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DRAFT Report of the Pacific Sardine Harvest Parameters Workshop

Pacific Fishery Management Council and the
Southwest Fisheries Science Center of the
National Oceanic and Atmospheric Administration

February 5-8, 2013

Scripps Institution of Oceanography
La Jolla, California

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1. OVERVIEW

A Workshop to examine possibilities to improve on management strategy concepts and elements currently in use for the Pacific sardine fishery in the Pacific Fishery Management Council (PFMC) process was held on Scripps Institution of Oceanography, during 5-8 February 2013. The participants (see Appendix A) included four members of the Scientific and Statistical Committee (SSC), representatives of the Coastal Pelagics Species (CPS) Advisory Subpanel, and representatives of the CPS Management Team, as well as scientists involved in identifying relationships between Pacific sardine productivity and environmental covariates, in quantifying the distribution of Pacific sardine, and in designing and implementing ecosystem models. The Panel generally followed the PFMC Terms of Reference for Stock Assessment Methodology Reviews.

Dr. André Punt, the Workshop Chair, called the meeting to order, and Kristen Koch (SWFSC) and Dr. Don McIsaac (PFMC) welcomed the participants. Dr. Punt then provided an overview of the aims of the Workshop and his understanding of Council expectations relative to each of the objectives. Extensive background materials, including a number of primary documents (Appendix B), were provided through an FTP site. Participants gave several presentations during the Workshop and responded to requests for additional information and analyses.

The Workshop had three objectives:

1. design a risk assessment projection model that can evaluate the current use of selected harvest control rule (HCR) parameters with regard to risk in jeopardizing long-term stock productivity, for potential Council decision making in 2013.
2. consider recommendations for:
    a. a new predictive relationship between recruitment success and environmental variables;
    b. a new estimate of the proportion of the stock that occurs in U.S. waters; and
3. prepare an initial plan for a full management strategy evaluation (MSE) for Council consideration in 2015.

Objectives 1 and 2 were the primary objectives for the Workshop, given the need to provide management advice using a selected HCR in November 2013. The Chair appointed rapporteurs for each objective (Objective 1: Dr. Alec MacCall; Objective 2a: Dr. Russ Vetter; Objective 2b, Mr. Josh Lindsay, Objective 3, Drs Brian Wells and Kevin Hill). Drs David Sampson and Tom Jagielo acted as coordinators for assembling conclusions and recommendations for future work. Sections 3, 4, 5 and 6 of this report outline the results of the detailed discussions related to each of objectives 2a, 2b, 1 and 3 respectively. Section 7 provides a summary of the major conclusions, while Section 8 outlines some key research recommendations.

In closing the Workshop, the Chair thanked the SWFSC for hosting the Workshop and the SWFSC staff (primarily Ms Jenny McDaniel), who provided logistical support to the Workshop, including updating the FTP site with presentations and documents throughout the meeting. The Chair also thanked the participants for the work they did prior to the Workshop in developing the background material and for the constructive way the discussions were conducted. He thanked the rapporteurs and specifically recognized the considerable effort made by Drs Larry Jacobson and Martin Lindegren, without whom it would not have been possible to draw definitive conclusions regarding an environmental variable for use in the harvest control rule (HCR) and the simulations to evaluate HCRs.

Alfred Lotka & Vito Volterra
(1880-1949) (1860-1940)

2. BACKGROUND

The harvest policy for Pacific sardine, *Sardinops sagax*, of the PFMC has been recognized as a forward thinking and innovative attempt to manage a highly dynamic coastal pelagic species, in part by incorporating an explicit recognition of the role of the environment in determining the productivity of the stock and allowable harvest rates through the incorporation of an environmental variable that varies the exploitation rate in the HCR (Jacobson and MacCall, 1995).

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.

The purpose of CUTOFF is to protect the stock when biomass is low. The purpose of FRACTION is to specify how much of the stock is available to the fishery when BIOMASS exceeds CUTOFF. The DISTRIBUTION term is in recognition that the stock ranges beyond U.S. waters and, therefore, is subject to foreign fisheries. In PFMC (1998), FRACTION is determined on the basis of a 3-year running average of the Scripps Pier sea surface temperature. The 3-year average is thought to capture a variety of oceanographic conditions that correlate with the abundance of new fish entering the fishery either through recruitment or migration into the stock. The averaged three years include the temperature conditions during the period leading up to spawning, the year of birth, and the next year of life prior to recruitment to the adult population.

In 2011, Amendment 13 to the CPS FMP was adopted to ensure that the FMP was consistent with advisory guidelines published at 50 CFR 600.310 with respect to a process for setting Annual Catch Limits (ACLs) and accountability measures (AMs). The formulae established by Amendment 13 for Pacific sardine are:

OFL	BIOMASS * F_{MSY} * DISTRIBUTION
ABC	BIOMASS * BUFFER * F_{MSY} * DISTRIBUTION
ACL	LESS THAN OR EQUAL TO ABC
HG	(BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION
ACT	EQUAL TO HG OR ACL, WHICHEVER VALUE IS LESS

The overfishing limit (OFL) is an annual catch amount that corresponds to the estimate of (annual) fishing mortality corresponding to maximum sustainable yield (MSY). For Pacific sardine, the OFL is based on a MSY proxy harvest rate, determined by the best available scientific information, applied to the best available estimate of 1+ biomass. Additionally, because a portion of the sardine population is in foreign waters, the OFL is adjusted using a parameter DISTRIBUTION which approximates the percentage of the population in the U.S. EEZ, as a way to constrain US harvest to an appropriate level, given the lack of international agreements on sardine harvests. The Acceptable Biological Catch (ABC) is a harvest specification set below the OFL that incorporates a scientific uncertainty buffer against overfishing (i.e., exceeding the OFL). An ACL is the level of annual catch of a population or population complex that is set to help prevent overfishing from occurring. The Pacific sardine fishery is managed to keep the total catch from all US sources below the ACL. ACLs are set no higher than the ABC, and the harvest guideline (HG) cannot exceed the ACL or the ABC. In cases where the result of the HG formula exceeds the ABC, the Council will set a lower ACL, HG, or Annual Catch Target (ACT) in response. Along with optimum yield (OY) considerations (which account for any relevant economic, social, or ecological factors, in providing the greatest overall benefit to the Nation), an HG or ACT may be utilized below an ACL to account for management uncertainty, discard or bycatch mortality and research take. These provisions are considered on an annual basis in response to changing resource status and fishery dynamics. Management measures since the implementation of Amendment 8 have led to total exploitation rates (over the U.S., Canada and Mexico) between 0.1 and 0.13.

Recently McClatchie *et al*. (2010) called into question the original relationship between Scripps Pier temperature and productivity proposed by Jacobson and MacCall (1995). This was a main driver for this workshop.

3. PREDICTIVE RELATIONSHIP BETWEEN RECRUITMENT SUCCESS AND ENVIRONMENTAL VARIABLES

The presentations and discussions under this item considered the following questions:

1. Is there still a relationship between the Scripps Pier temperature and sardine recruitment strength?
2. Are there better environmental relationships?
3. Are there better statistical formulations of the relationships between environmental time series and estimates of recruitment, and recruits-per-spawner?

Dr. Larry Jacobson provided the Workshop with an overview of the history and thinking that went into the original Jacobson and MacCall (1995) paper that formed the basis for it's inclusion into the Amendment 8 formulation of the HCR. Murphy and others had previously identified the Scripps pier temperature as a likely candidate for an environmental index. The recruits were identified as age-2 and spawning stock biomass was identified as age-2+ biomass. The 3-year average considers the year before birth and the two years after (assumed) birth on July 1. The basis of the analysis was Generalized Additive Models (GAMs) fits to log-recruitment and log-recruitment success (recruitment / spawning biomass) data using spawning biomass and sea surface temperature (SST) as predictors. Models for log-recruitment are most important for sardine but results for recruitment success were presented as well. Dr. Jacobson noted that spawning biomass and the Scripps Pier SST were approximately equally important in explaining recruitment. Dr. Jacobson also highlighted that environmental variables could be used both for tactical (i.e. assessment) purposes as well as evaluating harvest policies (strategic purposes).

In discussion, it was noted that ‘season’ for the analyses of Jacobson and MacCall (1995) was July 1 – June 30, and that spawning stock biomass was taken to be 2+ because the early VPA analyses only started at age-2 because few fish of ages 0 and 1 were caught in the historical fishery.

3.1 Presentation of alternative relationships

Dr. Sam McClatchie and his colleagues examined the time series of temperatures that have been used in modeling the relationship between sardine recruitment and temperature. Comparisons were made before applying any moving averages to the series (i.e., before creating 3-year or 5-

year averages). The temperature time series compared were: (a) Scripps (SIO) pier, (b) the NOAA Extended reconstructed sea surface temperature (ERSST) version 3b, and (c) the 5 to 15 m depth-averaged annual and spring California Cooperative Oceanic Fisheries Investigations (CalCOFI) temperatures. In addition they used modeling of advection and likely drift of sardine larvae and juveniles to determine whether recruitment was likely to occur where these temperature time series were measured. They found that the CalCOFI data for 1980, 1981, 1982, and 1983 were insufficiently sampled to be representative of the mean CalCOFI temperatures. Consequently, they recommended that these values should not be included in the modeling. Apart from these early years, they found that the ERSST ver.3b and the annual CalCOFI mean temperatures were comparable, and that the exact choice of ERSST grids in the CalCOFI region was not important. Modeling of the larval and juvenile drift from spawning in April until the end of September in three years with very different recruitment (2002 weak, 2003 strong, 2007 medium) showed that larvae and juveniles are likely to be advected far offshore and then southward into Mexican waters. This drift pattern was supported by drifter tracks. The modeled drift trajectories included the effect of ontogenetic development of vertical migration behavior. One caveat was that directed horizontal swimming by juveniles older than 50 days was not considered, and the effect of this is currently unknown, although various scenarios could be modeled to test the magnitude of the effect of horizontal swimming. Dr. McClatchie and his colleagues concluded that recruitment is likely to occur outside the region where the temperature time series are measured, and that Baja California ERSST time series should be considered as an index in the temperature-recruitment relationship.

In discussion, it was noted that the Scripps pier and satellite measurements are always on the warm side, and that it might be appropriate in future to use a temperature that is consistent with the habitat models in case the DISTRIBUTION parameter is based on such models.

Lindegren and Checkley (In press) showed that mean annual SST (5-15-m depth) averaged over the present (CalCOFI) area is a better predictor of recruitment than the 3-year running mean of SST at the Scripps pier and explains a significant degree of variability in recruitment and recruitment success. However, the temperature-recruitment relationship should be updated and revised when necessary, to provide the best available science for management

The Workshop noted that environmental data are available for years for which no recruitment and spawning stock biomass data are available (~1964-1980). However, it is known that biomass and recruitment were low during these years. It **agreed** that any relationship between temperature and recruitment should be tested using the data for these years (see Section 3.2 for results). The Workshop also noted that the available data on recruitment and spawning stock biomass came from four assessments (Murphy [1966], MacCall [1979], Hill *et al.* [2010], and Hill *et al* [2012]). The scales from each of these assessments are not identical and the Workshop therefore **recommended** that the next (2014) assessment consider (perhaps as a sensitivity test), a model which includes the entire period 1930-present.

3.2 Selection of a relationship

The Workshop initially discussed the most appropriate way to explore whether there is a relationship between the environment and recruitment. McClatchie *et al.* (2010) fitted a model between recruitment and spawning stock biomass and then regressed the residuals on environmental variables, whereas Jacobson and MacCall (1995) and Lindegren and Checkley (In press) fitted both spawning stock biomass and the environmental variable in a single analysis. The Workshop **agreed** that the latter approach was more appropriate statistically, and all of the analyses conducted during the Workshop used this approach.

The Workshop **agreed** that to maximize consistency among analyses, and for comparability with the risk analysis model, recruitment would be defined as age-0 abundance and spawning stock biomass as age-2+ biomass. Appendix C outlines how the results from the various assessments were used to construct the data on recruitment and age-2+ biomass for subsequent analysis. Recruits were defined as at June 1 to ensure comparability among assessments. In addition, only recruitment and age-2 biomass until 2008 were included in the analyses because recent estimates of recruitment are imprecise. Appendix C also includes the approach used to reconstruct the recruitment and spawning stock biomass values for 1965-1980 used in the analyses to test the predictive performance of any resulting relationship.

Table 1 lists the variables characterising local physical conditions, as well as regional ocean-atmospheric forcing considered as potential environmental variables. These variables were: (a) the SST measured daily at the SIO pier, (b) the averaged SST (NOAA_ERSST_V3; Smith *et al.*, 2008) for the four offshore grid squares used by McClatchie *et al.* (2010), (c) the mean 5-15m temperature (here also termed SST) from the regular CalCOFI area (i.e., averaged over all stations from line 76.7 to 93.3), which covers a large part of the southern California Bight, (d) the Pacific Decadal Oscillation (PDO), and (e) the Multivariate El Niño Southern Oscillation Index (MEI). The PDO and MEI are respectively proxies for SST variation across the North and Tropical Pacific. The following lags were considered to represent potential effects of temperature at different time periods: (i) the calendar year mean (abbreviated ann) by averaging monthly means from January to December; (ii) the fishing season mean (T) by averaging monthly means from July to June (in the following calendar year); (iii) a 3-year fishing season mean (T3) by averaging over the year of recruitment and the two years preceding recruitment; (iv) a 5-year fishing season mean (T5) by averaging from the two years preceding recruitment until two years after recruitment. In addition, three subsets of the data were considered during fitting (i.e., due to missing values) consisting of (i) the entire data set, (ii) a data set with all years with missing values for any of the variables removed and (iii) a subset including only 1984-2008, i.e., the years with standardized sampling of CalCOFI SST. The full set of indices is listed as Appendix D, with a spreadsheet which shows how the series were developed available from the PFMC offices.

Generalized Additive Models (GAMs; Hastie and Tibshirani, 1990; Wood 2006) were used to examine the relationship between sardine recruitment, age 2+ biomass (denoted here as SSB) and the set of temperature-related variables. The following linearized formulations with log-transformed recruitment (*R*) and recruitment success (*R*/*S*) estimates as responses were used:

$$\ln(\mathrm{R})_{\mathrm{t}} = a + s(\mathrm{SSB}_{\mathrm{t}}) + s(\mathrm{V}_{\mathrm{t}}) + \varepsilon$$

$$\ln(\mathrm{R/S})_{\mathrm{t}} = a + s(\mathrm{SSB}_{\mathrm{t}}) + s(\mathrm{V}_{\mathrm{t}}) + \varepsilon$$

where a is the intercept, s is a thin plate smoothing function (Wood, 2004), V is a potential predictor variable, and ε is the error term. Although the number of regression splines is optimized (and penalized) by the generalized cross validation criterion (GCV; Wood, 2004), the degrees of freedom of the spline smoother function (s) was further constrained to three knots (k=3) to allow for potential nonlinearities, but also to restrict flexibility during model fitting. Model selection was based on the AIC, deviance explained (DEV) and partial *F*-tests. In addition, an out-of-sample cross validation analysis was conducted by fitting the final set of models after sequentially omitting each single observation. The accuracy of each candidate model in predicting new data was evaluated using cross-validation (Picard and Cook, 1984). In testing, one recruitment observation was omitted at a time, the model was fit to the remaining data, and then used to predict the omitted recruitment observation. Predicted log-recruitment from the original model fit to all of the data and for the omitted observations were compared using correlation and R^2 statistics. Reliable models should have relatively high correlations and similar R^2 statistics.

Most stock-recruitment models were significantly better when they included an environmental variable (Appendix E), although the actual choice of variable differed when fitted to the entire data sets or selected subsets thereof. ERSST_T5 (i.e., a five-year running mean starting and ending two years before and after the recruitment event) was the most significant variable for recruitment and recruitment success for the entire data set, including output from three stock assessments (i.e., Murphy, 1966; MacCall, 1979; Hill e*t al*., 2010) (Table 2, Figures 1,2). ERSST_T5 and SIO_SST_T5 were the most significant variables for recruitment and recruitment success, respectively when missing data were excluded, i.e., to account for differences in the number of observations used during fitting (Table 2, Figures 1-2). However, mean annual CalCOFI SST was the most significant covariate for both recruitment and recruitment success when the models were fit to observations from 1984 to 2008 only, i.e., the recent period with consistent availability and sampling of environmental variables (i.e., primarily CalCOFI), as well as use of consistent stock assessment output (Hill *et al*., 2010) (Table 2, Figures 1-2). Residual diagnostics for the key models are shown in Appendix F.

The best log-recruitment model will be used to predict recruitment on the original arithmetic scale. It is therefore important to depict predicted recruitment and uncertainty in arithmetic scale recruitment as well as in the log scale used when fitting the model. Predicted arithmetic scale recruitment in each year (R_y) was calculated as:

$$R_y = e^{\widehat{lnR_y}+0.5\sigma^2}$$

where $\widehat{lnR_y}$ is a predicted value from the model, σ^2 is the variance of the residuals, and $e^{0.5\sigma^2}$ removes the bias due to the log transformation. Log-recruitment depends on both SSB and SST. Predicted recruitment was therefore calculated over the range of observed biomass levels assuming median SST (15.73°C - from the data used to fit the model) and over the range of observed SST given median spawning biomass (670 thousand t). Upper and lower 95% confidence interval bounds, $R_y e^{\pm 1.96\varepsilon_y}$ [1], were calculated from the standard errors for the log scale predicted values $\widehat{lnR_y}$.

The Workshop **agreed** with a suggestion from the analysts that mean annual CalCOFI SST (see Appendix G for how this index is computed) was the most significant variable for both recruitment and recruitment success during the period with standardized sampling design (spatial and temporal resolution) as well as consistent stock assessment estimates of recruitment and spawning biomass (Hill *et al*., 2010). Both models based on CalCOFI SST predict new data well (Table 2). Although, 1984-2008 is a subset of the available data, the functional forms of the SSB and SST relationships are consistent with those from previous studies (Jacobson and MacCall, 1995; Lindegren and Checkley, in press). The Workshop therefore **recommended** that this variable be used in future modeling work and that any relationship between FRACTION and an environmental variable be based on CalCOFI SST. The Workshop **agreed** that the results of this work further illustrated the usefulness and importance of continuing long-term monitoring efforts in general, and the CalCOFI program in particular.

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[1] The confidence intervals may be slightly too narrow because reductions in degrees of freedom due to estimating parameters may not have been fully accounted for.

The model predictions indicate that the model based on CalCOFI SST imply a strongly domed relationship between recruitment and spawning biomass (Figure 3) and an exponential relationship between recruitment and SSB (Figures 4, 5). The dome shape is not strongly supported by observations (i.e., two data points above 1.2 million t). Given uncertainty regarding the right hand side of the Figure 3, the Workshop **agreed** that sensitivity in the risk analysis model would be explored to both dome-shaped and asymptotic selectivity. Appendix H provides parametric approximations (domed and asymptotic) for the best GAM log-recruitment model, which may be useful for simulations in the MSE analyses. As in Jacobson and MacCall (1995), the best model indicates that recruitment will be very low at all spawning biomass levels if water temperatures are cold (Figure 4). The 95% confidence intervals for recruitment (Figures 2-3) may exaggerate uncertainty to some extent because they are not constrained by the data and population dynamics assumptions in the original assessment model. The trend in estimated recruitments from SS3 is likely robust so recruitment data and predicted recruitment values would not vary within their confidence intervals independently[2]. Rather, the data and predicted recruitment estimates would likely all vary in the same direction and to the same relative extent so that the shape of the predicted curve would be unchanged.

Recruitment estimates were hindcasted from 1950 to 1980 based on the observed SSB from 1950 to 1963 (MacCall, 1979), and SSB from 1964-1980 assuming a minimum level of 10,000 t to validate the predictive abilities of the final model during low SST conditions (data that were not included during model fitting). Since CalCOFI SST records are scattered and there are missing values between 1950 to 1984, a linear relationship between CalCOFI SST and the long-term SST records from the SIO pier were used to extend the CalCOFI SST time series back to 1950. The predicted recruitment estimates were compared with the observed values from 1950 to 1963 (MacCall, 1979) and to recruitment estimates from 1964-1980, assuming a level equal to replacement based on SSB at 10 kT (Appendix C). This validation exercise demonstrated that recruitment seems to be overestimated during the period of low SST from the mid-1960s onwards when forced by the SST proxy derived from the SIO pier (Figure 6). This is likely due to the linear relationship between CalCOFI and SIO pier SST overestimating temperatures at lower SSTs. However, the predicted recruitment estimates are in line with the low recruitment levels observed and assumed during the period if the available CalCOFI SST measurements, smoothed using a 5-year average to account for missing values, are used (Figure 6). Hence, the linear recruitment-SST relationship derived from fitting on data from 1984-2008 seems to hold even at lower temperatures outside the range used for fitting.

The analysts (Jacobsson and Lindegren) noted that the use of an annual average encompassing the environmental conditions experienced in the main spawning area by the adults prior to spawning, as well egg, larvae and juveniles, makes ecological sense and corresponds to theory regarding the importance of environmental effects during the critical early-life stages. Furthermore, an annual average has a far more practical application in terms of short-term recruitment predictions, compared to a 5-year mean based on data not yet collected. However, it was noted that basing management on annual SST may lead to large variation in Harvest Guidelines from one year to the next. They also noted that the CalCOFI program provides a spatially- and temporally-coherent collection of ecosystem data, including multiple abiotic and biotic variables, which will be of value for further research on sardine recruitment.

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[2] Ideally, this should be confirmed by, example, adding the CalCOFI index into the assessment as an index of recruitment.

