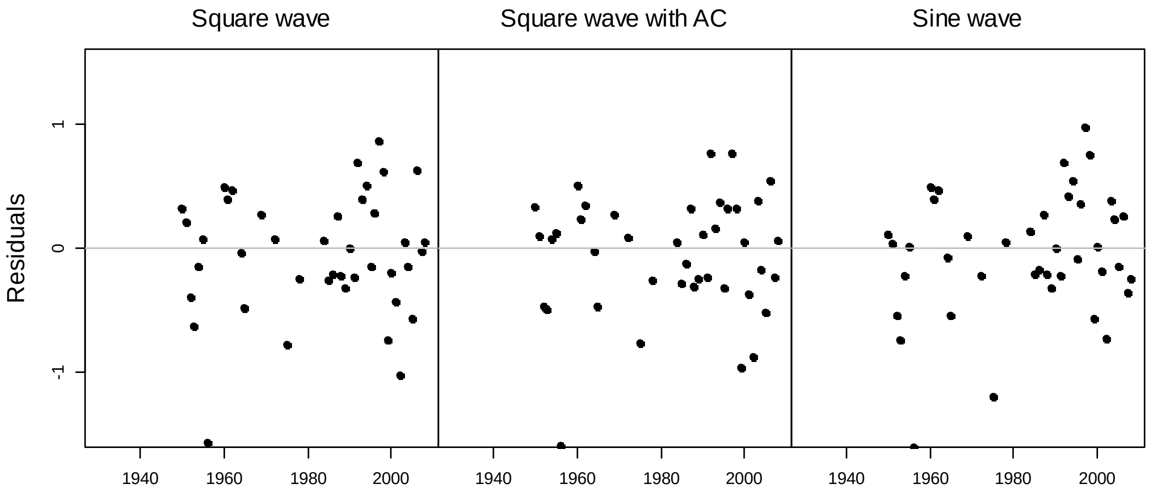

Figure App.B.6. Residual plot for the three models removing all five unusual years