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Assessing the Effects of Climate Change on U.S. West Coast Sablefish Productivity and on the Performance of Alternative Management Strategies

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Note: We are in the process of correcting a miss-specification in the recruitment equation used to forecast recruitment deviations based on sea level and white noise prior to the PFMC March Council meeting. The current results may be pessimistic as they likely underestimate the occurrence of occasional strong recruitments.

Abstract

U.S. west coast sablefish are commercially valuable, making assessing and understanding the impact of climate change on the California Current (CC) stock a priority for (1) forecasting future stock productivity, and (2) testing the robustness of management strategies to climate variability and change. The horizontal-advection bottom-up forcing paradigm describes large-scale climate forcing that drives regional changes in alongshore and cross-shelf ocean transport and directly impacts the transport of water masses, nutrients, and organisms. This concept describes a mechanistic framework through which climate variability and change alter sea level (SL), zooplankton community structure, and sablefish recruitment, all of which have been shown to be regionally correlated. This study forecasts potential future trends in sablefish productivity using SL from Global Climate Models (GCMs) as well as explores the robustness of harvest control rules (HCRs) to climate driven changes in recruitment by conducting a management strategy evaluation (MSE) of the currently implemented 40-10 HCR as well as an alternative Dynamic Unfished Biomass 40-10 HCR. A majority of the GCMs suggest that after about 2040 there will be a slight trend towards generally lower SLs relative to the global mean, with an increasing frequency of low SLs outside of the range of the historical observations, suggesting favorable conditions for sablefish in the northern CC by 2060. Projected SLs from the GCMs suggest that future sablefish recruitment is likely to fall within the range of past observations but may be less variable and is likely to exhibit decadal trends that result in recruitments that persist at lower levels (through about 2040) followed by somewhat higher levels (from about 2040 through 2060). Although this MSE suggests that spawning biomass and catches will decline, and then stabilize, into the future under both HCRs, the sablefish stock is not projected to fall below the stock size that would lead to a fishery closure during the period analyzed (through 2060). However, the 40-10 HCR triggers stock rebuilding plans

more frequently than the alternative Dynamic Unfished Biomass 40-10 HCR (based on the concept of a dynamic, rather than static, baseline stock size), suggesting that the alternative HCR is more robust to potential future climate driven changes in sablefish productivity.

Introduction

U.S. west coast sablefish (*Anoplopoma fimbria*) in the California Current (CC) ecosystem are subject to a valuable commercial target fishery, and thus have been the subject of frequent assessments of stock status during the past decade (Schirripa and Colbert 2005, Schirripa 2007, Stewart et al. 2011, Johnson et al. 2016). These stock assessments consistently show that the U.S. west coast sablefish stock has declined steadily since the 1980s, concurrent with high landings during 1976-1990 and highly variable, but declining recruitment (Johnson et al., 2016). Each of these assessments has considered data on sea level (SL) and/or zooplankton as correlates between productivity in the California current and sablefish recruitment success (Schirripa and Colbert 2006, Schirripa et al. 2009). This is consistent with the horizontal-advection bottom-up forcing paradigm (Di Lorenzo et al. 2013) that large-scale climate forcing drives regional changes in alongshore and cross-shelf ocean transport, directly impacting the transport of water masses, nutrients, and organisms. This concept provides a mechanistic framework through which climate variability and change alter SL, zooplankton community structure, and sablefish recruitment, all of which are regionally correlated (e.g. Bi et al. 2011). Essentially, SL serves as an index of horizontal ocean transport, horizontal transport drives feeding conditions, and feeding conditions during the pelagic life stages drive sablefish recruitment. Sea level integrates across regional wind forcing, temperature anomalies, and coastally trapped phenomena that all impact the availability of food resources for many species in the CC. Lower SL is associated with colder-than-average water, more upwelling, stronger southward currents and lower salinity (Hickey 1998). All these factors provide better habitat conditions for young sablefish, on the continental shelf. Furthermore, Grover and Olla (1987) found that larval sablefish stomachs contain smaller, less energy dense copepods during warm El Niño years, when copepod communities are dominated by warm-water species, than during colder La Niña years.