In discussion, it was noted that although modeled (global) data products (e.g., ERSST, Hadley) may well represent the long-term trends over larger areas, using actual observations in a geographically restricted area (CalCOFI) likely better represents the inter-annual variability (i.e., modeled data are often interpolated and therefore smoothed) needed to understand recruitment processes. In addition, using observations rather than model output is faster due to the time lag needed for model updating. Finally, climate model output is not better than the underlying observations used to validate it.

The Workshop requested that the analysts investigate curl-driven upwelling as a potential covariate to explain recruitment variability (Rykaczewski and Checkley, 2008). Although this covariate was statistically significant, the AIC was higher than the final model based on CalCOFI SST for both recruitment and recruitment success (Appendix I).

The Workshop noted that several new indices are under development (see Section 6.4 below) and **recommended** that the Council consider developing procedures which allow relatively a regular (every 5-7 years perhaps) evaluation of whether the selected environmental variable remains the best predictor of recruitment success.

4. PROPORTION OF THE SARDINE STOCK IN U.S. WATERS

Under Amendment 8 to the CPS FMP, the U.S. ABC/ HG for Pacific sardine is prorated by an “estimate of the portion of the stock resident in U.S. waters”. This is accomplished through the DISTRIBUTION parameter in the HG control rule, and was originally set at 87%. This is the default approach laid out in the FMP to account for the fact that some level of the sardine stock exists outside of US waters and can therefore be subject to foreign fisheries in the absence of an international agreement on the management of the resource. It was noted that the MSA does not mandate a harvest reduction to account for international fisheries. For stocks for which there is not an international agreement in place (a distinction between, for example, tuna and sardine), in the event that the stock becomes "...overfished, or is approaching a condition approaching a condition of being overfished due to excessive international fishing pressure, ...then the Secretary and/or the appropriate Council shall take certain actions..." This includes the Secretary or appropriate Council developing recommendations to end overfishing and rebuild the stock taking into account the relative impacts of the U.S. fishery. For the case of sardine, this would likely look something like what is being done with the DISTRIBUTION parameter.

Initial discussions during the Workshop focused on the difficulties inherent in the definition of the DISTRIBUTION parameter, including whether its value is time-invariant. This is because the proportion of Pacific sardine, like all CPS stocks, in U.S. waters varies seasonally and annually, and is affected by several variables. It has been hypothesized that the amount of seasonal movement by Pacific sardine depends on environmental conditions (warm water encourages movement to the north), biomass levels (such as northern feeding migrations when biomass is high), and age composition (large old fish tend to move farther north). There will be times when all of the stock is in U.S. waters and times when this proportion is much less. This was also identified in Amendment 8 as one of the disadvantages of using a single number to account for the transboundary nature of sardine: “The most serious disadvantage in prorating ABC for the stock in U.S. waters is that the portion of each stock in U.S. waters has to be estimated” (PFMC, 1998).

The definition of DISTRIBUTION and its estimation is tightly linked to sardine stock structure. The Workshop was advised that new research is underway to provide a better way to delineate the catches which can be attributed to the northern subpopulation of Pacific sardine (e.g., Demer *et al.*, submitted). However, the Workshop did not review this new research in the time available. It **supported** this type of research and **encouraged** refinement of the catch series (e.g., removing Ensenada catches) to be used in the stock assessment. A new approach for constructing a catch series for Pacific sardine could be considered during the next full assessment scheduled for 2014.

The Workshop note that the current 87% was based on an examination of CalCOFI data from 1951-1985 and aerial spotter data from 1962-1992, and that the distribution of the stock had changed markedly since then. It therefore **agreed** that any new basis for defining DISTRIBUTION should focus on data from the most recent decade or at the most, the last two decades.

Dr. David Demer provided an overview of Demer and Zwolinski (2013) [Primary Document 4], which used sardine biomass estimated from the 2012 assessment, annual landings at Mexico, the U.S., and Canada from 1993 to 2011, and the OFL and HG control rules to determine the annual upper and lower limits of the DISTRIBUTION parameter in the harvest guideline equations. Dr. Demer considered that between these limits, all values for DISTRIBUTION are valid within the harvest control rules; and selection of a value for DISTRIBUTION within that range is a policy choice. During 1993 to 2011, the annual mid-range DISTRIBUTION peaked in the 2000s and has since declined to period-low levels. The mean mid-range DISTRIBUTION was 52 or 59%, depending on the allocation of the landings to the northern subpopulation. The latter value, 59%, equals the full-year average value for DISTRIBUTION estimated from winter and spring fish egg and larvae data (ca. 1951-1985) and summer and fall aerial spotter data (ca. 1963-1992) (PFMC, 2011).

Dr. Demer also noted that prior year landings from Mexico and Canada could be used in conjunction with any or each of the harvest control rules, under assumptions in the CPS FMP to forecast annual estimates of DISTRIBUTION. He noted that this method for estimating and forecasting DISTRIBUTION breaks down when the harvest for the U.S. fishery in a given year does not depend ultimately on the biomass in U.S. waters.

The main concern with the approach in Demer and Zwolinski (2013) outlined by several participants is that catches only provide accurate measures of the relative proportion of a stock spatially when fishing mortality is spatially homogeneous. This assumption is unlikely to be valid for Pacific sardine because there are different management systems (catches are constrained in different ways in each country) and fleets in the three countries which exploit the stock. The Ensenada landings are likely a poor representation of the biomass of the northern subpopulation during the first semester, since the adult biomass generally moves offshore out of the range of the fishing fleet with the increase of coastal upwelling in March-April, so that the catch at the peak of upwelling may comprise only young of the year that remain available to in near coastal waters (T. Baumgartner, pers. comm). Dr. Tim Baumgartner and others also noted that most of the Ensenada catch, now assumed to be “northern” stock, in likely is from the southern stock. The value of DISTRIBUTION from the Demer and Zwolinski (2013) method was as high as 89% when the Ensenada catches were ignored.

The Workshop then considered all of the available data which might provide more direct information on the portion of the northern stock in U.S. waters. Dr. André Punt stated that the ideal way to characterize the distribution of the northern subpopulation was to conduct multiple surveys across the entire range multiple times a year, but such information was unavailable. A DISTRIBUTION breakout group was formed and charged with the task of identifying additional available data sources and approaches that could be used to estimate values for the proportion of the stock that occurs in U.S. waters.

Some participants of the breakout group supported the approach proposed by Demer and Zwolinski (2013), citing the advantages of its simplicity and readily available data for implementation. Although Demer and Zwolinski (2013) did not attempt to accurately estimate the proportion of the northern stock in U.S. waters, others were concerned about potential bias due to spatial and temporal heterogeneity of fishing mortality rates other participants were concerned about potential bias due to spatial and temporal heterogeneity of fishing mortality rates and the potential precedent of allocating catches based on international catches rather than biology. Also, a suggestion was put forward to consider using Demer and Zwolinski's method, but do so on smaller than annual time intervals.

Multiple participants proposed that models of the dynamic distribution of Pacific sardine habitat could be used to estimate the proportion of the stock that occurs in U.S. waters. Sardine habitat models are described in Zwolinski *et al*. (2011), Felix-Uraga *et al*. (2004), Kaplan *et al* (2012), and Ishimura *et al.* (2010) while other models are under development or available but not published (R. Parrish, T. Baumgartner, E. Curchitser, pers. comm). It was recognized that these habitat models could provide information about the seasonal distribution of potential habitat, but not sardine biomass. A suggestion was made that the presence of sardine within the potential habitat could be validated using catch and fishery-independent information (e.g., Zwolinski *et al*., 2012). Some fishery-independent data sources include the NMFS acoustic-trawl-method surveys (e.g., Zwolinski *et al*. 2012), the Canadian trawl surveys (e.g., CSAS, 2011), and aerial surveys (Jagielo *et al*., 2012). It was also recognized, that: 1) large area surveys occur infrequently, 2) fisheries operate in limited regions, and 3) potential habitat models indicate where sardine potentially could occur, but they do not indicate where, within the potential habitat, sardine may actually be at a given time. Dr. Richard Parrish noted that he developed a model which deals explicitly with Pacific sardine distribution and temperature relationships (see Section 6.4).

The breakout group also discussed: 1) intra-annual or annual estimates of DISTRIBUTION versus a constant value, 2) focusing on data from recent years (e.g., since 1990) in analyses to estimate the proportion of the stock that occurs in U.S. waters, 3) maintaining consistency in attributes of harvest guideline and stock assessment parameters, 4) integrating across all seasons when estimating DISTRIBUTION annually or for longer periods, and 5) considering two stocks of sardine in U.S. waters (Smith, 2005; Felix-Uraga *et al*., 2004; Demer et al., submitted; Demer and Zwolinski, 2013a,b [Primary Documents 4 and 6]).

The Workshop thanked the breakout group and agreed that synthesis and further evaluation of existing data was an important step in evaluating whether the DISTRIBUTION parameter should be revised.

5. PREPARATIONS FOR AN INITIAL MANAGEMENT STRATEGY EVALUATION

5.1 General Issues

The Workshop received informal guidance that the Council would prefer to see analyses which focus on management policies that are generally congruent with the range of parameter values considered in the Amendment 8 analysis, rather than an extensive exploration of permutations on which the Council had not yet had the opportunity to provide guidance. It was also clarified that the simulation results will not be used for a reconsideration of the threshold abundance used to define an overfished condition. This poses a potential conflict. Risk evaluation requires introducing components to the operating model that were not included in Amendment 8. However, because of the short time frame for a report to the Council, it is necessary to restrict new model specifications to those that are immediately feasible, while more difficult (but likely not unimportant) issues are assigned to future work, with no explicit commitment that the further work will be conducted. It must be emphasized that the proposed modeling and analysis will therefore not include all suspected and plausible sources of risk. An example is the model's lack of a spatial structure that accounts for environmental (temperature, El Niño) and demographic (abundance, age structure) influences on fish growth, distribution, productivity and availability (see Section 6.1 for possible ways to consider such effects within ecosystem models).

The Council may face difficult choices between simulated performance of new policies and consistency with previous policies. For example, even within the existing policy framework, choice of the "brackets" on maximum and minimum temperature-dependent FRACTION (presently 15% and 5%) will strongly change how temperature is used in alternative HCRs. The Workshop anticipates that the Council will consider the results of the simulation exercise, and may request further development and analyses.

A further complication is posed by limitations in the sardine stock assessments that provide much of the information needed to parameterize the operating model. Assessments that were intended to provide information required by the PFMC for tactical management purposes do not necessarily address issues related to evaluating risks associated with harvest policies. The operating model requires assessment output quantities that are not addressed in normal assessments. A further complication arises in that the existing modeling platform used to conduct the assessments (SS3) is presently incapable of addressing some issues, such as age-specific fecundity in the density-independent component of the stock-recruitment relationship that could have important risk-related consequences. A subset of these issues can be addressed approximately by making changes to the operating model, but the resulting operating model may then not be entirely consistent with the underlying assessments.

5.2 Updated operating model specifications

Mr. Felipe Hurtado presented a summary of the proposed specifications for the simulation model (Hurtrado *et al*., Primary Document 1). These specifications (a) replace the production model used in PFMC (1998) with a full age-structured model, (b) outline how environmental covariates (or scenarios regarding environmental variation) can impact recruitment, (c) list several areas of uncertainty which warrant consideration as scenarios, and (d) identify longer research tasks. The presentation of the model specification is divided in four parts: (a) modeling basic dynamics; (b) modeling recruitment and the environmental variable; (c) potential control rules and parameterization; and (d) candidate analyses and performance metrics.

Some participants suggested that the environmental effect could be incorporated directly in the stock-recruitment relationship. Although such a simpler model could be considered, the proposed model resembles a "state space" framework where process and observation components are addressed explicitly. This provides an ability to explore sources of uncertainty more thoroughly, and has implications about how autocorrelation and noise work in the system.

The Workshop agreed a number of changes to the specifications of the operating model (see Appendix J for the final version). The changes included restricting the number of alternative parameter values to constrain the required number of model runs to a feasible number, and adding some new sensitivity analyses. Specific changes to the document presented to the meeting were:

- Replace spawning stock biomass with age-2+ biomass for consistency with how the stock-recruitment relationship analyses were conducted (see Section 3).

- Consider variable amplitudes in the wave function generating regimes, so all aren't identical. Although the historical and present productive regimes differ in apparent amplitude, the sample size of two is minimally informative, especially given that the estimation methods and underlying data are not comparable. The Workshop **agreed** to consider three levels for the amplitude of the effect of the environmental driver on recruitment.
- Consider time-varying weight-at-age, as a function of abundance and or the environment. Further (future) sensitivity analyses could include correlated changes in other life history parameters such as natural mortality, M. It was noted that problems may arise if growth is allowed to change because how changing growth would impact assessment error is unknown, and the application of the stock assessment by generating assessment data and applying SS3 is not simulated. It is therefore not clear whether this sensitivity test covers all aspects of the impacts of time-varying weight-at-age.
- Consider time-varying selectivity, as a function of abundance and or the environment. Appendix J includes specifications for time-varying selectivity (alternative mixes of California and Pacific Northwest selectivity patterns) as a function of the environmental driver. The same issues related to the interaction between assessment error and time-varying parameters as noted above were raised.
- The proposed specifications do not address distribution/allocation issues, both domestically (California vs. Oregon/Washington areas) and internationally because the proposed operating model uses a single fishery with a composite selectivity curve, and does not explicitly address distribution issues. Although historical evidence indicates that distribution is closely related to stock productivity and is likely to be related to risk, the modeling complications (note the difficulties in just estimating the fraction of the resource in U.S. waters in Section 4 above) require this issue to be addressed in a later effort. A crude representation of the impact of international fishing was developed for use in sensitivity analyses (see Section D.1 in Appendix J).
- *Natural mortality rate (M):* only use 0.4yr^{-1}, which is the present default value used for stock assessment, and is considered to be the most likely value. However, the value of M is not known precisely, and almost certainly varies with time and location among other things. The assessment is known to be highly sensitive to this parameter, implying that the simulations would also be sensitive. However, each alternative value of M would require a nearly complete revision of all other parameter values, and consideration of alternative values for M cannot be accomplished in available time.
- *Recruitment variability* (σ_R)*:* examine 0.5, 0.752, 0.9. This variability is residual to the portion accounted for by the primary environmental signal.
- *Serial correlation of recruit anomalies* (ρ_R)*:* The residuals in the GAM outputs (Section 3) have negligibly small serial correlation (the estimate is 0.091).
- *Biomass observation error variability* (σ_B)*:* 0.36, and 0.5, with a sensitivity run of 0.268.
- *Serial correlation of observation errors* (ρ_B)*:* Appropriate values are not clearly defined given available information. However, a value of zero would be misleading because successive assessments tend to be similar in reality because they are based on essentially the same data and make similar assumptions. An unintended consequence of assuming a zero value for ρ_B is that averaging successive assessment results would very quickly tend toward an accurate value. Values of 0.50 and 0.707 (the latter implies that half of the variance is associated with serial correlation) should be considered.

- *Hyperstability of abundance estimates:* Consider a sensitivity run where observed biomass is related to true biomass according to a power of 0.5 (this also requires specifying an arbitrary reference abundance level, set to 150,000t for the analyses for the April Council meeting). This sensitivity run is motivated by an apparent retrospective tendency for assessments to show some degree of hyperstability in terminal abundance estimates.
- *Environmental wave forms:* Use (a) a square wave with a period of 60 years, and (b) a square wave, but with longer bad periods than good. Sensitivity runs include, (c) different shape going down (gradual) from going up (sharp), (d) a sine wave, and (e) a square wave with a period of 100 years (see Table 3 and Figure 1 of Appendix J for more details).
- *Observation error in environmental index:* This value can be taken from a comparison of multiple candidate indexes using among-index variability to approximate within-index variability (see Adjunct A of Appendix J).
- *Sigma and rho in true environmental state:* Values can be calculated from the residuals of fitting the index to a square wave (see. Adjunct A of Appendix J).

The specifications in Appendix J assume that the allowable catch will be taken in each year. This may not be realistic, especially if a MAXCATCH is not present in the management policy. Although the operating model could be modified to include a dynamic capacity constraint, the specifications would be difficult to justify.

5.3 Performance measures

The long list of potential performance measures in Hurtado *et al*. (Primary Document 1) needs to be trimmed to useful quantities. Some features such as abundance and catch can be summarized by probability distributions. In addition to the frequency of closures (due to biomass falling below the CUTOFF), the distribution of lengths of closures is a desirable output. Summary statistics on age distributions may allow indirect evaluation of issues that cannot be addressed directly in the present model. Even though the proposed operating model will have a single selectivity curve representing a “composite” fishery, approximate probability distributions of abundances available to individual fleets can be tracked by means of available biomass based on the selectivity curves from the stock assessment.

Some statistics should be based only on open fishing years. For example, overall mean catch (including zeroes) may be less useful than a combination of two statistics such as mean catch during open fishing years and the frequency of closed years.

In addition to the rebuilding from low abundances that occur occasionally in the simulated time series, it may be worth simulating specific rebuilding scenarios. How does policy behave in worst-case depletion? Initial conditions may be different if low abundance is due to natural causes (older fish would be present) or due to fishing pressure, where older fish would be absent.

5.4 Harvest policy options

The Workshop **agreed** that all of the operating model scenarios should be run for the set of harvest policy options in Table 3. The Workshop also agreed that a sensitivity run should be conducted where the management policy is based on a 3-year average, to explore the implications of smoothing year-to-year management fluctuations[3]. A constant live bait catch of

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[3] During adoption of the report, a participant queried “In cases where the environmentally-based E_{msy} is applied, I wonder if it’s appropriate to apply a lower bracket in the calculation of OFLs? In other words, can we apply an

2,000t will be removed from the population each year for all harvest policy options (except zero catch). This constant level of removal was part of the original Amendment 8 analysis.

6. PREPARE AN INITIAL PLAN FOR A FULL MANAGEMENT STRATEGY EVALUATION (MSE) FOR COUNCIL CONSIDERATION IN 2015.

This section of the report reviews information on ecosystem models for the California Current Ecosystem, and considers other elements that could form the basis for an MSE which evaluates the impact of the HCR for Pacific sardine on the broader ecosystem, including the role of sardines as forage for higher level non-human predators and other general optimum yield-type considerations.

In addition to describing a review of ecosystem models, the Workshop Terms of Reference also suggests that the Workshop "…develop an initial plan for a process and a two-year schedule for a full MSE, for consideration at the April, 2013 Council meeting." While the Workshop **agreed** that an ecosystem model which included the entire distribution of Pacific sardine, including northern Baja, should be determined prior to embarking on a full MSE, there remains the possibility of initiating an approximate two-year MSE that would re-visit the very fundamentals on which current U.S. sardine management is based. These fundamentals encompass OY elements, the relative value of sustainable fishing opportunities for coastal communities versus the benefit of sardines to the ecosystem, the value of consistent harvest versus maximizing harvest opportunities, the possibility for international management, and others. If the Council wished to embark on a full MSE, it could follow the process presented in PFMC (2012).

6.1 Overview of ecosystem models

Dr. André Punt provided an overview of the types of models which have been proposed for use in management, and in particular for conducting MSEs. These models can be categorized as heuristic (i.e., to provide a conceptual understanding), strategic (to assist decision makers select among policies), and tactical (to implement policies). Single-species assessments (such as the SS3 assessment for Pacific sardine) are primarily tactical, but strategic evaluations can be based on them. Models of Intermediate Complexity (MICE) (Plaganyi *et al.*, in press) involve constructing multi-species models which include a small set of species focused on particular management problems. The parameters of MICE are estimated by fitting them to available data. MICE are primarily used for providing strategic advice, but could be tailored for tactical purposes. End-to-end models (such as Atlantis and Ecosim) are able to represent a broad range of species and trophic levels, environmental forcing, including climate impacts, and multiple types of anthropogentic impacts on the system. End-to-end models are not designed for providing tactical management advice, but rather to evaluate management policies (i.e., to conduct MSE). Unlike single-species models and MICE, end-to-end models are almost always not fit to data and instead rely on expert judgement for many of the values for their parameters. Atlantis and Ecosim models have been developed for several ecosystems worldwide, and the results from Atlantis have directly impacted management in Australia. A key issue with MICE and end-to-end models is how to summarize the outputs in a way that is meaningful to decision makers.

E_{msy} of 5% when SST tells us to apply something lower (e.g. 2%)?" This issue should be discussed further during the April Council meeting

The Workshop **agreed** that the purpose of ecosystem models is not to determine absolute values of abundance or biomass but, rather, to evaluate and rank the likely tradeoffs between objectives in response to modeled management strategies. The Workshop noted that a key step in the process of conducting an MSE for Pacific sardine so that ecosystem and economic considerations are accounted for is that the objectives need to be specified clearly so that the analysts can produce the types of outputs to allow options to be compared. It is **recommended** that the Council and its advisory bodies will need to work with the analysts to ensure that model outputs adequately reflect the management objectives if end-to-end models are to be used as the basis for MSE for Pacific sardine.

The Workshop considered four ecosystem models which are available for parts of the California Current system in terms of scope, purposes and current state of development.

6.1.1 The Northern California Current Ecosim Model (Ecosim-NCC)

This model was originally developed by Field *et al*. (2006) to investigate the impacts of environmental variability, predation and fishing on the Northern California Current ecosystem. The Ecosim-NCC model is not spatially explicit, but represents the area from the US-Canada border (48^{o} 23’ N. latitude) to Cape Mendocino (40^{o} 26’ N. latitude) and out to 1200 meters depth. The model has 63 functional groups (groups of functionally similar species that are aggregated and modeled as a single variable) and is initialized at 1960. The Ecosim code base simulates predator-prey relationships between functional groups, implicit refuges from predation, and time-varying diets, but it is not spatially disaggregated (Walters, 2000; Christensen and Walters, 2004). At its core, Ecosim solves a set of differential equations on a monthly time step, based on initial conditions (biomasses) and rate parameters that represent predation and growth rates of biomass pools. The Field *et al*. (2006) implementation of Ecosim does not include age structure of populations, nor does it track size-at-age or gape relationships (i.e., prey size relative to predator mouth size). The Ecosim model is driven with two indices related to environmental conditions. The first is an index of ocean production (Logerwell *et al*., 2003) that represents local ocean conditions and lower trophic level productivity. The second is the Pacific Decadal Oscillation (Mantua *et al*., 1997), a broad-scale index of the ocean’s physical environment, including temperature. Ecosim-NCC models Pacific sardine as an individual species. However other forage fish are not modelled explicitly. This model has been included in analyses for the 2011 Integrated Ecosystem Assessment (Levin and Schwing, 2011), the 2012 Integrated Ecosystem Assessment, and analyses of potential food-web impacts of forage fish harvest (Kaplan *et al*., In press; Smith *et al*., 2011).

6.1.2 The Northern California Current ECOTRAN model

This model covers the region from the southern Oregon border (42.00^{0}N) to Cape Flattery, Washington (48.34^{0}N) and cross-shelf between the 1- and 183-m isobaths (26,000 km2). This model describes the trophic interactions between >80 major functional groups and 10 fishery gear types in the benthic and pelagic environments of the Northern California Current upwelling system (Steele and Ruzicka, 2011; Ruzicka *et al.*, 2012). The approach derives a bottom–up transform of a top–down ECOPATH model, couples this to a simple microbial web with physical forcing, and then uses the resulting end-to-end model for scenario construction. This steady state format also provides a framework and initial conditions for different dynamic simulations. The model can be applied to other shelf ecosystems with a wide range of physical forcing, coupled benthic/pelagic food webs, and nutrient recycling. The model is not spatially-explicit. NCC ECOTRAN currently models the following as distinct groups: sardine, anchovy, smelt (whitebait, eulachon), shad, herring, saury, juvenile salmon, mesopelagic fish, and planktivorous rockfish. NCC ECOTRAN complements other California Current ecosystem models in two areas: 1) assessing small pelagic (especially sardine) risks and management scenarios that can be influenced by climate, and 2) providing Monte Carlo simulations to address observational uncertainties and natural variability in scenario simulations. This model has proven useful for examining scenarios of alternative (forage fish, krill, jellyfish) food web pathways (Ruzicka *et al*., 2012).

6.1.3 The California Current Atlantis Model

This model covers the region from the Canadian border to Point Conception (34°27' N. latitude), and out to 1200 m depth. The model domain is divided into 82 spatial cells and up to five vertical depth layers per cell. The full model is detailed in Horne *et al*. (2010). An earlier implementation of the model has been used to investigate the effects of ocean acidification (Kaplan *et al*., 2010), and the latest version has been used to contrast harvest strategies (Kaplan *et al*., 2012; Kaplan and Leonard, 2012). This new version contains updated estimates of abundance from stock assessments and surveys, as well as added spatial resolution in Central California. The model includes 60 functional groups, ranging from phytoplankton to marine mammals, birds, and harvested fish groups. The model has particular emphasis on groundfish species, modelling some species such as Dover sole (*Microstomus pacificus*) and canary rockfish (*Sebastes pinniger*) as single species with multiple life history stages, rather than aggregated functional groups. Water temperature and the flux of nutrients and plankton are forced with a repeating loop of output for years 1958-2005 from a ROMS (Regional Ocean Modeling System) hydrodynamic model. The Atlantis model has been calibrated against historical estimates of abundance for 1950-2007, from stock assessments and survey data, as detailed in Horne *et al*. (2010). One of the key inputs, the diet matrix that initializes the predator-prey relationship, has been published by Dufault *et al*. (2009). Like Ecosim, Atlantis is a code base that solves a set of differential equations to simulate food web and fishery dynamics. Atlantis operates on a 12-hour time step, and includes migrations and foraging movement, age structure and dynamic size-at-age for vertebrates, and simpler biomass pools for invertebrates and primary producers (Fulton, 2004; Fulton *et al*., 2005). Predator-prey models explicitly calculate spatial overlap between species, and predator gape. Fulton *et al*. (2011) compare the California Current model to other Atlantis models, and summarize lessons learned from this and other applications of Atlantis. Forage fish (small planktivores) are modeled as an aggregated functional group that includes Pacific sardine, northern anchovy, Pacific herring, and smelt.

Atlantis is spatially-explicit (map–based). It has been included in analyses for the 2011 Integrated Ecosystem Assessment (Levin and Schwing, 2011), the 2012 Integrated Ecosystem Assessment, and analyses of potential food-web impacts of forage fish harvest (Kaplan *et al*., In press; Smith *et al*., 2011). Published versions of the model have finer resolution for groundfish species; pelagic species tend to be aggregated into coarse functional groups. Importantly, the model is unable to capture cyclic behavior in functional groups as seen for sardine.

It is important to recognize that Atlantis was originally conceived of to improve our understanding of ecosystem structure, and the variability of ecosystem components in the absence of thorough data. This is a useful attribute of the model, but means that the model will be unequally informed across ecosystem component groups. Therefore, it can be used to elucidate patterns that would not be observable from the current data time-series, but cannot be used for tactical decision making. Rather, Atlantis is better suited to provide strategic advice about the possible consequences to ecosystem components when faced, individually and in concert, with environmental or managerial perturbations. As a result, Atlantis could be considered a very high level model used to allow for a common currency between any number of user groups or sectors to evaluate the trade-offs between them under a number of management strategies.

6.1.4 NEMURO-SAN

This model covers the region from the tip of the Baja Peninsular to Vancouver Island. It is intended to capture the dynamics and climate response of forage species such as sardine and anchovy in the California Current. NEMURO-SAN is an end-to-end model being developed within the widely-used ROMS circulation model. The concentration-based NEMURO (Nutrient-Phytoplankton-Zooplankton-type) submodel provides lower trophic level dynamics, including multiple nutrients, two phytoplankton and three zooplankton fields. A multi-species, individual-based, full life cycle submodel simulates fish population and community dynamics, including fishing fleets as one of the predator species. A preliminary version focuses on anchovies and sardines in the California Current System. Using a 10-km resolution ROMS model, the authors have demonstrated how the submodels can be integrated simultaneously for a multi-decadal historical simulation (1958-2006). NEMURO-SAN is spatially-explicit, models sardine and anchovy as distinct species, and may be well suited to capturing climate and oceanographic impacts on these stocks as well as movement of purse seine fleets.

The Workshop was interested in this model for a number of reasons. For example, it is based on first principles and well-informed functional relationships. The model results include growth curves and biomass estimates which can be used for validation purposes. The Workshop was impressed with the ability of the model to estimate the dynamics of sardine abundance retrospectively; the model captured the cyclic nature of sardine abundance.

In the present form, this model can simulate the production of sardine and anchovy, but not the production of migratory fishes that feed on them. Specifically, the model does have a predator component, but predators are introduced to the system from outside of the model bounds. Ultimately, NEMURO-SAN is not capable of evaluating the impact of sardine as forage on transitory predators. Rather, the predators act to control the sardine and allow for a dynamic mortality component to the model. This is critical and suggests that this model as currently developed may be useful for understanding variability in sardine abundance, but not the impact of this variability on higher trophic level production.

6.1.5 General comments on ecosystem models and recommendations

The models discussed were inconsistent in terms of responses to simulated perturbations. Therefore, the workshop **recommended** that an ensemble approach be taken. Specifically, robust results can be identified, and more trust placed in those results, by examining the outcomes of a number of models. The Workshop was concerned generally with the inability to validate model results (although see NEMURO-SAN). Without validation, the Workshop was concerned that ecosystem models may not even provide appropriate strategic advice. It was suggested that single species models could be used to validate the simulated patterns observed for species in the ecosystem model.

The Workshop noted that only the NEMURO-SAN model has an environmental driver controlling, in part, the dynamics of sardine. That model produced surprisingly accurate trends in sardine abundance. However, a goal of the Council is to additionally determine the role of sardine dynamics on the remainder of the ecosystem. Currently, the NEMURO-SAN model is not capable of addressing this issue. A more complete and properly parameterized ecosystem model specifically including sardine and the environment would be needed.

The Workshop **agreed** that none of ecosystem models presented were sufficiently well developed to form the basis for an MSE, and that substantial modifications would need to be made before they could be used for this purpose. The Workshop identified any ecosystem model would need (minimally) to include the following features:

1. It must cover the entire range of the northern subpopulation of Pacific sardine (Baja California to northern Vancouver Island) – the implications of the southern boundary of the northern subpopulation changing with temperature, and perhaps even entering U.S. waters presents a unique challenge to correctly representing space in an ecosystem model.
2. The fisheries in Mexico, California, the Pacific Northwest and Canada must be explicitly represented (owing in particular to differences in selectivity).
3. The model hindcasts must be validated. For example, they should replicate the behavior of major ecosystem components (especially sardine) during 1930-present.
4. The dynamics of sardine should be modeled to a level consistent with the level of complexity developed during the workshop for objective 1.
5. Management of other groups in the ecosystem (e.g. groundfish / salmon) should be based on the control rules actually in place (rather than assuming constant catch or constant fishing mortality).

The Workshop did not have sufficient time to assess how long it would take to modify each of the four ecosystem models to include all of these features. However, the time is likely to be years rather than months.

6.2 Economic models

Dr. Sam Herrick presented two economic analyses of the indirect effects of sardine harvest in the California Current. They involved the static (Ecopath) version of Ecosim-NCC. Hanneson *et al*. (2009) analyzed how marginal changes in sardine catch would impact harvest of other members of the food web. This work assumed the linear relationships built into Field *et al*.'s (2006) Ecopath system of equations, and did not model dynamic responses in the populations of predators or forage species. Hanneson and Herrick (2010) used a sardine yield-per-recruit model to estimate how sardine biomass would change with fishing, and then linked this to the abundance of harvested predators based on transfer efficiencies calculated from the Field *et al*. (2006) static Ecopath model. Early iterations of this model demonstrate the potential to evalaute the cost, through lost opportunity, to harvest additional biomass of predators.

While early in development, the Workshop was interested in promoting the advancement of this modeling approach, including groundtruthing the data, including a wider suite of community members, and improving functional relatonships underlying the biological interactions between forage and predators (e.g., prey switching could impact the results).

6.3. Alternative control rules

Dr. David Demer note that there are two stocks of Pacific sardine in the California Current and that the southern subpopulation resides mostly off the west coast of Baja California, Mexico, but portions of it may periodically reside in waters off southern California (CA). The northern subpopulation resides mostly off the west coast of the U.S., but portions of it may periodically reside in waters off Mexico and Canada. The segregated stocks migrate seasonally and synchronously along the coast. The latitudinal ranges of the migrations increase with stock biomass and fish size. Different seawater habitats, characterized by predominantly different ranges of sea-surface temperature, may be used to differentiate the landings from the two stocks. Currently, the PFMC aims to limit the annual total exploitation of the northern subpopulation to less than 15% (FRACTION) of the age-1+ biomass less 150,000 t (CUTOFF). However, the stock is not managed tri-nationally, and the U.S. harvest guideline does not currently explicitly account for landings off Canada nor control the Mexican and Canadian landings. Therefore, the PFMC currently assumes a constant 87% of the northern stock resides off the U.S. west coast. However, this DISTRIBUTION fraction is likely not constant; the distribution of sardine within its potential habitat is neither homogenous nor predictable; and the proportions of sardine habitat associated with each country are not equivalent to their fractions of the total landings from the stock. Dr Demer noted that the total fishing fraction and the proportions of it that are associated with each country may be estimated annually from landings from each country and estimates of the biomass of the northern subpopulation. Dr. Demer noted that assuming that the landings off Mexico and Canada in one year are good estimates for their values during the following year, a simple model is proposed for setting the U.S. quotas such that the annual total tri-national landings more consistently match the target-fishing fraction.

The Workshop noted that replacing the DISTRIBUTION parameter with the proposed rule would be a policy choice made at the Council level. It **recommended** that if the Council wishes to explore this new strategy in the context of a full MSE, then the most appropriate place to apply this approach would be in the calculation of U.S. OFLs and not the HGs.

Workshop participants noted that there are still uncertainties regarding the alternative stock structure hypothesis outlined by Dr. Demer. For example, ocean drift models indicate that a large quantity of egg production from the northern subpopulation is advected to northern-central Baja California each spring, so the Ensenada fleet is potentially catching large quantities of recruits from the northern subpopulation. While it is likely that southern subpopulation migrates into the Southern California Bight (SCB) on a seasonal basis (summer-fall), it is unclear whether northern subpopulation recruits (ages 0 & 1) fully emigrate from the SCB during warmer months. Finally, the Workshop noted that separating sardine catch by stock source would require the Council add the southern subpopulation to the CPS-FMP (and/or exclude some of Ensenada landings from the stock assessment model) and hence likely manage the sardine resource differently.

6.4 Alternative environmental indexes

Several additional environmental indexes are currently under development. The Workshop did not consider these explicitly under Section 3, but noted that their performance could be evaluated using similar methods in the future. The Workshop **agreed** that it would be desirable for the Council to have a more flexible framework for reviewing and including new research on sardine and the environment as it becomes available.

Dr. Sam McClatchie proposed combining a set of standardized time series variables that are affected by regional ENSO conditions in an EOF to create a quantitative metric of ENSO conditions in the California Current System. Following examples from the climate literature, indicators can then be constructed from the raw variables and from EOFs to index extreme ENSO conditions that are likely to be related to successful sardine recruitment. He suggested that a modification of the U.S. Climate Extremes Index (CEI) could be used to create an ENSO Sardine Extreme Index (ENSO SEI). The composite ENSO SEI, once appropriately scaled, could be incorporated directly into the stock-recruitment relationship for sardine to produce a stock-recruitment-environment equation that incorporates the effects of the relevant ENSO-related environmental extremes on sardine recruitment, while accounting for the dominant stock-recruitment relationship.

Dr. David Checkley highlighted recent research papers by SIO and SWFSC researchers regarding sardine and the environment. In summary, these papers have shown that: 1) spawning habitat of sardine can be characterized by temperature, salinity, dynamic height, upwelling, chlorophyll-a, and zooplankton; 2) wind-stress curl-driven upwelling can explain significant variability in annual surplus production of sardine (1982-2004); 3) sardine egg and larva abundance are related to SST and sea level (1951-2008); and 4) empirical observations are the basis for these relationships.

In response to a request related to the prospects for seeing a wind-stress curl index for sardine in the future, Dr. Checkley stated that it is difficult to develop the wind-stress curl index, but data for other elements (temperature, salinity, dynamic height, upwelling, chlorophyll, zooplankton) are relatively easy to obtain. Dr. Lindegren compared the performance of an existing wind-stress curl index to the current candidate index (CalCOFI SST) and found that it did not perform better than CalCOFI-SST and had a higher AIC value (Appendix I).

Dr. Richard Parrish provided a brief presentation regarding sardine and the environment. Data were presented to show that SSTs in the Gulf of Alaska and off northern Baja California (extreme ends of the distribution of the northern subpopulation) are in phase with respect to low and high frequency variability even though the absolute temperature differs by 10^0C. He also presented data regarding ocean transport, sea level pressure, and wind stress. He raised the question of whether upwelling or source water is more important to productivity in the CCS. He indicated that sea level pressures resulting in a net onshore flow of (nutrient-poor offshore) waters resulted in poorer recruitment than when water comes from a northern source.

7. SUMMARY OF CONCLUSIONS

1. Inclusion of the mean 5-15m temperature data from the regular CalCOFI area significantly improves the fit to the stock-recruitment data for 1984-2008 and should be used in the operating model to evaluate harvest policy options and well as in some of the candidate harvest control rules.
2. Spawning stock biomass and CalCOFI SST explain about equal proportions of the variance in recruitment and both need to be included in predictive relationships.
3. Several new environmental indexes are under development. There needs to be some (but not too much) flexibility related to being able to base the environmental index used in HCRs to reflect the best available science regarding prediction of recruitment.
4. The current value for DISTRIBUTION of 0.87 was developed when there was no appreciable biomass off Canada and was based on information up to 1992. The data which pertains to the distribution of sardine biomass in U.S. waters is patchy, but efforts should be made to assemble and synthesize the available information.
5. Appendix J lists a set of model specifications which capture a larger range of uncertainties than that on which Amendment 8 is based and provides a basis for analyses which could be completed by the April 2013 Council meeting. However, some key uncertainties cannot be represented in this version of the operating model (e.g., because they would require additional runs of the assessment and spatial/trophic structure), and so calculations based on Appendix J will not encompass the full range of uncertainty.
6. The currently available ecosystem models are not sufficiently well developed to form the basis for an evaluation of the impact of sardine control rules on broader ecosystem impacts (See Section 6.1.4).

7. Ecosystem models should not be used to provide quantitative predictions of the impacts of alternative HCRs, but rather to evaluate trade-offs qualitatively; ideally multiple ecosystem models should be applied to identify which conclusions are robust to the choice of the specific assumptions underlying the ecosystem model.
8. The specifications for the analyses should be reviewed during the April 2013 Council meeting and modified as necessary. The HCR options in Table 3 were not selected to be fully inclusive, but rather to consider options which are similar to the current control rule and those included in Amendment 8 to the CPS FMP.

8. KEY RESEARCH RECOMMENDATIONS

1. Conduct further validation of the selected index by basing cross-validation testing on random subsets of the data (e.g., 75%) and by fitting the environment-recruitment model to up to a given year (e.g. 1990) and predicting future years; this exercise would be conducted for each successive year.
2. Conduct an assessment which includes the full range of years with data. This will increase the ability to select among environmental indexes because a wider range of spawning biomasses and values for environmental variables will be available.
3. Assemble and synthesize the available information could be used to refine the value for DISTRIBUTION.
4. Include a case in which environmental covariates are used to split the catches between the southern and northern subpopulations in the next assessment (initially as a sensitivity test).
5. Collect additional food habits data; lack of diet data is a constraint on the construction of ecosystem models.
6. Consider including CalCOFI SST as an index of recruitment in the next stock assessment.

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Table 1. Climate covariates used during model fitting.

Variable	Month	Aggregation	Source
SST_SIO_ann	Jan-Dec	Calendar year	http://www.shorestation.ucsd.edu/
SST_CC_ann	Jan-Dec l	Calendar year	http://calcofi.org/data.html
ERSST_ann	Jan-Dec	Calendar year	ftp://ftp.ncdc.noaa.gov/pub/data/cmb/ersst/
PDO_ann	Jan-Dec	Calendar year	http://jisao.washington.edu/pdo/PDO.latest
MEI_ann	Jan-Dec	Calendar year	http://www.esrl.noaa.gov/psd/enso/mei/
SST_SIO_T	July-June	Fishing year (T)	
SST_CC_T	July-June	Fishing year (T)	
ERSST_T	July-June	Fishing year (T)	
PDO_T	July-June	Fishing year (T)	
MEI_T	July-June	Fishing year (T)	
SST_SIO_T3	July-June	Mean T-2 to T	
SST_CC_T3	July-June	Mean T-2 to T	
ERSST_T3	July-June	Mean T-2 to T	
PDO_T3	July-June	Mean T-2 to T	
MEI_T3	July-June	Mean T-2 to T	
SST_SIO_T5	July-June	Mean T-2 to T+2	
SST_CC_T5	July-June	Mean T-2 to T+2	
ERSST_T5	July-June	Mean T-2 to T+2	
PDO_T5	July-June	Mean T-2 to T+2	
MEI_T5	July-June	Mean T-2 to T+2	

Range of data used in modeling for each data set.

Statistic	Data set		
	Full	Short	1984-2008
N	62	36	25
Min SSB	6	13	13
Max SSB	3,804	1,496	1,496
Min CC annual SST	13.5	13.5	14.9
Max CC annual SST	16.8	16.8	16.8
Min Scripps SST	15.5	16.2	16.5
Max Scripps SST	19.2	19.2	19.2

Table 2. Summary of selected ln(*R*) and ln(*R*/*S*) models fitted using the entire data set (ALL), data set with NAs removed (No NA) and from 1984-2008 only (1984-). G/L indicates non-linear or linear covariate, R2 is the explained variance of the final models, GCV_R2/ MSE_R2 indicate the proportion of variance explained and mean squared error for in- and out-of-sample predictions, and r the Pearson´s correlation between in and out-of-sample observations.