The SL-sablefish recruitment relationship has been the subject of considerable discussion within the PFMC stock assessment review process and is compelling from an ecological standpoint. The use of SL indices has not had a large effect on stock assessment model results (Johnson et al. 2015) due its congruency with the fishery and survey data and the relatively low explanatory power (R^2 ~ 35%) (Stewart et al. 2011). While the fishery and survey data are informative about recruitment strengths (the number of age-1 fish entering the sablefish population), the SL-recruitment relationship can be used to produce decadal scale recruitment forecasts using the International Panel on Climate Change (IPCC) Global Climate Model (GCM) SL outputs. Such forecasts would allow fishery managers to respond to expected long term shifts in productivity and uncertain environmental conditions in the face of climate change. It is important to evaluate how resilient current fishery harvest control rules (HCRs) are to climate change and variability and to consider alternatives that might be more responsive to long term directional changes in the productivity of fish stocks. Ideally, fisheries should be managed using management strategies that are robust to climate change and variability. Therefore, this study uses Management Strategy Evaluation (MSE) to assess the interaction between climate change and fishing using projections of near-shore SL from the IPCC Coupled Model Inter-comparison Project Phase 5 (CMIP5) GCMs to produce multi-decadal recruitment projections. Specific goals are to (1) forecast future stock productivity, and (2) test the robustness of management strategies to climate variability and change.

Methods

This study uses the MSE approach, simulation testing with feedback, to compare the relative effectiveness for achieving management objectives among different combinations of data collection schemes, methods of analysis and subsequent processes leading to management actions (Punt et al. 2016), to investigate how fishery HCRs perform given climate-induced changes in SL that directly impact future sablefish recruitment (Figure 1). Both the operating and estimation models used the Stock Synthesis assessment-modeling framework (Methot and Wetzel 2012).

Sea Level Data

The CMIP5 set of GCMs were selected based on the results of Rupp et al. (2013), where 41 models were ranked according to the normalized error score from the first 5 principal components of an empirical orthogonal function analysis of 18 performance metrics. The best ranking GCM from each model family was chosen, resulting in 20 GCMs. One additional model from the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) was included, resulting in a set of 21 potential GCMs for use in this study. We chose to use the RCP8.5 emissions scenario as it most closely approximates current carbon emissions. GCM output was accessed online via the CMIP5 data portal (http://cmippcmdi.llnl.gov/cmip5/data_portal.html) during November 2014 and February 2015. Model outputs for monthly SL were available and downloaded for 17 of the 21 selected CMIP5 GCMs from the RCP8.5 emissions scenario. Sea level information was restricted to the grid cells closest to shore for each model along the US west coast from 40 to 49 degrees north. Each set of model output SLs were used to calculate a normalized time series of annual spatio-temporal mean SLs (from April through June), and standard deviations. The use of deviations in sea level from the long-term mean is the same approach used to prepare the original tide gauge data. Model output SL data from 6 CMIP5 models were eliminated due to 1) unrealistic disconnects between historical and projection period SLs (HadGEM2.ES, NorESM1.M, CMCC.CM), 2) a flat line mean SL with a large variance that provides no information about future SL for the CC region (MIROC5, EC.EARTH), and 3) initial MSE runs crashing (bcc.csm1.1) (Figure 3). The remaining 11 CMIP5 model output SLs were used to drive recruitment for the MSEs: CCSM4, CanESM2, GFDL.CM3, GFDL.ESM2G, Inmcm4, IPSL.CM5A.MR, MPI.ESM.MR, MRI.CGCM3, CNRM.CM5, GISS.E2.R.CC, and CESM1.CAM5 (Figure 3).

It bears noting that the specific measure of SL considered here, “zos”, reflects the regional effects of water mass and thermodynamic advection, and wind-driven and thermohaline circulations. It is separate from the modeled thermal expansion of the world’s ocean as a whole, represented by the “zostoga” variable (Church et al. 2013). It also is independent of other elements of the climate system changing with time influencing global mean sea levels, notably the contributions from ice sheets, glaciers, and land water storage. In other words, to the extent that observed SL represents a valid measure of regional horizontal ocean transports in the historical record, zos is an appropriate measure of future regional transports in climate model simulations.

Operating Model

We use an operating model to represent the 'true' state of the system for this simulation analysis. The operating model is a modification of the current stock assessment model used for management (Johnson et al. 2016) that is described in the estimation model section below, with one exception: the generation of future age-1 recruitment deviations is a function of the previous year's SL, such that 36% of the recruitment deviation is explained by SL (Stewart et al. 2011) and 64% of the recruitment deviation is explained by a draw from a random normal with mean = 0 and standard deviation = 0.65. **(Note that the standard deviations used here should have been 0.6 for the sea level and 0.8 for the white noise, a correction is under way)** A cutoff is applied to the recruitment deviation if it is larger than the maximum value over the historical period (2.589). Operating model parameters are treated the same as in the estimation model (Johnson et al. 2015). Both the operating and estimation models used Stock Synthesis (SS) (Methot and Wetzel 2012), version 3.24U. The configuration files for SS include the data, control, starter, and forecast files. The projection period for the MSE extends from 2016 through 2060.

First, the operating model for each IPCC GCM SL index *i* was run through the year 2016. This is the reference run. Then, for each IPCC GCM SL index *i* and projection year *y*, two model configurations were run in sequence. First, for year *y*, a calculation-only run was completed without estimating recruitment. This was used to generate fishery and survey length- and age-composition as well as the survey index. The purpose of the calculation-only run was to generate the expected length and age composition values for year *y*, that are then sampled to generate the 'observed' length and age composition observations for year *y* during the second step. The starter file for the calculation-only projection runs differed from that used for the reference and full projection runs by indicating that the run would perform no estimation and that the file with the estimated parameter values (the PAR file) would be read in and used to set all parameter values. The calculation-only run applied the projected catches for year *y* from the run for year *y*-1, set the recruitment deviation for year *y*-1 as specified above and for year *y* to 0, and did not estimate any parameters. Second, the full estimation run for year *y* is used to obtain the true state of the system with observation error. At the end of the projection period, this iterative approach provides the operating model time series of true and observed stock sizes and recruitments as well as catch limits for each year in the projection. Catch limits are fully attained during the projection period. For each year during the projection period, the observed data generated from the operating model were appended to the data file from the previous year. The changes to the control file between year *y*-1 and year *y* were to increment the end-year designations for catch and applying bias for the recruitment deviations.

Starting with the reference run, for each year during the projection period the MSE steps are (Figure 1):

1. The operating model was run with configuration files from year *y*-1, with
    a. the projected catches for year *y* from the run for year *y*-1 added to the data file
    b. the recruitment deviation for year *y*-1 set to 0.35 * the relationship with the SL index for year *y*-1 + 0.65 * a random draw from *N*(0, 0.65) in the PAR file
    c. the recruitment deviation for year *y* set to 0 in the PAR file

The operating model generates the 'observed' length and age composition data and the survey index for year *y*.

2. The estimation model was run for year *y*, with

   a. the starter file from the reference run
   b. the 'observed' length and age composition data for year y added to the data file
   c. the discard values added to the data file
   d. the 'observed' survey index added to the data file
   e. the environmental index added to the data file

   The estimation model calculates the projected fleet-specific catches for year *y+1*.