Response	**Data**	**Model**	**Covariate**	**G/L**	**R2**	**# Table**	**GCV_R2_in**	**GCV_R2_out**	**GCV_MSE_in**	**GCV_MSE_out**	**r inout**
ln(R)	ALL	12	ERSST_T5	G	0.59	3	0.59	0.52	1.10	1.20	1.00
ln(R/S)	ALL	12	ERSST_T5	L	0.36	6	0.36	0.26	0.85	0.91	1.00
ln(R)	No NA	12	ERSST_T5	G	0.69	4	0.69	0.55	0.91	1.10	0.99
ln(R/S)	No NA	4	SIO_SST_T5	L	0.49	7	0.49	0.39	0.79	0.88	1.00
ln(R)	1984-	5	SST_CC_ann	L	0.68	5	0.68	0.56	0.70	0.83	0.99
ln(R/S)	1984-	5	SST_CC_ann	G	0.76	8	0.76	0.63	0.51	0.63	0.99

Table 3. Harvest control options. Runs will also be conducted under zero harvest

			Amendment 8 options		
Option	**A**	**F**	**L**	**M**	**OFL**
FRACTION (%)	20	5-25*	Emsy	DEmsy	45
CUTOFF	50	100	0	0	$0.33B_0$
MAXCAT	400	400			
			Present HG (Option J) Variants		
Option	**HG (J)**	**HG Variant-1**	**HG Variant-2**	**HG Variant-3**	**HG Variant-4**
FRACTION (%)	5-15*	5-Emsy*	5-Emsy*	5-Emsy*	5-Emsy*
CUTOFF	150	150	$0.10B_0$	$0.20B_0$	$0.33B_0$
MAXCAT	200	200	200		
			Other variants		
Option	**Alt-1**	**Alt-2**	**Alt-3**	**Alt-4**	**Alt-5**
FRACTION (%)	0-20*	5-2Emssy*	Best Fit	Best Fit	Link to Quartiles
CUTOFF	$0.20B_0$	$0.20B_0$	Best Fit	Best Fit	150
MAXCAT	200	200	-	-	200

Emsy – stochastic Emsy
DEmsy – deterministic Emsy
* SST is in harvest control rule

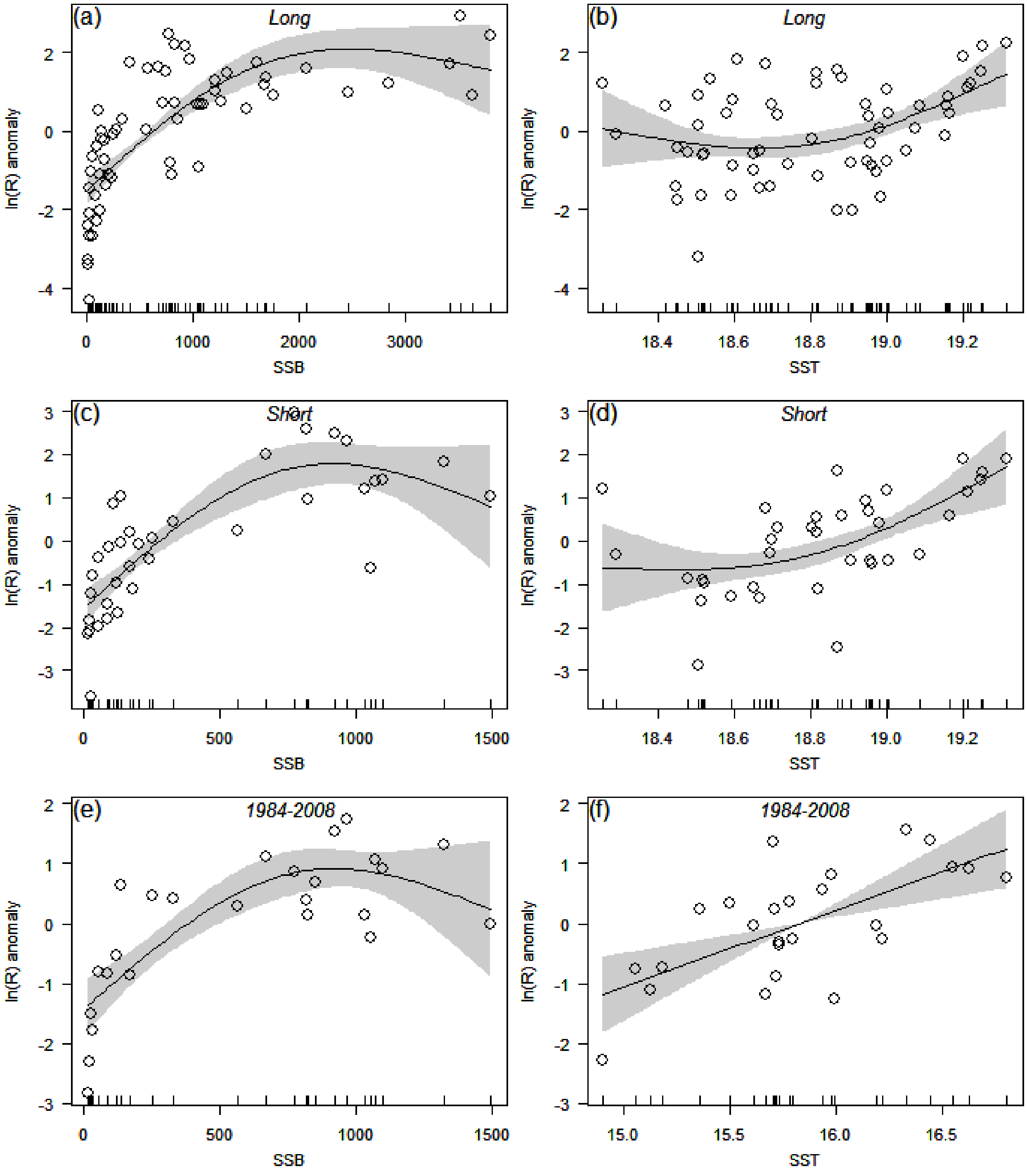


Figure 1. The effects of SSB (a, c, e), ER_SST_T5 (c, e) and CalCOFI annual SST on sardine recruitment when fitted to the entire data set (long), when removing NAs (short), and from 1984-2008.

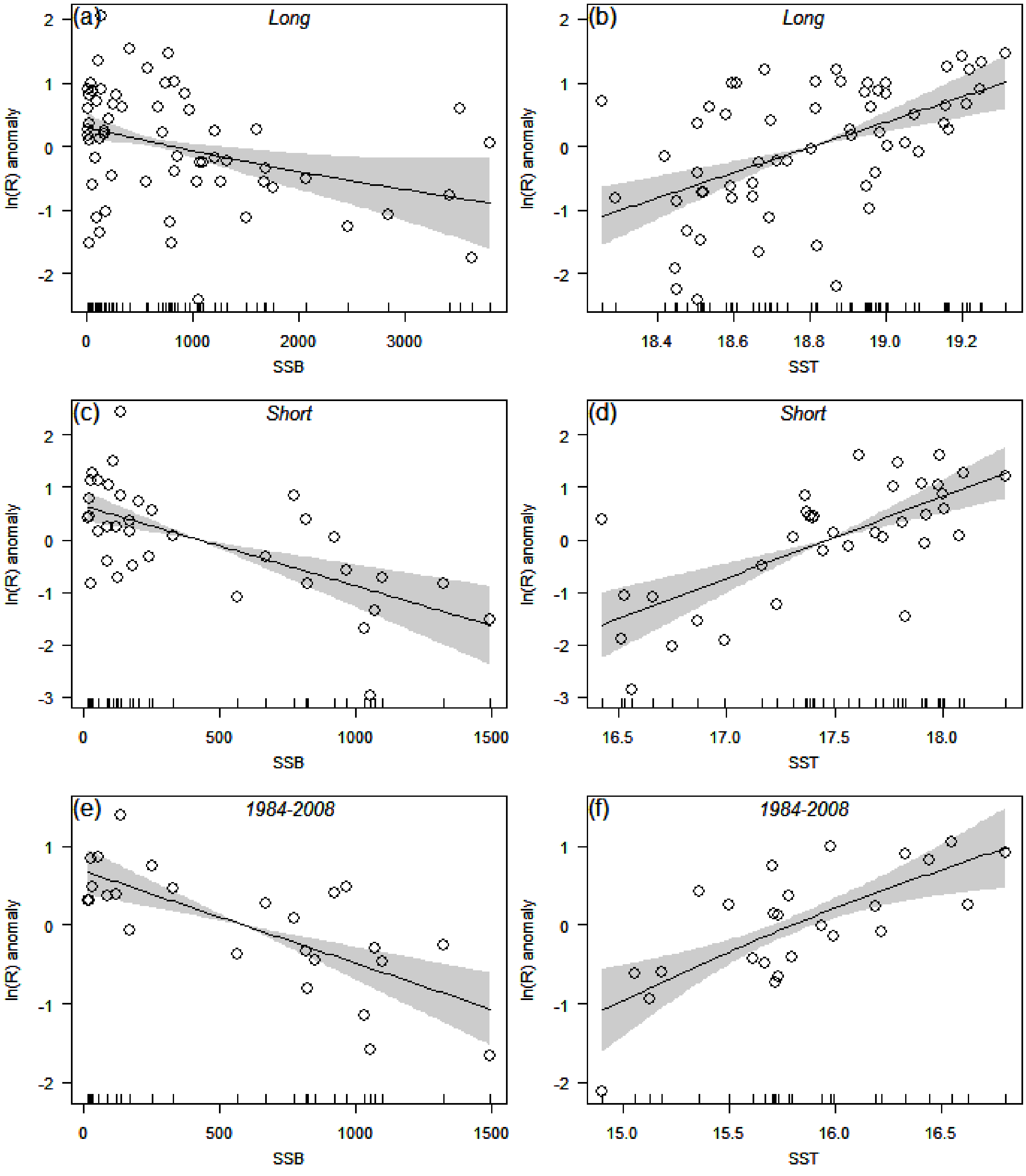


Figure 2. The effects of SSB (a, c, e), ER_SST_T5 (c, e) and CalCOFI annual SST on sardine recruitment success when fitted to the entire data set (long), when removing NAs (short), and from 1984-2008.

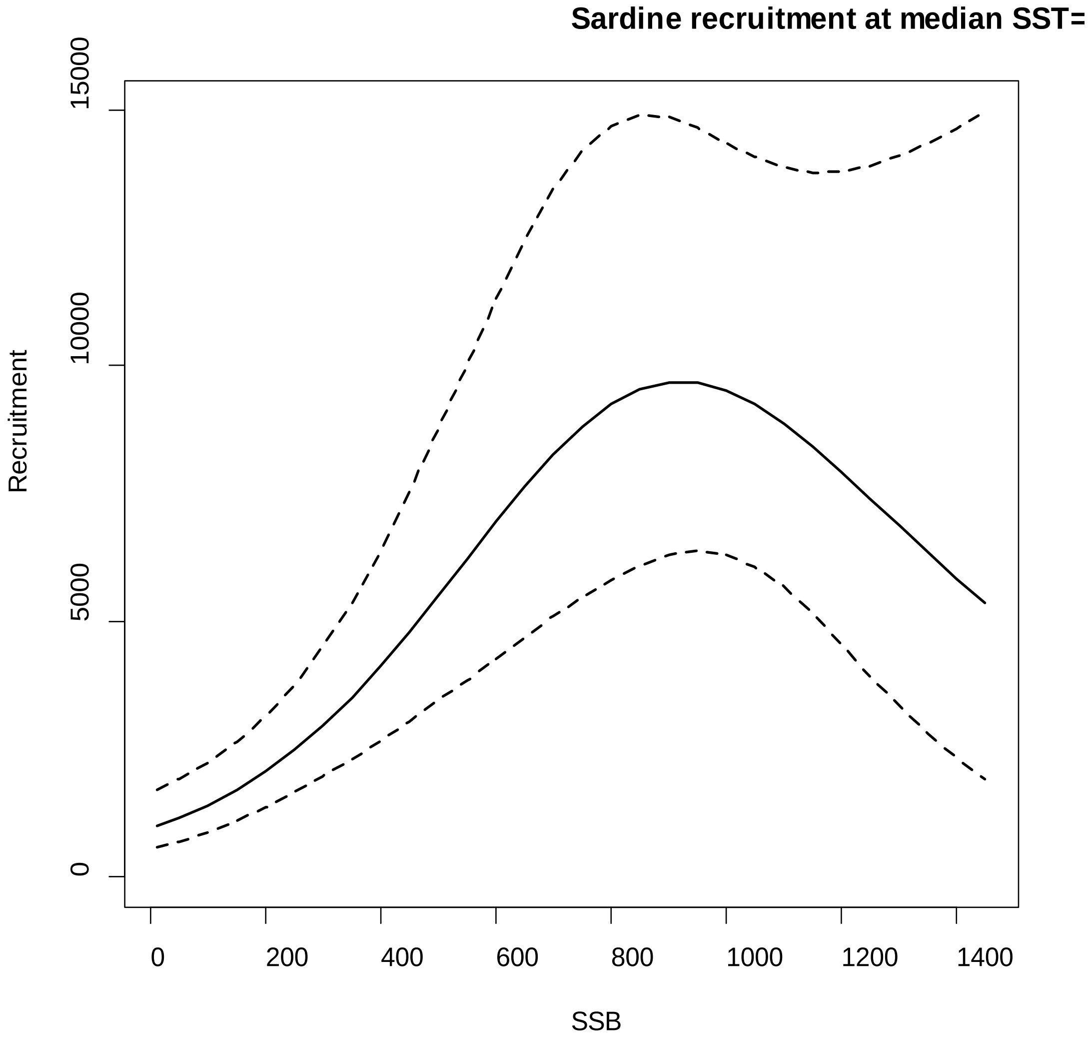


Figure 3. Predicted arithmetic recruitment (millions) from the best model for log-recruitment over a range of biomass levels, assuming median SST (thousand tones) (15.73^{o}C), with a 95% confidence interval.

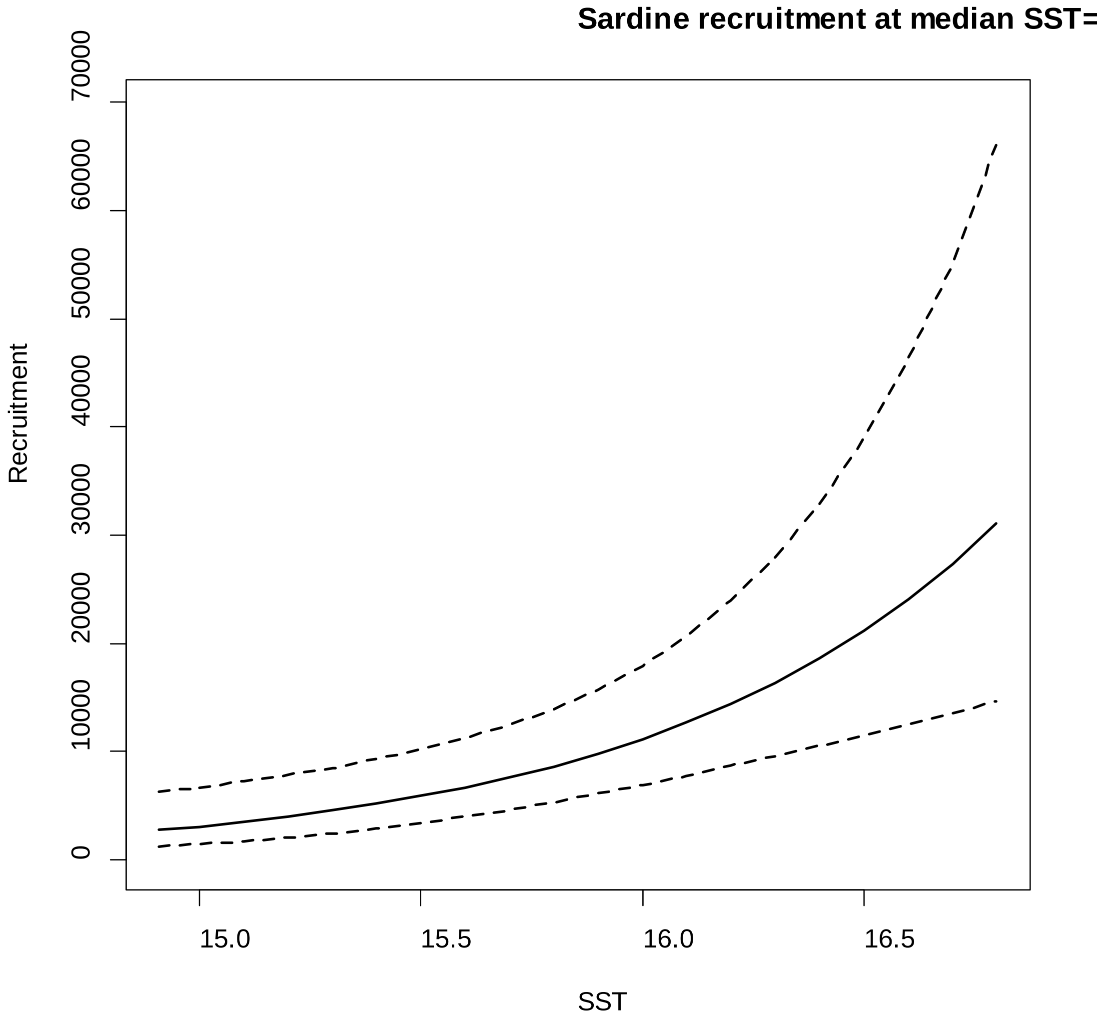


Figure 4. Predicted arithmetic recruitment (millions) from the best model for log-recruitment over a range of SST values, assuming median spawning biomass (670 thousand t), with a 95% confidence interval.

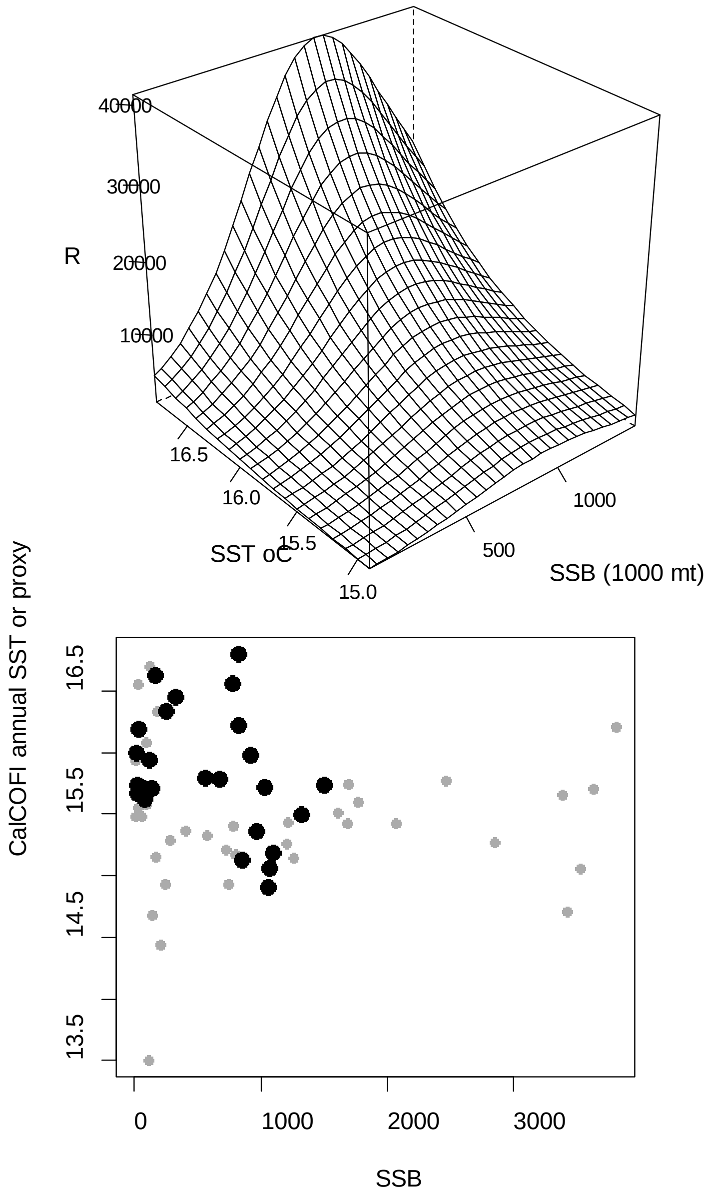


Figure 5. Top: Predicted recruitment (millions) over the range of spawning biomass (SSB) and SST data used in fitting the best sardine recruitment model. Bottom: SSB and SST data used when fitting the best sardine recruitment model (black circles) and data that were excluded because they were collected before 1984 or because annual CalCOFI SST data were not available (grey circles). Note that the range of SST and SSB data in the top panel is narrower than in the bottom panel.

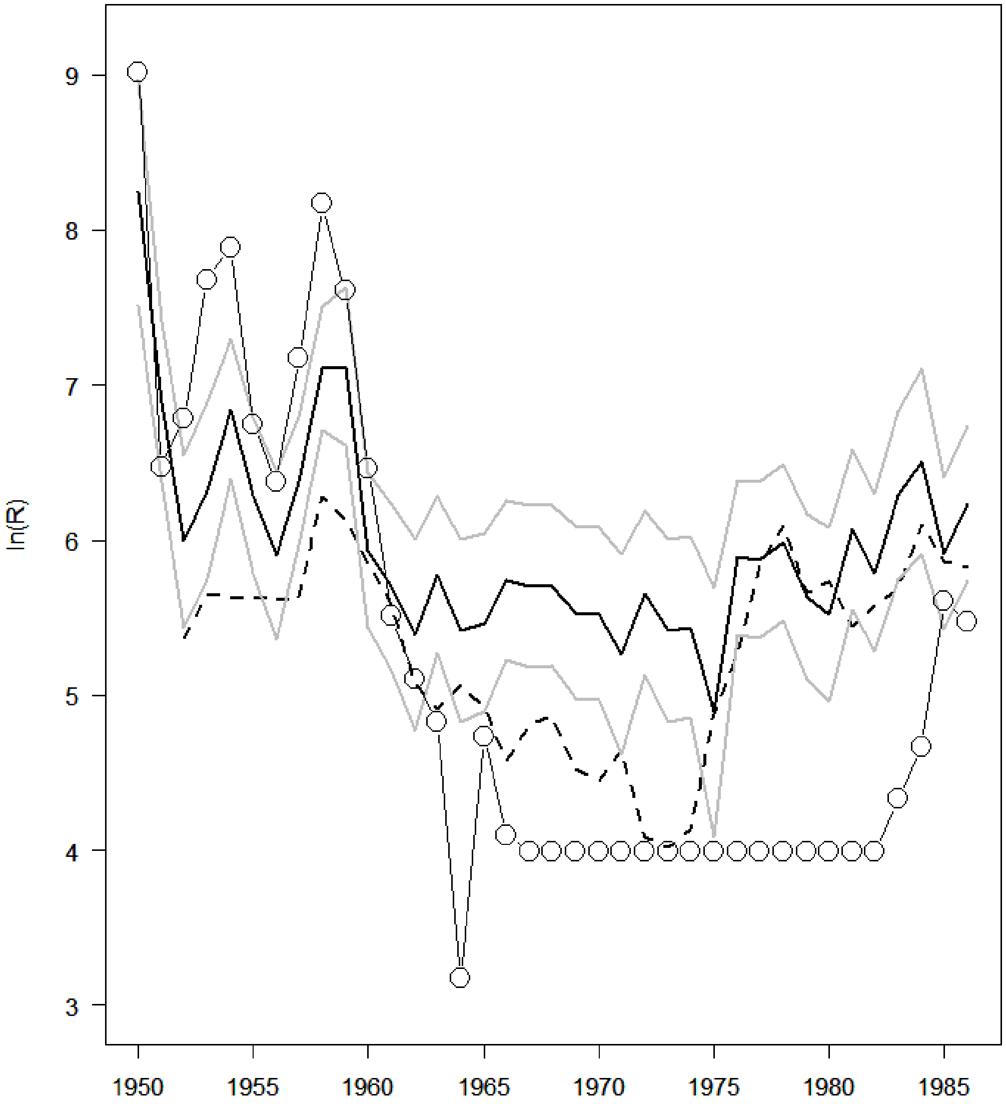


Figure 6. Hindcasted log-recruitment estimates predicted from the final stock-recruitment model using SSB from previous stock assessments 1950-1963, SSB from 1964-1980 assuming a minimum level of 10 kT and SST rescaled from SIO Pier SST to CalCOFI SST based on a linear relationship. Circles indicate observed (and assumed) recruitment estimates, while black and grey lines show the predicted values with 95% CI. The dashed black line represents recruitment predictions based on 5-year averaged CalCOFI SSTs.

APPENDIX A

Attendance List

Name	**Affiliation**
Panelists	
André Punt (Chair)	University of Washington/SSC
Kevin Hill (Obj. 3 Rapporteur)	SWFSC
Josh Lindsay (Obj. 2b Rapporteur)	NMFS/SWR
Russ Vetter (Obj. 2a Rapporteur)	SWFSC
Brian Wells (Obj. 3 Rapporteur)	SWFSC
Alec McCall (Obj. 1 Rapporteur)	SWFSC
Dave Checkley	Scripps Inst. of Oceanography
Paul Crone	SWFSC
David Crabbe	PFMC member
Enrique Curchitser	Rutgers University
David Demer	SWFSC
Kerry Griffin	PFMC staff
Mark Helvey	NMFS/SWR
Sam Herrick	SWFSC
Felipe Hurtado	University of Washington
Larry Jacobson	NEFSC
Tom Jagielo	SSC
Kristen Koch	SWFSC
Tony Koslow	Scripps Inst. of Oceanography
Martin Lindegren	Scripps Inst. of Oceanography
Kirk Lynn	CPSMT/Cal Dept of Fish and Wildlife
Sam McClatchie	SWFSC
Don McIsaac	PFMC Exec. Director
Sarah McTee	CPSAS/Env. Defense Fund
Richard Parrish	Independent
Diane Pleschner-Steele	CPSAS/Cal. Wetfish Producers Assoc.
Chelsea Protasio	CPSMT/Cal Dept of Fish and Wildlife
David Sampson	SSC/Oregon State University
Alan Sarich	CPSMT/Quinault Tribe
Cyreis Schmitt	CPSMT/OR Dept of Fish and Wildlife
Lorna Wargo	CPSMT/WA Dept of Fish and Wildlife
Other Attendees	
Kevin Piner	SWFSC
Ralf Goericke	Scripps Inst. of Oceanography
Dan Huppert	SSC
Ray Conser	SWFSC, retired
Ben Enticknap	Oceana

Geoff Shester	Oceana
Jerry Thon	Commercial
Ashleen Benson	Marine Resources Assessment Group, Canada
Linnea Flostrand	Canada DFO
Nancy Lo	SWFSC, retired
Ed Weber	SWFSC
Bev Macewicz	SWFSC
Ryan Kapp	Commercial
Darrell Kapp	Commercial
Rebecca Asch	Scripps Inst. Of Oceanography
Erin Reed	SWFSC
Sean MacConnachie	Canada DFO
Steve Marx	Pew Oceans Commission
Tim Baumgartner	CICESE, Mexico
Josiah Renfree	SWFSC
Louie Zimm	Groundfish Advisory Subpanel (PFMC)
Kevin Stierhoff	SWFSC

SWFSC = Southwest Fisheries Science Center
NEFSC = Northeast Fisheries Science Center
NMFS = National Marine Fisheries Service
SWR = Southwest Region
PFMC = Pacific Fishery Management Council
CPSMT = Coastal Pelagic Species Management Team (PFMC)
CPSAS = Coastal Pelagic Species Advisory Subpanel (PFMC)
DFO = Department of Fisheries and Oceans

APPENDIX B

Primary Documents

1. Objective 1
    a. Hurtado, Punt, Hill, and MacCall - *Draft specifications and thoughts related to calculations to evaluate control rules for Pacific sardine* (Primary Document 1)
2. Objective 2
    a. Jacobson and Mcclatchie - *Comment – stock recruitment and temperature-recruit modeling for Pacific sardine in Jacobson and MacCall (1995) and McClatchie et al (2010) (Primary Document 2)*
    b. Lindegren and Checkley – *Temperature dependence of Pacific sardine (Sardinops sagax) recruitment in the California Current Ecosystem revisited and revised (in press) (Primary Document 3)*
    c. Demer and Zwolinski – *An estimate of the average portion of the northern stock of Pacific sardine (Sardinops sagax) residing in the U.S exclusive economic zone (Primary Document 4)*
3. Objective 3
    a. Demer and Zwolinski - *Optimizing U.S.-harvest quotas to meet the target total exploitation of an internationally exploited stock of Pacific sardine (Sardinops sagax).* (Primary Document 5)
    b. Kaplan - *Review of ecosystem models*
    c. McClatchie - *Revised2 HG workshop*

Demer, D.A. and Zwolinski, J.P. 2013a <draft workshop ms>. 20 p.
Demer, D.A. and Zwolinski, J.P. 2013b <draft workshop ms>. An estimate of the average portion of the northern stock of Pacific sardine (*Sardinops sagax*) residing in the U.S. exclusive economic zone.7p.

BACKGROUND/OTHER

Proposed agenda
PFMC Methodology Review Process Terms of Reference
Terms of Reference Sardine Harvest Parameters Workshop
Appendix B to Amendment 8
Sardine control rule(s) overview (Lindsay PPT)
MSE description (Punt, from SSC June 2012)
Re-evaluation of Fmsy for Pacific sardine in the absence of an environmental covariate (Hill et al, from 2011 sardine stock assessment)
Jacobson and MacCall 1995 – *Stock-recruit models for Pacific sardine (Sardinops sagax)*
McClatchie et al 2010 *Reassessment of temperature-recruit relationship (CJFAS)*
Smith 2008 *Improvements to NOAAs land-ocean temp analysis*
Smith Reynolds 2003 *Improved extended reconstruction of SST*
McClatchie - *Stand alone2 HG current state appendix*

Data

CalCOFI annual and spring mean temp

ERSST to compare with CalCOFI
SIO Temp 1916-2012
SIT Temp annmean 1980-2010
SIO temp MOMEAN 1916-2012
Asch and Checkley – *Dynamic height: a key variable for identifying the spawning habitat of small pelagic fishes*
Rykaczewski Checkley – *Influence of ocean winds on the pelagic ecosystem in upwelling regions (PNAS)*

APPENDIX C

Construction of the recruitment and age-2+ biomass series used in the modeling

Alec MacCall

Murphy (1966) and MacCall (1979) use age-2 as the reference age of recruitment. More recent assessments use age-0 as the age of recruitment (a nominal abundance based on a constant assumed natural mortality rate). Also, the definition of spawning stock biomass (SSB) has varied among sources. For example, Murphy (1966) assumed that before 1950 only half of the age-2 fish were spawning, but later all of them were. Detailed maturity data at the annual level are lacking, so a uniform definition of SSB as being all fish age-2 and older is a useful approximation. Ignoring the variability in egg production due to age-specific fecundity is a larger source of error variability than is ignoring fluctuations in age of first maturity, which is a portion of the former issue.

Reconstruction of age-0 recruitments

Murphy (1966) and MacCall (1979) reported initial numbers of fish at age-2. To obtain numbers at age-0, the age-2 values were inflated by two years of inverse natural mortality (exp(2*0.4) = 2.226). The effect of catches at ages 0 and 1 were ignored. Results are given in Table App.C.1.

Reconstruction of 1930 and 1931 SSB

Murphy (1966) reported recruitments at age-2 for 1932 and 1933. These were the 1930 and 1931 cohorts using the age-0 reference age. However, Murphy's SSB estimates begin in 1932. Approximate values of SSB in 1930 and 1931 were obtained by use of Pope's approximation where the catch is assumed to be removed at mid-year. Numbers at age (from Murphy's Table 14) were back-projected by one year of inverse natural mortality (exp(0.4) = 1.492) and were assigned weights at one year younger (Murphy's Table 16). The catches (in weight) for 1930 and 1931 were obtained from Murphy's Table 1, and back-projected by one-half a year ((exp(0.4/2) = 1.221), and added to the above values. The 1930 SSB was obtained by a second iteration of this procedure (Table App.C.1). Performance of this reconstruction was validated by comparing Murphy's reported age-2+ biomasses for 1932 to 1940 with biomasses reconstructed from the following year's information (Figure App.C.1).

Reconstruction of recruitment and SSB from 1965 to 1980

Most analyses of sardine stock and recruitment data ignore the years from 1965 to 1980 for which no estimates are available. About all we know is that the abundance was very low and did not increase noticeably during this period. This practice of omitting 1965-1980 has the unintended consequence of overestimating the long-term average sardine reproductive success. It may be better to reconstruct approximate stock and recruitment values for these years by assuming a low abundance (during this period the abundances were so low that precision is relatively unimportant) and using associated recruitment rates that would have achieved replacement in the absence of fishing.

Deleting the final year from MacCall (1979) due to lack of VPA convergence, the estimated SSB in 1964 was 11,000 tons. The first SSB reported from recent assessments (Hill *et al.*, 2010) was 10,300 tons in 1981. The values for 1965 through 1980 were assumed to be 10,000 tons. Actual values are thought to have been lower than this, if anything. Recruitment rates were based on a mortality rate of $M = 0.4\text{yr}^{-1}$ and weights as given in Murphy's Table 16, which indicate that a single recruit would generate 0.185 kg of age 2+ spawning biomass over its lifetime. The age-0 recruitment necessary to replace one kilogram of SSB is the inverse of this value, or 5.415 recruits, so the age-0 recruitments from 1963 to 1980 were set at 54 million (Table App.C.1).

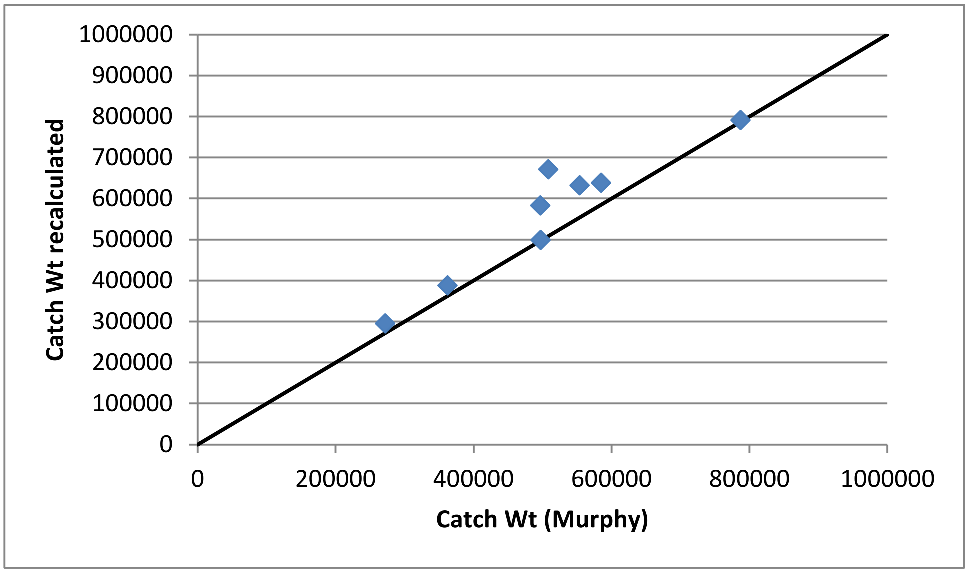


Figure App.C.1. Validation of SSB reconstructions from 1932 to 1940 published values.

Table App.C1. Historical values of sardine stock and recruitment.

Year	Biomass	Age 0
	2+, 10^3tons	**10^6 fish**
1930	**3377**	**8860**
1931	**3804**	**19318**
1932	3524	**31607**
1933	3415	**9120**
1934	3625	**6278**
1935	2845	**11980**
1936	1688	**15445**
1937	1207	**15051**
1938	1201	**26279**
1939	1608	**32141**
1940	1760	**13692**
1941	2458	**7273**
1942	2065	**8279**
1943	1677	**5308**
1944	1260	**3617**
1945	720	**3710**
1946	566	**8624**
1947	405	**9483**
1948	740	**8212**
1949	793	**645**
1950	780	**884**
1951	277	**2163**
1952	136	**2664**
1953	202	**850**
1954	239	**588**
1955	170	**1309**
1956	108	**3530**
1957	90	**2014**
1958	177	**641**
1959	122	**247**
1960	88	**165**
1961	54	**125**
1962	27	**24**
1963	21	**114**
1964	11	**60**
1965	**10**	**54**
1966	**10**	**54**
1967	**10**	**54**
1968	**10**	**54**
1969	**10**	**54**
1970	**10**	**54**
1971	**10**	**54**
1972	**10**	**54**
1973	**10**	**54**
1974	**10**	**54**
1975	**10**	**54**
1976	**10**	**54**
1977	**10**	**54**
1978	**10**	**54**
1979	**10**	**54**
1980	**10**	**54**

APPENDIX D
The indexes considered during Workshop

Year	SSB_age2+	R_age0	SIO_SST_ann	SIO_SST_T	SIO_SST_T3	SIO_SST_T5	SST_CC_ann	SST_CC_T	SST_CC_T3	SST_CC_T5
1930	3377000	8860	17.44167	18.15833	17.69722	17.135	NA	NA	NA	NA
1931	3804000	19318	18.49167	17.31667	17.13333	17.03	NA	NA	NA	NA
1932	3523506	31607	16.30833	15.925	16.63333	16.75333	NA	NA	NA	NA
1933	3414643	9120	15.66667	16.65833	16.55833	16.78667	NA	NA	NA	NA
1934	3625110	6278	17.54167	17.09167	16.84167	17.03	NA	NA	NA	NA
1935	2844931	11980	16.70833	16.775	17.11667	16.97333	NA	NA	NA	NA
1936	1688271	15445	17.61667	17.48333	17.13333	17.14667	NA	NA	NA	NA
1937	1206556	15051	17.03333	17.14167	17	17.30667	NA	NA	NA	NA
1938	1201113	26279	16.69167	16.375	17.15833	17.20167	NA	NA	NA	NA
1939	1607531	32141	17.175	17.95833	17.30278	17.19667	NA	NA	NA	NA
1940	1759938	13692	17.34167	17.575	17.49722	17.27667	NA	NA	NA	NA
1941	2457563	7273	17.65833	16.95833	17.21667	16.93833	NA	NA	NA	NA
1942	2064752	8279	17.01667	17.11667	16.95	16.79833	NA	NA	NA	NA
1943	1677385	5308	17	16.775	16.71944	16.81	NA	NA	NA	NA
1944	1260080	3617	16.48333	16.26667	16.63889	16.665	NA	NA	NA	NA
1945	720000	3710	16.60833	16.875	16.71944	16.53667	NA	NA	NA	NA
1946	566000	8624	16.825	17.01667	16.76111	16.57167	NA	NA	NA	NA
1947	405000	9483	16.89167	16.39167	16.51389	16.535	NA	NA	NA	NA
1948	740000	8212	16.08333	16.13333	16.32222	16.43833	NA	NA	NA	NA
1949	793000	645	16.53333	16.44167	16.42222	16.375	NA	NA	NA	NA
1950	780000	884	16.40833	16.69167	16.55556	16.46833	15.40368	14.26635	NA	NA
1951	277000	2163	16.625	16.53333	16.43333	16.5	15.29012	14.64754	NA	NA
1952	136000	2664	16.28333	16.075	16.40278	16.42667	14.6784	14.04742	14.32043	14.46474
1953	202000	850	16.25833	16.6	16.425	16.53	14.44392	14.2029	14.29929	14.41738
1954	239000	588	16.85833	16.6	16.50833	16.86667	14.93508	15.15951	14.46994	14.22383
1955	170000	1309	16.49167	16.325	16.65833	17.16167	15.15146	14.02954	14.46398	14.54843
1956	108000	3530	16.375	17.05	17.04444	17.36167	13.49907	13.67976	14.28961	14.83289
1957	90000	2014	17.375	17.75833	17.62778	17.40333	16.08645	15.67045	14.45992	14.93327
1958	177000	641	17.85	18.075	17.81111	17.235	16.33305	15.62516	14.99179	15.11549
1959	122000	247	18.36667	17.6	17.40278	16.99333	16.69939	15.66141	15.65234	15.23649
1960	88000	165	16.61667	16.53333	16.78056	16.75	15.5778	14.94068	15.40908	15.14425
1961	54000	125	16.525	16.20833	16.43056	16.51667	15.48333	14.28477	14.96228	15.06449
1962	27000	24	16.23333	16.55	16.53889	16.565	15.55526	15.20923	14.81156	14.72581
1963	21000	114	16.96667	16.85833	16.61389	16.65833	16.55827	15.22636	14.90679	14.60981
1964	11000	60	16.44167	16.43333	16.68889	16.81667	15.04767	13.96802	14.80121	14.80029
1965	10000	54	16.53333	16.775	16.62778	16.78833	14.5901	14.36066	14.51835	14.66948
1966	10000	54	17.00833	16.675	16.93056	16.82667	16.18217	15.23715	14.52194	14.36233
1967	10000	54	16.94167	17.34167	16.91111	16.71833	NA	14.55523	14.71768	14.56907

1968	10000	54	16.95	16.71667	16.89444	16.69667	NA	13.6906	14.49432	14.61928
1969	10000	54	16.65	16.625	16.525	16.64667	15.35002	15.00174	14.41585	14.30136
1970	10000	54	16.63333	16.23333	16.475	16.50833	NA	14.61167	14.43467	14.2379
1971	10000	54	16.18333	16.56667	16.63056	16.41167	NA	13.64759	14.42033	14.42033
1972	10000	54	16.86667	17.09167	16.56111	16.39333	15.15788	NA	14.12963	13.90549
1973	10000	54	16.45	16.025	16.41944	16.58667	NA	NA	13.64759	13.84453
1974	10000	54	16.48333	16.14167	16.10278	16.68833	NA	13.45719	13.45719	13.943
1975	10000	54	15.53333	16.14167	16.60556	16.845	14.29889	14.4288	13.943	14.6258
1976	10000	54	17.26667	17.53333	17.09167	17.01667	NA	NA	13.943	15.00295
1977	10000	54	17.24167	17.6	17.31389	17.21167	NA	15.9914	15.2101	15.5182
1978	10000	54	17.43333	16.80833	17.13611	17.10833	15.6876	16.13441	16.06291	15.74863
1979	10000	54	16.83333	17	16.975	17.11	NA	NA	16.06291	15.35168
1980	10000	54	16.625	17.11667	17.04444	17.36667	NA	15.12008	15.62724	15.41512
1981	6306	76	17.61667	17.01667	17.24722	17.50667	NA	14.16085	14.64046	15.17536
1982	8365	106	17.11667	17.60833	17.57222	17.64833	NA	16.24515	15.17536	15.28301
1983	9963	271	17.96667	18.09167	17.8	17.765	NA	NA	15.203	15.3727
1984	12820	239	18.31667	17.7	17.87222	17.68833	15.99283	15.60595	15.92555	15.7406
1985	20521	268	17.20833	17.825	17.70833	17.445	15.66987	15.47886	15.54241	15.48578
1986	27359	654	17.71667	17.6	17.55	17.39667	15.73054	15.63244	15.57242	15.42388
1987	32990	885	17.55833	17.225	17.23333	17.37	16.19182	15.22586	15.44572	15.26225
1988	53726	1270	16.975	16.875	17.18611	17.385	15.71291	15.17628	15.34486	15.28139
1989	84348	1084	17.175	17.45833	17.34167	17.56667	15.61665	14.79779	15.06664	15.26745
1990	119208	2261	17.88333	17.69167	17.60833	17.81	15.93865	15.57455	15.18287	15.40625
1991	134165	5354	16.95	17.675	17.83333	17.90167	15.70547	15.56278	15.31171	15.54399
1992	168037	3910	18.24167	18.13333	17.96667	18.005	16.62638	15.91985	15.68573	15.74789
1993	250493	10078	18.26667	18.09167	18.04722	18.09667	16.33465	15.86499	15.78254	15.77125
1994	329328	11130	18	17.91667	18.07222	18.28833	16.44578	15.8173	15.86738	15.7449
1995	562105	4223	17.80833	18.20833	18.08611	18.07833	15.79355	15.69133	15.79121	15.83659
1996	821223	6252	18.00833	18.13333	18.47778	17.92167	16.21949	15.43104	15.64656	15.77619
1997	819628	17156	19.15	19.09167	18.08889	17.79333	16.80187	16.37828	15.83355	15.6922
1998	771761	19743	18.15833	17.04167	17.75556	17.61333	16.55176	15.563	15.79077	15.45188
1999	1095610	3624	16.51667	17.13333	17.24722	17.31	15.18552	15.39736	15.77955	15.34539
2000	1495570	2928	17.69167	17.56667	17.31111	17.49833	15.73355	14.48971	15.15002	15.07494
2001	1324120	7959	17.35833	17.23333	17.45833	17.77167	15.4982	14.89859	14.92855	15.0094
2002	1054790	804	17.4	17.575	17.59722	17.825	14.90527	15.02604	14.80478	15.02401
2003	922151	18578	17.675	17.98333	18.01944	17.985	15.98058	15.23533	15.05332	15.07217
2004	670161	9617	18.325	18.5	18.10556	18.00167	15.78369	15.47037	15.24391	15.12692
2005	966770	10448	18.26667	17.83333	18.12222	17.97667	15.36299	14.73055	15.14542	14.85684
2006	1032250	3277	18.10833	18.03333	17.84167	17.915	15.71901	15.17229	15.1244	14.8191
2007	1071390	3596	17.675	17.65833	17.85	17.72667	15.06105	13.67564	14.52616	14.70808
2008	848438	2674	17.75	17.85833	17.90278	NA	15.12961	15.04663	14.63152	14.72086

Continued

Year	ERSST_ann	ERSST_T	ERSST_T3	ERSST_T5	PDO_ann	PDO_T	PDO_T3	PDO_T5	MEI_ann	MEI_T	MEI_T3
1930	18.9407	19.02753	NA	NA	-0.10417	0.4525	0.212222	0.156333	1.205083	1.612333	0.754611
1931	19.12153	18.62147	18.48733	18.57814	0.738333	0.36	0.274167	0.091	0.957167	0.431667	0.927333
1932	18.10517	17.813	18.25543	18.59512	-0.02083	-0.215	0.199167	0.319	0.50825	0.022083	0.688694
1933	17.7099	18.33183	18.4139	18.66705	-0.68	-0.1525	-0.0025	0.475667	-0.65233	-0.8445	-0.13025
1934	18.9902	19.09687	18.84704	18.95069	1.1825	1.15	0.260833	0.615667	-0.402	-0.16183	-0.32808
1935	18.95743	19.11243	19.06347	19.05275	0.798333	1.235833	0.744444	0.693667	-0.01075	0.293917	-0.23747
1936	19.32753	18.9811	19.10826	19.07602	1.730833	1.06	1.148611	0.804	0.299917	0.161917	0.098
1937	18.9673	19.23123	19.01814	19.15777	0.324167	0.175	0.823611	0.7415	0.049833	-0.30742	0.049472
1938	19.17597	18.8421	19.09552	19.22081	0.155	0.399167	0.544722	0.864667	-0.81533	-0.82125	-0.32225
1939	18.80297	19.21323	19.19217	19.16327	0.065	0.8375	0.470556	0.903833	-0.07108	0.840583	-0.09603
1940	19.43127	19.52117	19.34358	19.15476	1.769167	1.851667	1.029444	0.918333	1.107083	1.441417	0.486917
1941	19.5063	19.29633	19.25368	18.97242	1.994167	1.255833	1.315	0.820167	1.686167	1.114167	1.132056
1942	18.94397	18.94353	19.01313	18.73899	0.465833	0.2475	1.118333	0.619833	-0.12883	-0.75633	0.59975
1943	19.09173	18.79953	18.68153	18.65159	0.114167	-0.09167	0.470556	0.175667	-0.33575	-0.0095	0.116111
1944	18.5074	18.30153	18.48503	18.59503	-0.12667	-0.16417	-0.00278	-0.10283	-0.04333	-0.24533	-0.33706
1945	18.34447	18.35403	18.50497	18.50278	-0.19	-0.36917	-0.20833	-0.13467	-0.26108	-0.20925	-0.15469
1946	18.57873	18.85933	18.6247	18.53686	-0.58333	-0.13667	-0.22333	-0.40033	-0.02667	0.023333	-0.14375
1947	18.92463	18.66073	18.61944	18.60717	0.5	0.088333	-0.13917	-0.65417	-0.29592	-0.0855	-0.09047
1948	18.4079	18.33827	18.49031	18.50592	-0.87417	-1.42	-0.48944	-0.85617	0.1115	-0.06	-0.04072
1949	18.31657	18.47193	18.50526	18.44832	-1.22833	-1.43333	-0.92167	-0.989	-0.38467	-0.97875	-0.37475
1950	18.62127	18.70557	18.5102	18.44549	-1.81	-1.37917	-1.41083	-1.08667	-1.29958	-1.03733	-0.69203
1951	18.52143	18.3531	18.47713	18.41717	-0.76917	-0.80083	-1.20444	-0.88083	0.134417	0.690917	-0.44172
1952	18.4289	18.37273	18.34999	18.25403	-0.86583	-0.4	-0.86	-0.72567	0.16575	0.220833	-0.04186
1953	18.21597	18.32413	18.3424	18.28939	-0.15667	-0.39083	-0.53056	-0.9205	0.460083	0.161667	0.357806
1954	18.48703	18.33033	18.18144	18.4751	-0.29083	-0.6575	-0.48278	-0.9155	-0.53367	-1.13625	-0.25125
1955	17.87927	17.88987	18.25003	18.71475	-1.94833	-2.35333	-1.13389	-0.69817	-1.54842	-1.67392	-0.88283
1956	18.20527	18.5299	18.57368	18.86889	-1.80417	-0.77583	-1.26222	-0.57183	-1.2615	-0.37475	-1.06164
1957	18.95753	19.30127	19.11786	19.0018	0.2275	0.686667	-0.81417	-0.4075	0.81125	1.4375	-0.20372
1958	19.5236	19.5224	19.30822	18.95567	0.643333	0.240833	0.050556	0.06	1.115667	0.752417	0.605056
1959	19.34083	19.101	19.05928	18.82052	-0.02667	0.164167	0.363889	-0.09617	0.484083	0.139833	0.776583
1960	18.72913	18.55443	18.65156	18.66747	0.0575	-0.01583	0.129722	-0.38967	-0.07075	-0.06758	0.274889
1961	18.54007	18.29923	18.49307	18.51413	-0.8175	-1.55667	-0.46944	-0.59767	-0.05558	-0.47942	-0.13572
1962	18.25683	18.62553	18.56064	18.50451	-1.15833	-0.78083	-0.78444	-0.76567	-0.615	-0.35258	-0.29986
1963	19.01253	18.75717	18.57232	18.59288	-0.68583	-0.79917	-1.04556	-0.81283	0.354667	0.439583	-0.13081
1964	18.3633	18.33427	18.53259	18.70919	-0.77	-0.67583	-0.75194	-0.63367	-0.60317	-0.53225	-0.14842
1965	18.41637	18.50633	18.52723	18.76956	-0.31417	-0.25167	-0.57556	-0.60267	0.832333	1.356167	0.421167
1966	18.64113	18.7411	18.81818	18.80281	-0.45917	-0.66083	-0.52944	-0.505	0.62675	-0.21508	0.202944
1967	18.91243	19.2071	19.0024	18.73781	-0.73417	-0.62583	-0.51278	-0.309	-0.62292	-0.65875	0.160778

1968	19.2387	19.059	18.92221	18.61053	-0.40333	-0.31083	-0.5325	-0.5445	-0.20242	0.616333	-0.08583
1969	18.65937	18.50053	18.58028	18.47141	-0.09833	0.304167	-0.21083	-0.687	0.937417	0.5635	0.173694
1970	18.50777	18.1813	18.26219	18.31683	-0.3975	-1.42917	-0.47861	-0.62933	-0.45242	-1.4175	-0.07922
1971	18.066	18.10473	18.26583	18.22001	-1.29083	-1.37333	-0.83278	-0.74283	-1.42675	-0.48375	-0.44592
1972	18.3769	18.51147	18.30077	18.16245	-0.92167	-0.3375	-1.04667	-0.882	1.118167	1.462917	-0.14611
1973	18.31313	18.2861	18.27134	18.29775	-0.80417	-0.87833	-0.86306	-0.82733	-0.31217	-1.61408	-0.21164
1974	18.2908	18.01647	18.06534	18.41885	-0.33667	-0.39167	-0.53583	-0.37267	-1.29025	-0.86083	-0.33733
1975	17.7638	17.89347	18.2304	18.48711	-1.10167	-1.15583	-0.80861	-0.243	-1.38225	-1.5415	-1.33881
1976	18.46757	18.78127	18.59723	18.74753	0.008333	0.9	-0.21583	-0.10233	-0.12867	0.731417	-0.55697
1977	18.70337	19.11697	18.84188	18.96109	0.230833	0.310833	0.018333	0.1135	0.70475	0.674667	-0.04514
1978	19.13877	18.6274	19.02097	18.98903	0.235833	-0.175	0.345278	0.517833	0.32575	0.283833	0.563306
1979	18.80327	19.31853	18.96908	18.95154	0.335	0.6875	0.274444	0.375667	0.5835	0.87175	0.610083
1980	19.0381	18.9613	19.06693	19.05224	0.6025	0.865833	0.459444	0.514	0.719	0.228917	0.4615
1981	19.0716	18.92097	18.93726	18.91085	0.918333	0.189167	0.580833	0.839333	0.03875	0.285333	0.462
1982	18.8526	18.9295	18.99379	18.98417	0.114167	1.0025	0.685833	0.797167	1.348	2.577417	1.030556
1983	19.14387	19.1309	18.89066	19.00078	1.648333	1.451667	0.881111	0.803167	1.785333	0.24475	1.035833
1984	18.8854	18.61157	19.02347	18.96247	0.8375	0.476667	0.976944	1.045833	-0.2315	-0.54967	0.7575
1985	18.8349	19.32793	18.98117	18.90429	0.449167	0.895833	0.941389	1.142833	-0.49508	-0.13317	-0.14603
1986	19.3245	19.004	19.0233	18.9815	1.239167	1.4025	0.925	0.812833	0.491667	1.435917	0.251028
1987	18.87487	18.73797	18.86066	18.95205	1.820833	1.4875	1.261944	0.712833	1.89	1.186917	0.829889
1988	18.69637	18.84	18.85852	18.94411	0.531667	-0.19833	0.897222	0.353833	-0.61283	-1.45008	0.390917
1989	18.93627	18.9976	19.0061	19.16419	-0.17917	-0.02333	0.421944	0.1815	-0.82883	0.037417	-0.07525
1990	19.2605	19.1807	19.04753	19.21365	-0.35583	-0.89917	-0.37361	0.104667	0.41625	0.513667	-0.29967
1991	18.6814	18.9643	19.32779	19.19907	-0.41917	0.540833	-0.12722	0.405333	0.811	1.532667	0.694583
1992	19.6832	19.83837	19.29664	19.24933	0.928333	1.103333	0.248333	0.362	1.515583	1.12825	1.058194
1993	19.3992	19.08727	19.28346	19.31391	1.416667	1.305	0.983056	0.717167	1.180083	0.822333	1.161083
1994	18.92873	18.92473	19.148	19.25359	-0.15167	-0.24	0.722778	0.732333	0.877167	1.048667	0.99975
1995	19.1056	19.432	19.21464	19.08569	0.6425	0.876667	0.647222	0.803333	0.4665	-0.22725	0.547917
1996	19.3816	19.2872	19.41864	19.00334	0.640833	0.616667	0.417778	0.417	-0.30575	0.166083	0.329167
1997	19.6674	19.53673	19.0239	18.81365	1.460833	1.458333	0.983889	0.269333	1.857833	2.833917	0.92425
1998	18.9812	18.24777	18.76583	18.68147	0.245833	-0.62667	0.482778	0.025	0.924833	-0.89358	0.702139
1999	17.9678	18.513	18.41478	18.51579	-1.06333	-0.97833	-0.04889	-0.25017	-1.01233	-1.01133	0.309667
2000	18.76047	18.48357	18.54096	18.69459	-0.59	-0.345	-0.65	-0.32767	-0.72883	-0.44325	-0.78272
2001	18.5731	18.6263	18.60607	18.80212	-0.5625	-0.75917	-0.69417	-0.09333	-0.36583	0.060083	-0.46483
2002	18.48677	18.70833	18.82547	18.86929	0.220833	1.070833	-0.01111	0.232333	0.629667	0.83325	0.150028
2003	19.07693	19.14177	18.96691	18.88165	0.969167	0.545	0.285556	0.326167	0.541083	0.319417	0.40425
2004	19.06033	19.05063	19.00393	18.81693	0.345	0.65	0.755278	0.4525	0.44825	0.600583	0.584417
2005	18.89457	18.8194	18.85271	18.69545	0.375	0.124167	0.439722	0.09	0.183333	-0.2445	0.225167
2006	18.94013	18.6881	18.63076	18.65158	0.190833	-0.1275	0.215556	-0.28867	0.299167	0.549833	0.301972
2007	18.53637	18.38477	18.53574	18.52016	-0.19583	-0.74167	-0.24833	-0.36367	-0.34492	-0.89225	-0.19564
2008	18.31503	18.53437	18.58347	18.44857	-1.2925	-1.34833	-0.73917	-0.57083	-0.69283	-0.34067	-0.22769

Abbreviations:
SST: Sea Surface Temperature
SIO: Scripps Institute of Oceanography Pier;
CC: CalCOFI
ERSST: Extended reconstructed sea surface temperature (ERSST) version 3b;
PDO: Pacific Decadal Oscillation;
MEI: Multivariate El Niño Southern Oscillation Index;

ann: the calendar year mean by averaging monthly means from January to December;
T: the fishing season mean by averaging monthly means from July to June (in the following calendar year);
T3: a 3-year fishing season mean by averaging over the year of recruitment and the two years preceding recruitment;
T5: a 5-year fishing season mean by averaging from the two years preceding recruitment until two years after recruitment.

APPENDIX E
The full set of model selection statistics

Table App.E.1. Summary statistics for ln(R) models fitted with non-linear (G) and linear (L) temperature covariates to the entire data set. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. Different lengths in base models and models with covariates, i.e., due to NAs are indicated by NA. (The best models are shown in bold).

Covariate	Model	N_G	N_L	DF_G	DF_L	EDF_G	AIC_G	AIC_L	DEV_G	DEV_L	R2_G	R2_L	P_GB	P_LB	P_GL
SIO_SST_ann	1	62	62	57.67	58.06	1.37	204.22	204.49	0.5	0.5	0.53	0.52	0.08	0.09	0.12
SIO_SST_T	2	62	62	57.36	58.06	1.7	202.57	204.37	0.52	0.5	0.55	0.52	0.03	0.09	0.05
SIO_SST_T3	3	62	62	57.53	58.06	1.53	201.19	201.92	0.53	0.52	0.55	0.54	0.02	0.02	0.09
SIO_SST_T5	4	61	61	56.45	57.06	1.62	196.55	197.75	**0.55**	0.53	0.57	0.56	NA	NA	0.07
SST_CC_ann	5	39	39	34.41	35.12	1.74	128.47	131.05	0.46	0.41	0.51	0.45	NA	NA	0.03
SST_CC_T	6	41	41	36.6	37.1	1.52	137.34	138.1	0.48	0.47	0.52	0.5	NA	NA	0.09
SST_CC_T3	7	40	40	35.61	36.08	1.52	131.04	131.82	0.54	0.53	0.58	0.56	NA	NA	0.09
SST_CC_T5	8	40	40	36.07	36.07	1	128.88	128.88	**0.56**	0.56	**0.59**	0.59	NA	NA	0
ERSST_ann	9	62	62	58.06	58.06	1	205.13	205.13	0.49	0.49	0.52	0.52	0.14	0.14	0
ERSST_T	10	62	62	57.38	58.06	1.67	204.41	205.87	0.5	0.49	0.53	0.51	0.09	0.22	0.06
ERSST_T.3	11	61	61	56.43	57.07	1.63	199.92	201.08	0.52	0.5	0.54	0.53	NA	NA	0.07
ERSST_T5	**12**	**61**	**61**	**56.22**	**57.05**	**1.83**	**193.68**	**198.08**	**0.56**	**0.53**	**0.59**	**0.55**	**NA**	**NA**	**0.01**
PDO_ann	13	62	62	58.05	58.05	1	205.97	205.97	0.48	0.48	0.51	0.51	0.24	0.24	0
PDO_T	14	62	62	58.05	58.05	1	205.83	205.83	0.49	0.49	0.51	0.51	0.22	0.22	0
PDO_T3	15	62	62	58.06	58.06	1	206.13	206.13	0.48	0.48	0.51	0.51	0.27	0.27	0
PDO_T5	16	62	62	57.35	58.05	1.7	203.88	205.76	0.51	0.49	0.54	0.51	0.07	0.21	0.05
MEI_ann	17	62	62	58.05	58.05	1	204.39	204.39	0.5	0.5	0.52	0.52	0.09	0.09	0
MEI_T	18	62	62	58.05	58.05	1	205.17	205.17	0.49	0.49	0.52	0.52	0.14	0.14	0
MEI_T3	19	62	62	58.05	58.05	1	205.22	205.22	0.49	0.49	0.52	0.52	0.15	0.15	0
MEI_T5	20	62	62	58.05	58.05	1	204.87	204.87	0.49	0.49	0.52	0.52	0.12	0.12	0

Table App.E.2. Summary statistics for ln(R) models fitted with non-linear (G) and linear (L) temperature covariates when removing all years including NAs. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. (The best models are shown in bold).

Covariate	Model	N_G	N_L	DF_G	DF_L	EDF_G	AIC_G	AIC_L	DEV_G	DEV_L	R2_G	R2_L	P_GB	P_LB	P_GL
SIO_SST_ann	1	36	36	32.12	32.12	1	117.91	117.91	0.5	0.5	0.54	0.54	0.13	0.13	0
SIO_SST_T	2	36	36	32.13	32.13	1	116.89	116.89	0.52	0.52	0.56	0.56	0.07	0.07	0
SIO_SST_T3	3	36	36	32.19	32.19	1	113.75	113.75	0.56	0.56	0.59	0.59	0.01	0.01	0
SIO_SST_T5	4	36	36	32.16	32.16	1	106.47	106.47	0.64	0.64	0.67	0.67	0	0	0
SST_CC_ann	5	36	36	31.48	32.09	1.64	118.55	120.08	0.5	0.47	0.55	0.52	0.19	0.63	0.06
SST_CC_T	6	36	36	31.38	32.1	1.79	115.86	119.96	0.54	0.47	0.59	0.52	0.05	0.57	0.01
SST_CC_T3	7	36	36	31.78	32.09	1.35	119.51	119.8	0.48	0.48	0.53	0.52	0.34	0.48	0.11
SST_CC_T5	8	36	36	32.1	32.1	1	116.24	116.24	0.53	0.53	0.57	0.57	0.05	0.05	0
ERSST_ann	9	36	36	32.1	32.1	1	118.26	118.26	0.5	0.5	0.54	0.54	0.17	0.17	0
ERSST_T	10	36	36	32.1	32.1	1	118.43	118.43	0.5	0.5	0.54	0.54	0.18	0.18	0
ERSST_T.3	11	36	36	32.12	32.12	1	115.8	115.8	0.53	0.53	0.57	0.57	0.04	0.04	0
ERSST_T5	**12**	**36**	**36**	**31.33**	**32.08**	**1.76**	**105.99**	**108.96**	**0.65**	**0.61**	**0.69**	**0.65**	**0**	**0**	**0.03**
PDO_ann	13	36	36	31.67	32.1	1.43	118.96	119.41	0.49	0.48	0.54	0.52	0.24	0.36	0.11
PDO_T	14	36	36	32.09	32.09	1	119.03	119.03	0.49	0.49	0.53	0.53	0.27	0.27	0
PDO_T3	15	36	36	31.44	32.11	1.63	118.53	119.72	0.5	0.48	0.55	0.52	0.18	0.46	0.08
PDO_T5	16	36	36	31.53	32.09	1.58	115.55	116.59	0.54	0.52	0.59	0.56	0.04	0.06	0.08
MEI_ann	17	36	36	31.44	32.12	1.67	116.59	118.16	0.53	0.5	0.58	0.54	0.07	0.16	0.06
MEI_T	18	36	36	32.09	32.09	1	117.36	117.36	0.51	0.51	0.55	0.55	0.09	0.09	0
MEI_T3	19	36	36	31.17	32.14	1.91	111.03	119.47	0.6	0.48	0.64	0.52	0	0.38	0
MEI_T5	20	36	36	32.12	32.12	1	116.99	116.99	0.52	0.52	0.56	0.56	0.08	0.08	0

Table App.E.3. Summary statistics for ln(R) models fitted with non-linear (G) and linear (L) temperature covariates when fitting from 1984 to 2008 only. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. (The best models are shown in bold).

Covariate	**Model**	**N_G**	**N_L**	**DF_G**	**DF_L**	**EDF_G**	**AIC_G**	**AIC_L**	**DEV_G**	**DEV_L**	**R2_G**	**R2_L**	**P_GB**	**P_LB**	**P_GL**
SIO_SST_ann	1	36	36	32.12	32.12	1	117.91	117.91	0.5	0.5	0.54	0.54	0.13	0.13	0
SIO_SST_T	2	36	36	32.13	32.13	1	116.89	116.89	0.52	0.52	0.56	0.56	0.07	0.07	0
SIO_SST_T3	3	36	36	32.19	32.19	1	113.75	113.75	0.56	0.56	0.59	0.59	0.01	0.01	0
SIO_SST_T5	4	36	36	32.16	32.16	1	106.47	106.47	0.64	0.64	0.67	0.67	0	0	0
SST_CC_ann	**5**	**36**	**36**	**31.48**	**32.09**	**1.64**	**118.55**	**120.08**	**0.5**	**0.47**	**0.55**	**0.52**	**0.19**	**0.63**	**0.06**
SST_CC_T	6	36	36	31.38	32.1	1.79	115.86	119.96	0.54	0.47	0.59	0.52	0.05	0.57	0.01
SST_CC_T3	7	36	36	31.78	32.09	1.35	119.51	119.8	0.48	0.48	0.53	0.52	0.34	0.48	0.11
SST_CC_T5	8	36	36	32.1	32.1	1	116.24	116.24	0.53	0.53	0.57	0.57	0.05	0.05	0
ERSST_ann	9	36	36	32.1	32.1	1	118.26	118.26	0.5	0.5	0.54	0.54	0.17	0.17	0
ERSST_T	10	36	36	32.1	32.1	1	118.43	118.43	0.5	0.5	0.54	0.54	0.18	0.18	0
ERSST_T.3	11	36	36	32.12	32.12	1	115.8	115.8	0.53	0.53	0.57	0.57	0.04	0.04	0
ERSST_T5	12	36	36	31.33	32.08	1.76	105.99	108.96	0.65	0.61	0.69	0.65	0	0	0.03
PDO_ann	13	36	36	31.67	32.1	1.43	118.96	119.41	0.49	0.48	0.54	0.52	0.24	0.36	0.11
PDO_T	14	36	36	32.09	32.09	1	119.03	119.03	0.49	0.49	0.53	0.53	0.27	0.27	0
PDO_T3	15	36	36	31.44	32.11	1.63	118.53	119.72	0.5	0.48	0.55	0.52	0.18	0.46	0.08
PDO_T5	16	36	36	31.53	32.09	1.58	115.55	116.59	0.54	0.52	0.59	0.56	0.04	0.06	0.08
MEI_ann	17	36	36	31.44	32.12	1.67	116.59	118.16	0.53	0.5	0.58	0.54	0.07	0.16	0.06
MEI_T	18	36	36	32.09	32.09	1	117.36	117.36	0.51	0.51	0.55	0.55	0.09	0.09	0
MEI_T3	19	36	36	31.17	32.14	1.91	111.03	119.47	0.6	0.48	0.64	0.52	0	0.38	0
MEI_T5	20	36	36	32.12	32.12	1	116.99	116.99	0.52	0.52	0.56	0.56	0.08	0.08	0

Table App.E.4. Summary statistics for ln(R/S) models fitted with non-linear (G) and linear (L) temperature covariates to the entire data set. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. Different lengths in base models and models with covariates, i.e., due to NAs are indicated by NA. (The best models are shown in bold).

Covariate	**Model**	**N_G**	**N_L**	**DF_G**	**DF_L**	**EDF_G**	**AIC_G**	**AIC_L**	**DEV_G**	**DEV_L**	**R2_G**	**R2_L**	**P_GB**	**P_LB**	**P_GL**
SIO_SST_ann	1	62	62	58.77	58.77	1	177.37	177.37	0.16	0.16	0.19	0.19	0.03	0.03	0
SIO_SST_T	2	62	62	58.6	58.6	1	177.24	177.24	0.17	0.17	0.2	0.2	0.02	0.02	NA
SIO_SST_T3	3	62	62	58.44	58.44	1	172.77	172.77	0.23	0.23	0.26	0.26	0	0	0
SIO_SST_T5	4	61	61	57.49	57.49	1	166.52	166.52	0.27	0.27	0.3	0.3	NA	NA	0
SST_CC_ann	5	39	39	35.28	36	1.72	119.29	121.28	0.16	0.1	0.22	0.15	NA	NA	0.05
SST_CC_T	6	41	41	37.24	38	1.76	120.98	123.65	0.21	0.14	0.26	0.19	NA	NA	0.03
SST_CC_T3	7	40	40	36.65	36.91	1.35	118.54	118.78	0.17	0.16	0.22	0.2	NA	NA	0.11
SST_CC_T5	8	40	40	36.97	36.97	1	112.66	112.66	0.28	0.28	0.32	0.32	NA	NA	0
ERSST_ann	9	62	62	58.66	58.66	1	175.64	175.64	0.19	0.19	0.22	0.22	0.01	0.01	0
ERSST_T	10	62	62	58.74	58.74	1	177.52	177.52	0.16	0.16	0.19	0.19	0.03	0.03	0
ERSST_T.3	11	61	61	57.42	57.42	1	168.62	168.62	0.25	0.25	0.28	0.28	NA	NA	0
ERSST_T5	**12**	**61**	**61**	**57.81**	**57.81**	**1**	**160.29**	**160.29**	**0.34**	**0.34**	**0.36**	**0.36**	**NA**	**NA**	**0**
PDO_ann	13	62	62	59	59	1	171.4	171.4	0.24	0.24	0.26	0.26	0	0	0
PDO_T	14	62	62	59	59	1	170.73	170.73	0.25	0.25	0.27	0.27	0	0	0
PDO_T3	15	62	62	58.59	58.59	1	169.17	169.17	0.27	0.27	0.3	0.3	0	0	0
PDO_T5	16	62	62	58.88	58.88	1	162.08	162.08	0.34	0.34	0.37	0.37	0	0	0
MEI_ann	17	62	62	59	59	1	174.75	174.75	0.19	0.19	0.22	0.22	0	0	0
MEI_T	18	62	62	59	59	1	175.45	175.45	0.19	0.19	0.21	0.21	0.01	0.01	0
MEI_T3	19	62	62	58.89	59	1.11	174.76	174.78	0.2	0.19	0.22	0.22	0.01	0.01	0.09
MEI_T5	20	62	62	59	59	1	170.51	170.51	0.25	0.25	0.27	0.27	0	0	0

Table App.E.5. Summary statistics for ln(R/S) models fitted with non-linear (G) and linear (L) temperature covariates when removing all years including NAs. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. (The best models are shown in bold).

Covariate	**Model**	**N_G**	**N_L**	**DF_G**	**DF_L**	**EDF_G**	**AIC_G**	**AIC_L**	**DEV_G**	**DEV_L**	**R2_G**	**R2_L**	**P_GB**	**P_LB**	**P_GL**
SIO_SST_ann	1	36	36	33	33	1	107.48	107.48	0.2	0.2	0.24	0.24	0.01	0.01	0
SIO_SST_T	2	36	36	33	33	1	106.21	106.21	0.23	0.23	0.27	0.27	0	0	NA
SIO_SST_T3	3	36	36	33	33	1	99.88	99.88	0.35	0.35	0.39	0.39	0	0	NA
SIO_SST_T5	**4**	**36**	**36**	**33**	**33**	**1**	**93.07**	**93.07**	**0.46**	**0.46**	**0.49**	**0.49**	**0**	**0**	**0**
SST_CC_ann	5	36	36	32.12	32.5	1.58	111.34	112.23	0.13	0.1	0.2	0.16	0.16	0.29	0.07
SST_CC_T	6	36	36	32.18	32.74	1.82	107.92	111.62	0.2	0.11	0.27	0.16	0.02	0.19	0.01
SST_CC_T3	7	36	36	32.45	32.62	1.48	110.02	110.39	0.15	0.14	0.21	0.2	0.07	0.08	0.08
SST_CC_T5	8	36	36	32.77	32.77	1	105.44	105.44	0.25	0.25	0.29	0.29	0	0	0
ERSST_ann	9	36	36	32.8	32.8	1	109.98	109.98	0.14	0.14	0.2	0.2	0.06	0.06	0
ERSST_T	10	36	36	32.73	32.73	1	110.65	110.65	0.13	0.13	0.19	0.19	0.09	0.09	0
ERSST_T.3	11	36	36	33	33	1	106.35	106.35	0.22	0.22	0.27	0.27	0	0	0
ERSST_T5	12	36	36	32.52	32.52	1	101.63	101.63	0.33	0.33	0.37	0.37	0	0	0
PDO_ann	13	36	36	32.18	32.92	1.66	107.9	109.35	0.21	0.16	0.27	0.21	0.02	0.03	0.07
PDO_T	14	36	36	32.69	32.69	1	109.56	109.56	0.16	0.16	0.21	0.21	0.05	0.05	0
PDO_T3	15	36	36	31.53	33	1.89	103.71	108.92	0.3	0.17	0.37	0.21	0	0.02	0.01
PDO_T5	16	36	36	32.75	32.75	1	102.54	102.54	0.31	0.31	0.35	0.35	0	0	0
MEI_ann	17	36	36	32.41	33	1.52	109.71	110.4	0.16	0.13	0.22	0.18	0.06	0.06	0.1
MEI_T	18	36	36	32.49	32.57	1.09	109.89	109.91	0.15	0.15	0.21	0.21	0.06	0.06	0.07
MEI_T3	19	36	36	32.17	33	1.81	107	110.66	0.22	0.12	0.29	0.17	0.01	0.07	0.02
MEI_T5	20	36	36	33	33	1	106.97	106.97	0.21	0.21	0.25	0.25	0.01	0.01	0

Table App.E.6. Summary statistics for ln(R/S) models fitted with non-linear (G) and linear (L) temperature covariates when fitting from 1984 to 2008 only. The number of observations (N), residual degrees of freedom (DF), estimated degrees of freedom for the covariate smooth terms (EDF), Akaike´s Information Criteria (AIC), deviation explained (DEV), explained variance (R2), significance of the likelihood ratio test (P) between models with and without covariates (i.e., the base model (B) with SSB effect only), as well as between models fitted with non-linear (G) and linear (L) covariates. (The best models are shown in bold).

Covariate	Model	N_G	N_L	DF_G	DF_L	EDF_G	AIC_G	AIC_L	DEV_G	DEV_L	R2_G	R2_L	P_GB	P_LB	P_GL
SIO_SST_ann	1	25	25	21.97	22	1.03	56.81	56.82	0.57	0.57	0.61	0.6	0.04	0.04	0.05
SIO_SST_T	2	25	25	21.39	22	1.61	58.85	60.07	0.54	0.51	0.59	0.55	0.16	0.45	0.08
SIO_SST_T3	3	25	25	22	22	1	58.12	58.12	0.54	0.54	0.58	0.58	0.09	0.09	0
SIO_SST_T5	4	24	24	21	21	1	55.79	55.79	0.54	0.54	0.58	0.58	NA	NA	0
SST_CC_ann	**5**	**25**	**25**	**21.73**	**22**	**1.27**	**44.49**	**44.68**	**0.74**	**0.73**	**0.76**	**0.76**	**0**	**0**	**0.12**
SST_CC_T	6	25	25	21.87	22	1.13	56.76	56.82	0.57	0.57	0.61	0.6	0.04	0.04	0.1
SST_CC_T3	7	25	25	22	22	1	56.55	56.55	0.57	0.57	0.61	0.61	0.03	0.03	0
SST_CC_T5	8	25	25	22	22	1	58.37	58.37	0.54	0.54	0.58	0.58	0.11	0.11	0
ERSST_ann	9	25	25	22	22	1	55.3	55.3	0.59	0.59	0.63	0.63	0.01	0.01	0
ERSST_T	10	25	25	22	22	1	60.48	60.48	0.5	0.5	0.54	0.54	NA	NA	0
ERSST_T.3	11	25	25	22	22	1	58.1	58.1	0.55	0.55	0.58	0.58	0.09	0.09	0
ERSST_T5	12	25	25	21.65	21.65	1	59.27	59.27	0.53	0.53	0.58	0.58	0.21	0.21	0
PDO_ann	13	25	25	22	22	1	58.39	58.39	0.54	0.54	0.58	0.58	0.11	0.11	0
PDO_T	14	25	25	21.78	21.78	1	60.85	60.85	0.5	0.5	0.54	0.54	NA	NA	0
PDO_T3	15	25	25	22	22	1	58.97	58.97	0.53	0.53	0.57	0.57	0.17	0.17	0
PDO_T5	16	25	25	21.23	21.77	1.77	57.73	60.47	0.56	0.5	0.61	0.55	0.09	0.54	0.03
MEI_ann	17	25	25	22	22	1	55.1	55.1	0.6	0.6	0.63	0.63	0.01	0.01	0
MEI_T	18	25	25	21.95	21.99	1.05	59.44	59.45	0.52	0.52	0.56	0.56	0.25	0.25	0.05
MEI_T3	19	25	25	21.57	22	1.43	53.5	53.97	0.63	0.61	0.66	0.65	0.01	0.01	0.11
MEI_T5	20	25	25	22	22	1	60.38	60.38	0.5	0.5	0.54	0.54	0.9	0.9	0

APPENDIX F
Residual plots for the fit of the best model to each data set

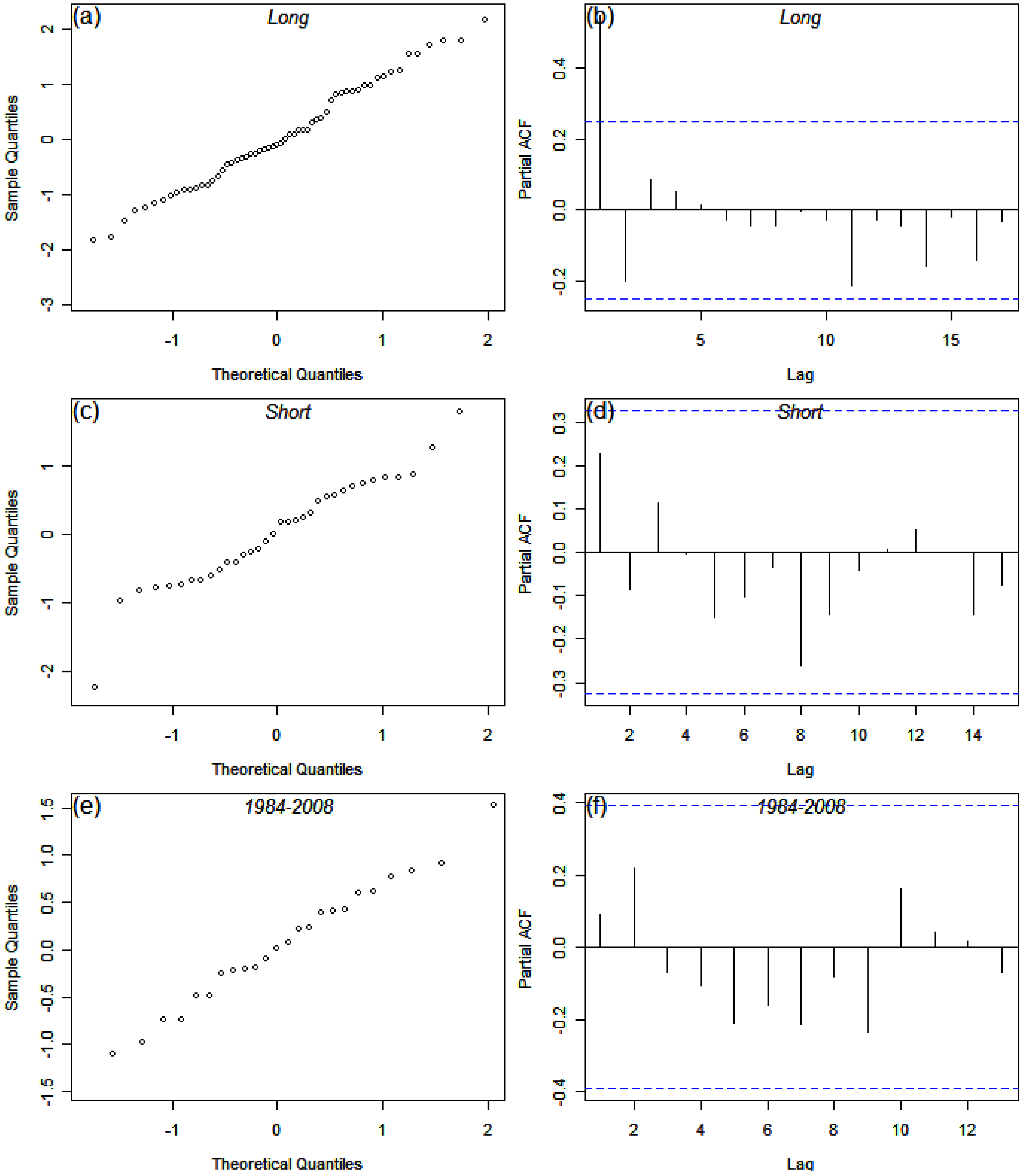


Figure App.E.1. (a, c, e) Normal probability plots and (b, d, f) partial autocorrelation plots of recruitment model residuals when fitted to the entire data set (long), when removing NAs (short), and from 1984-2008.

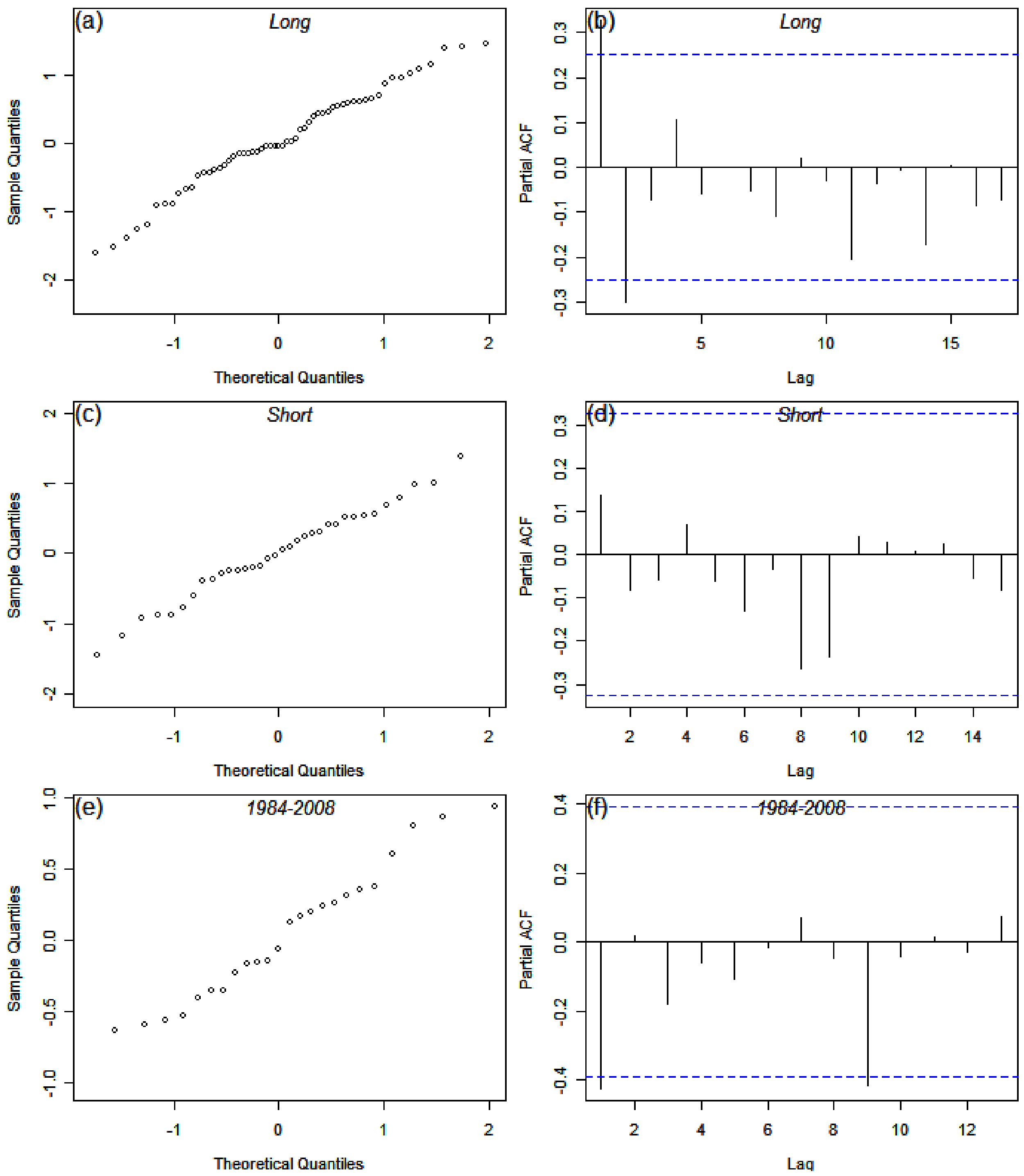


Figure App.E.2. (a, c, e) Normal probability plots and (b, d, f) partial autocorrelation plots of recruitment success model residuals when fitted to the entire data set (long), when removing NAs (short), and from 1984-2008.

APPENDIX G
Appendix – definition of CalCOFI index

1. Login into the CalCOFI data base at: http://sio-calcofi.ucsd.edu/db/login.php
2. Extract and export all temperatures between the depths 5 to 15 meters and lines 76.7 to 93.3 (i.e., the regular CalCOFI area)
3. Exclude years prior to 1984
4. Compute monthly averages across all stations
5. Compute yearly means by averaging monthly means from January to December
6. Compare with the time-series below and check for consistency.

Year	SST_CC_ann
1984	15.99283
1985	15.66987
1986	15.73054
1987	16.19182
1988	15.71291
1989	15.61665
1990	15.93865
1991	15.70547
1992	16.62638
1993	16.33465
1994	16.44578
1995	15.79355
1996	16.21949
1997	16.80187
1998	16.55176
1999	15.18552
2000	15.73355
2001	15.4982
2002	14.90527
2003	15.98058
2004	15.78369
2005	15.36299
2006	15.71901
2007	15.06105
2008	15.12961

APPENDIX H

Parametric forms for the CalCOFI-based index

Larry Jacobson and Martin Lindgren

The best spawner-recruitment model for Pacific sardine was fit as a generalized additive model (GAM):

$$\log R_y \sim \alpha + s\left(S_y, k = 3\right) + \beta T_y + \varepsilon_y$$

where R_y is recruitment in season y, α is an intercept parameter, $s(x, k=3)$ is a nonlinear smooth function of x, k controls smoothness by limiting the number of parameters in $s(x, k=3)$, S_y is spawning biomass, β is a slope parameter, T_y is SST, and ε_y is a normally distributed statistical error. The best model was dome-shaped in spawning biomass, with predicted recruitments declining above about 900 thousand t.

GAM's are handy for statistical modeling, but their functional form may not be easy to replicate in another programming language. Therefore, a parametric form of the best recruitment model was developed for use in the management strategy analysis program for Pacific sardine.

The best GAM model involves about 3.8 parameters (α, β and two parameters in the smooth term). This suggest that the GAM model could be approximated using a linear polynomial regression model with four parameters (i.e. one intercept parameter, one parameter for SST and two parameters spawning biomass).

The steps taken in constructing the approximation were as follows (see R code below):

1) Calculate a grid of spawning biomass and SST values at closely spaced intervals over the range of observed values. Predict log-recruitment over the grid using the GAM model.
2) Add the bias correction $0.5\sigma^2$ to the predicted log-recruitments from the GAM model.
3) Fit a linear regression model with linear and quadratic terms for spawning biomass and a linear term for SST to the predicted log-recruitments with bias correction from the best model
4) For use later, predict log-recruitments with the bias correction using the linear model. Back-transform predictions from the linear model to approximate arithmetic recruitment $\tilde{R}$. The back-transformed linear model and linear model parameters are the basis of approximation (see R code and, in particular, function ApproxSardineSR below).
5) Calculate and plot the relative errors ($e = \frac{\hat{R}-\tilde{R}}{\hat{R}}$ where $\hat{R}$ is a prediction from the best GAM model) to check the accuracy of the approximation (Figure App.H.1).

The approximation predicts arithmetic recruitments to within about ± 6% of predictions from the GAM model except at spawning biomass levels near zero and the maximum level where the relative errors are about 8% (see below).

The management strategy analysis may require a recruitment model that does not decline at high spawning biomass. To approximate such a model, take the derivative of recruitment in the linear regression model with respect to spawning biomass, set the derivative to zero and solve for the spawning biomass $\tilde{S} = \frac{-\beta}{2\beta_2}$ (β and β_2 are linear and quadratic spawning biomass parameters) at which recruitment is maximized. Set recruitment equal to the maximum recruitment at the current SST value if spawning biomass exceeds $\tilde{S}$.

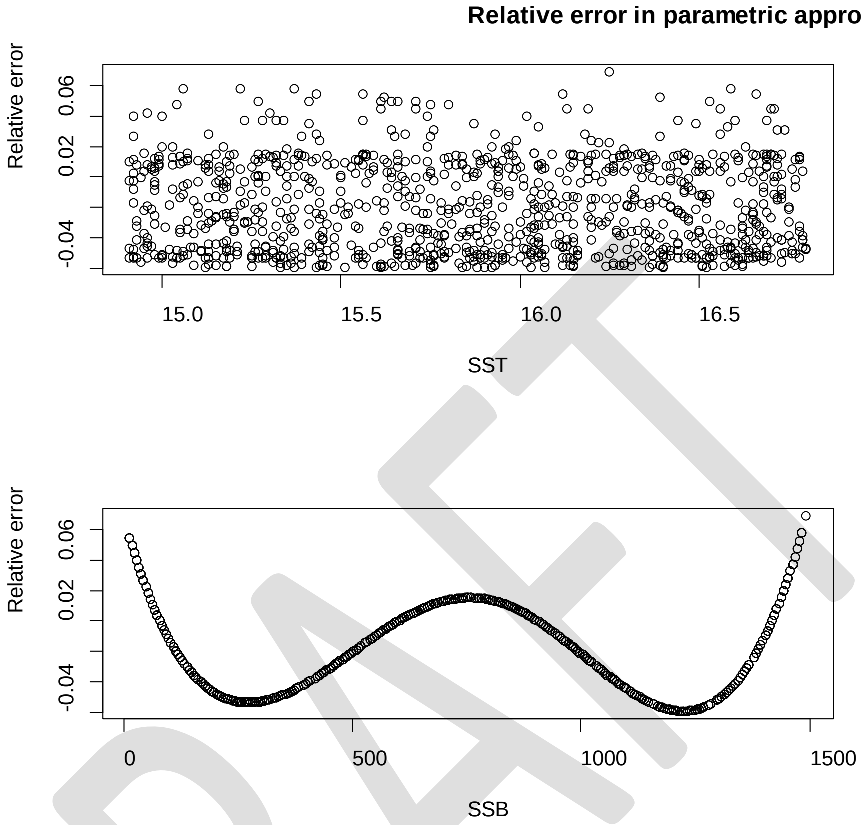


Figure App.H.1. Relative error in approximating predictions from the best GAM model for Pacific sardine using the back-transformed linear model described in this appendix. Relative error is $e = \frac{\hat{R}-\tilde{R}}{\hat{R}}$ where $\hat{R}$ is a prediction from the best GAM model and $\tilde{R}$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

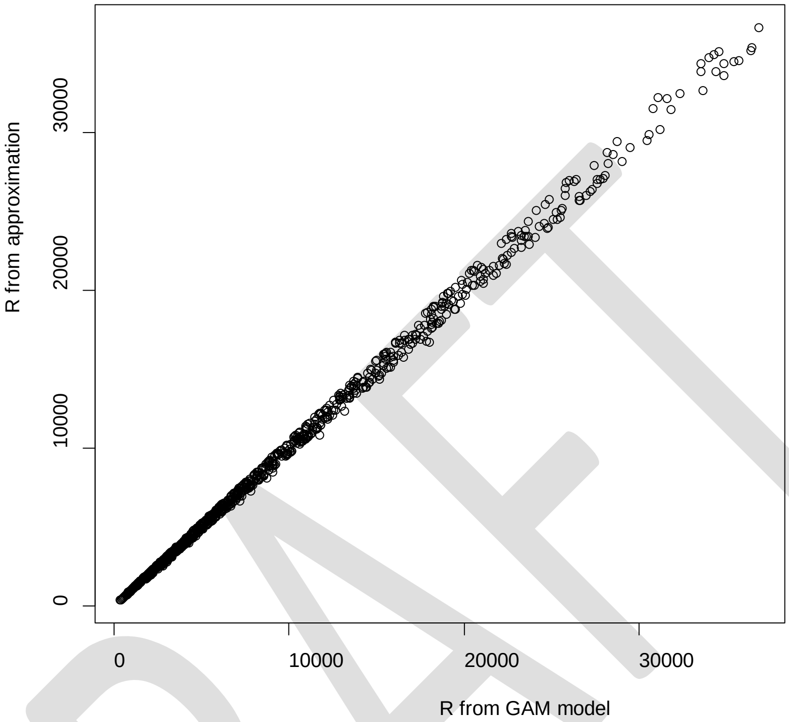
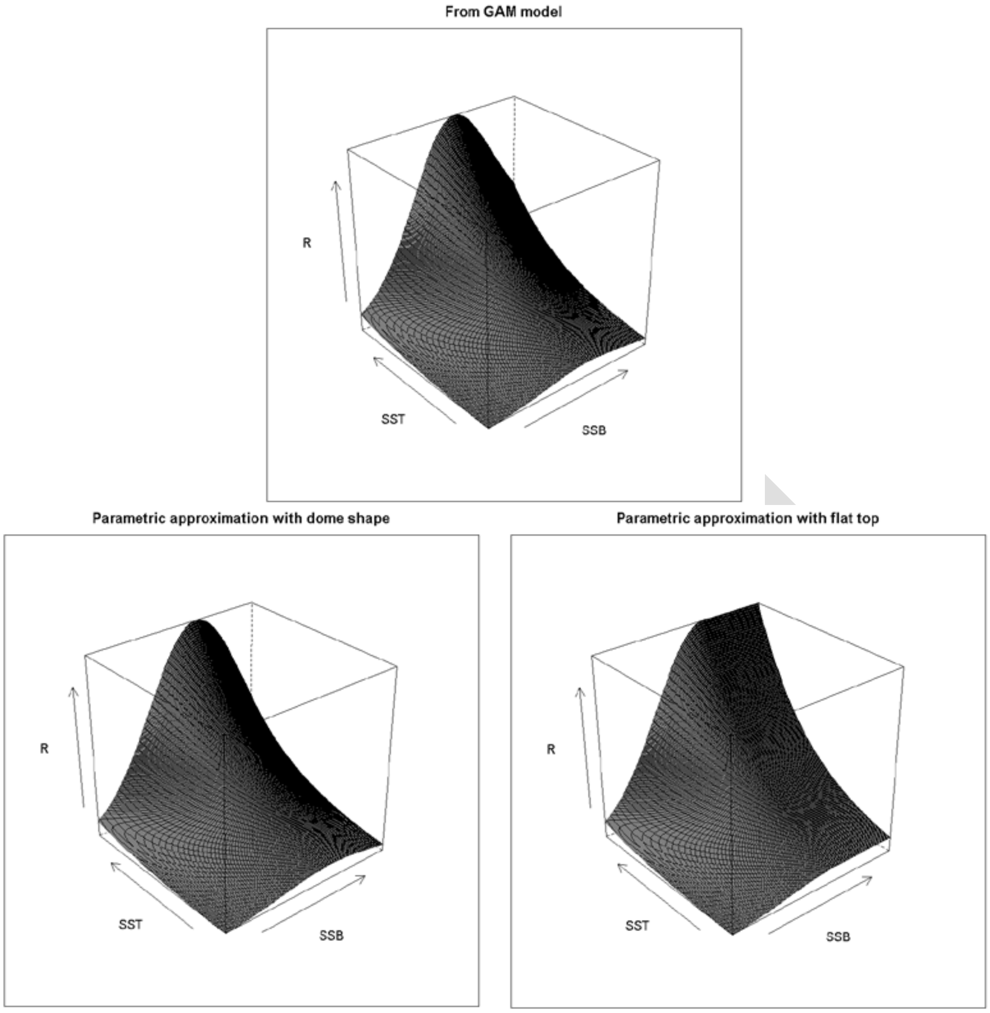


Figure App.H.2. Correspondence between predicted values from the best GAM and the ApproxSardineSR function. Results shown are for a random sample (N=1,000) of spawning biomass and SST points.


From GAM model

Parametric approximation with dome shape

Parametric approximation with flat top

Figure App.H.3. Predicted recruitments from the best GAM model (top) and from the ApproxSardineSR function (bottom) for a range of spawning biomass and SST levels. The approximations are the same at spawning biomass levels less than the level where the domed approximation reaches its peak (about 950 thousand t).

The ApproxSardineSR function in R for sardine and code used to parameterize and test it.

```
#####################################
# This code was used to build an approximation to the best
#  sardine spawner recruit GAM model identified at the 2013
#  harvest parameter workshop.  The model looks like:
#          ln(R)~s(SSB,k=3) + SST
# The code hear estimates paramters for the approximation,
#  tests it, defines an R function that could be implemented
#  in other languages and finally tests the function.
# This code was written to go with Appendix F in the workshop
#  report.
#                          Larry Jacobson, 12 February 2013
#####################################
rm(list=ls())
library(mgcv)
library(lattice)
windows(record=TRUE)

d<-"C:\\Users\\ljacobso\\Documents\\Pacific_Sardine\\Sardine HG WG\\Rstuff\\"

############################################################
#load the best log R model for sardine and drag out the data
load(file=paste(d,"bestR8408.Rdata",sep=""))
#extract data
dat8408<-bestR8408$model
summary(dat8408)

#look at original model df
summary(bestR8408)

#will need the log scale residual variance later
s2<-bestR8408$sig2

############################################################
#make a data grid for estimating the approximation
summrySSB<-summary(dat8408$SSB)
summrySST<-summary(dat8408$SST_CC_ann)

vSSB4plot<-c(seq(summrySSB[1],summrySSB[6],5))
vSST4plot<-c(seq(summrySST[1],summrySST[6],0.01))

pspSSB<-rep(vSSB4plot,length(vSST4plot))
pspSST<-rep(vSST4plot,each=length(vSSB4plot))
wfdat<-as.data.frame(cbind(SSB=pspSSB,SST_CC_ann=pspSST))
row.names(wfdat)<-paste(1:dim(wfdat)[1])

############################################################
#get predictions from the GAM model over the data grid
#     --need arithmetic R including bias correction
wfdat$RhatModel<-exp(predict(bestR8408,newdata=wfdat))*exp(0.5*s2)
names(wfdat)
summary(wfdat)

#after some exprimentation, I end up with a linear model that is
# quadratic in biomass and linear in SST - this is a form similar
# to the GAM model
#!!!important to use log RhatModel to get the bias correction in!!!

lngam<-lm(log(RhatModel)~SSB+I(SSB^2)+SST_CC_ann,data=wfdat)
summary(lngam)

#calculate approximations
lnRapprox<-predict(lngam)
Rapprox<-exp(lnRapprox)

#relative errors
relerrs<-(with(wfdat,RhatModel-Rapprox)/Rapprox)
summary(relerrs)
```

```
#quantify the amount of relative errors in the approximation
# relative to predictions from the GAM model
par(mfrow=c(2,1))
uze<-sample(1:length(relerrs),1000)

plot(relerrs[uze]~wfdat$SST[uze],xlab="SST",
     ylab="Relative error",
main="Relative error in parametric approximation")
plot(relerrs[uze]~wfdat$SSB[uze],xlab="SSB",ylab="Relative error")

############################################################
#      VERSION 2
#A parametric approximation to the best sardine GAM model
# for recruitment as a function of SSB and SST based on the
# linear model shown above.  Take care in applying the
# function to SST levels outside of 14.9-16.8 degrees C
# and spawning biomass levels above 1500 thousand t.
#                        Larry Jacobson, Feb. 10, 2013

ApproxSardineSR<-function(SSB,SST,FlatTop=FALSE){
#
#parameters for polynomial regression (first step)
   a <- -1.338750e+01
   B1 <- 4.999496e-03
   B2<- -2.600599e-06
   T1<-  1.280965e+00
   ansr<-a + B1*SSB + B2*SSB^2 +
              T1*SST
   if (FlatTop) {
#parameters for flat top ajustment
#  start by finding the biomass where R starts to decline (use derivative)
     ssbGoesFlat<- -B1/(2*B2)
     maxlnR<- a + B1*ssbGoesFlat + B2*ssbGoesFlat^2 +
              T1*SST
     ansr<-ifelse(SSB>ssbGoesFlat,maxlnR,ansr)
   }
   return(exp(ansr))
}


###########################################################
#compare GAM and approximate predictions
par(mfrow=c(1,1))
CheckApprox<-ApproxSardineSR(SSB=wfdat$SSB,SST=wfdat$SST,FlatTop=FALSE)
plot(CheckApprox[uze]~wfdat$RhatModel[uze],
     xlab="R from GAM model",
     ylab="R from approximation")

#A series of wireframe plots
wfdat$RhatAproxDomed<-ApproxSardineSR(SSB=wfdat$SSB,SST=wfdat$SST_CC_ann,FlatTop=FALSE)

wfdat$RhatAproxFlat<-ApproxSardineSR(SSB=wfdat$SSB,SST=wfdat$SST_CC_ann,FlatTop=TRUE)

wireframe(RhatModel~SSB+SST_CC_ann,data=wfdat,arrows=FALSE,
          xlab="SSB",ylab="SST",zlab="R",
          main="From GAM model")

wireframe(RhatAproxDomed~SSB+SST_CC_ann,data=wfdat,arrows=FALSE,
          xlab="SSB",ylab="SST",zlab="R",
          main="Parametric approximation with dome shape")

wireframe(RhatAproxFlat~SSB+SST_CC_ann,data=wfdat,arrows=FALSE,
          xlab="SSB",ylab="SST",zlab="R",
          main="Parametric approximation with flat top")
```

APPENDIX I
Stock-recruitment model using curl-driven upwelling index

```
Formula:

datS$ln_R0 ~ s(datS$SSB, k = 3) + s(datS$Curl_driven_upwell,  k = 3)

Parametric coefficients:

            Estimate Std. Error t value Pr(>|t|)

(Intercept)   8.1038     0.1616   50.16   <2e-16 ***

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:

                           edf Est.rank      F  p-value

s(datS$SSB)                1.897        2 16.331 5.93e-05 ***

s(datS$Curl_driven_upwell) 1.801        2  5.153   0.0155 *

R-sq.(adj) =  0.583   Deviance explained = 64.7%

GCV score = 0.80365   Scale est. = 0.65262   n = 25

Formula:

datS$ln_RS0 ~ s(datS$SSB, k = 3) + s(datS$Curl_driven_upwell,  k = 3)

Parametric coefficients:

            Estimate Std. Error t value Pr(>|t|)

(Intercept)   9.3056     0.1212   76.76   <2e-16 ***

Approximate significance of smooth terms:

                           edf Est.rank     F p-value

s(datS$SSB)                1.000        1 8.505 0.00821 **

s(datS$Curl_driven_upwell) 1.829        2 6.222 0.00749 **

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.662   Deviance explained = 70.1%

GCV score = 0.43387   Scale est. = 0.36742   n = 25


AIC(fitR_Curl_1984): 66.47012        >         AIC(fitR_final_1984):  62.22628
```

AIC(fitRS_Curl_1984): 51.41737 > AIC(fitRS_final_1984): 44.49302

Conclusion: The CalCOFI annual SST is a better predictor than the curl-driven upwelling index.

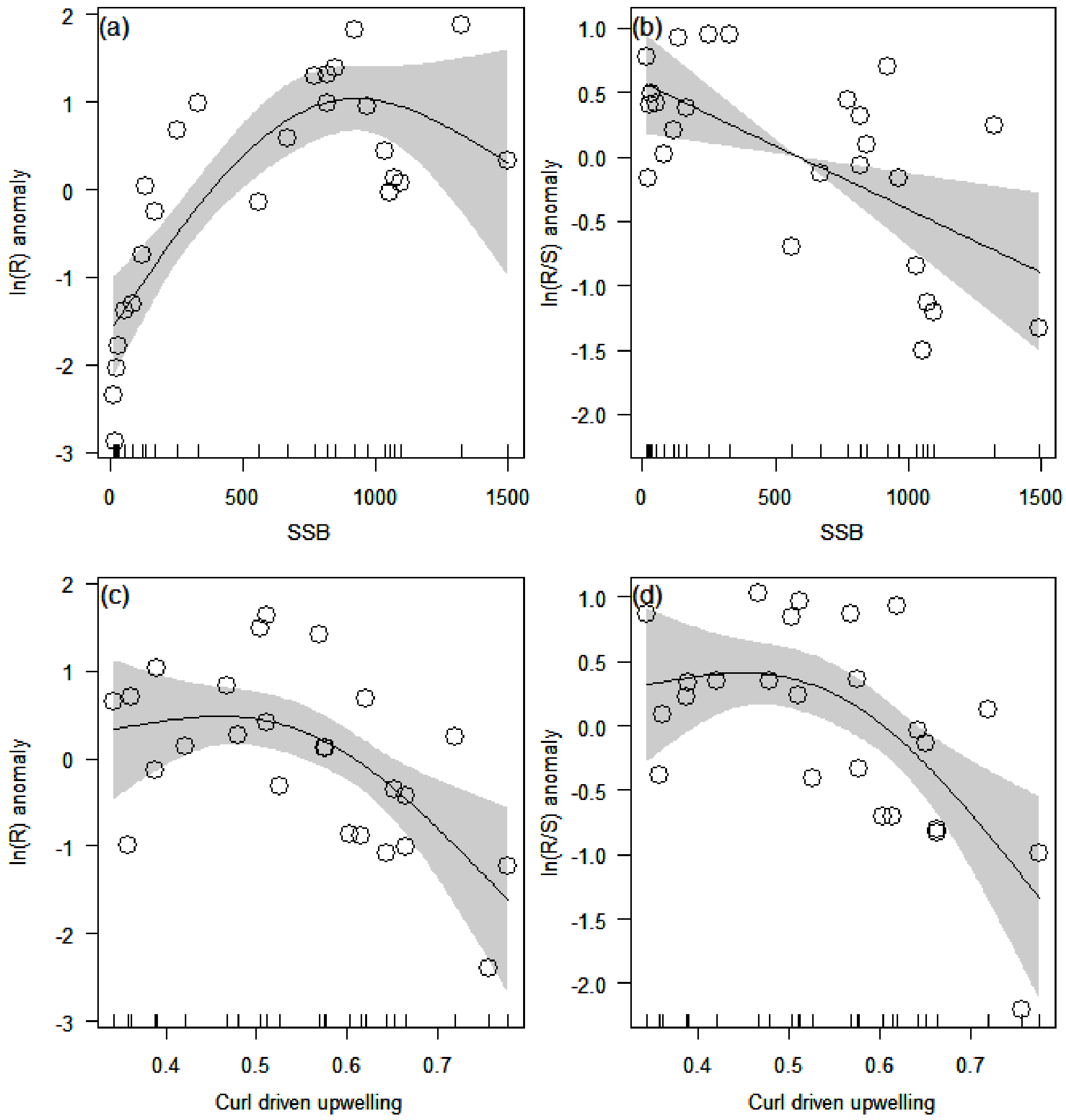


Figure App.I.1. The effects SSB (a, b) and curl-driven upwelling (c, d) on sardine recruitment when fitted to data from 1984-2008.