The catches for year *y* for each fishing fleet were taken from the catches projected for year *y* by the model run for year *y*-1 (in the Stock Synthesis output file Report.sso). The discard values for year *y* for each fishing fleet were taken from the average of the most recent 5 years of discard values (2010 – 2014) in the reference run data file and were constant over the projection period. The environmental index for year *y* came from the IPCC GCM SL output. The NWCBO survey index for year *y* was calculated from its catchability, its selectivity-at-age, and the numbers-at-age in year *y*, with lognormal error applied. The length and age composition data for year *y* from the calculation-only run were sampled from the expected length and age composition data for year y for each fishing and survey fleet.

Estimation Model

The estimation model is a modification of the current U.S. west coast sablefish (Johnson et al. 2015) Stock Synthesis assessment model that has been implemented for management. The 2015 model period models the population from 1900 through 2014, with 2015 being the first forecast year, and uses both survey (indices, lengths, and ages) and commercial fishery (discards, lengths, and ages) data. Specifically, primary sablefish data sources include: 1) landings and length- and age-frequencies of commercial catch; 2) commercial discard length compositions, rates, and mean observed individual body weight; and 3) relative biomass indices from the National Marine Fisheries Service (NMFS) Northwest Fisheries Science Center (NWFSC) Shelf-Slope trawl survey (2003-2014), NWFSC slope survey conducted from 1998-2002, Alaska Fisheries Science Center (AFSC) slope survey (1997-2001), and AFSC/NWFSC triennial shelf trawl survey (1980-2004) (Johnson et al. 2016). Fishery removals were assigned to three fleets: pot, hook-and- line, and trawl. The 2015 assessment modeled males and females as having independent dynamics, with separate estimated von Bertalanffy growth curves and natural mortality. Beverton-Holt stock-recruitment steepness is fixed at 0.6 in the assessment.

The 2015 stock assessment model explores the impact of modeling the annual normalized spatio-temporal mean tide gauge SL (from April through June for 40-49 degrees north), and standard deviations, during 1970 to 2014 as a survey index of recruitment deviations, but does not include these data in the base case model (Johnson et al. 2016). While the availability of SL data predate observations of sablefish length- and age-compositions by decades, the investigation of the SL index in the management model is confined to those years that also have information-rich length-and age-composition data (starting during 1970). The 2015 stock assessment concludes that the addition of the 1970-2014 SL data has little impact on stock assessment outcomes.

This study modifies the 2015 stock assessment model used for management by using all available SL data from tide gauges, 1925-2014, and estimating SL informed recruitment deviations during the same years. The bias adjustment of the stock-recruitment relationship is modified from the 2015 management model to account for the early use of the tide gauge SL data, such that the last early year of data without a bias adjustment is 1930, the first year with full bias adjustment is 1970, and the bias adjustment is phased out between 2014 and 2015 (Methot and Taylor 2011). The use of SL from 1925-1969 to hind-cast recruitment strength provides a consistent treatment of recruitment during both the early model period the forecast period where fishery and survey length and age composition data, that typically inform recruitment estimates, are limited or absent. During the early model and forecast periods the SL data weakly inform recruitment. Additional modifications include fixing the following parameters at estimated values from the 2015 stock assessment: the length at the minimum age and the coefficient of variability (CV) parameters of the length-at-age curve, natural mortality for both sexes, and the added standard deviations for the indices, as early MSE runs that estimated these values produced similar estimates with very little variability but greatly increased overall run time.

Harvest Control Rules

The MSE simulations were performed for three HCRs. First, a baseline no-fishing rule. Second, the HCR currently used by the Pacific Fishery Management Council (PFMC) for sablefish. The PFMC

HCR depends upon the estimation of unfished spawning biomass (B_0), setting the target reference point (stock size) at 40% of B_0, the limit reference point at 25% of B_0, and the point at which the fishery is closed at 10% of B_0. This HCR is commonly referred to as the 40-10 HCR (PFMC 2016). The aforementioned reference points are meant to be relatively static, changing only when the estimate of B_0 changes between subsequent assessments. Third, an alternative HCR based on the estimation of a time series of dynamic unfished spawning biomass (dynamic B_0) (MacCall et al. 1985). The time series of dynamic B_0 is the estimated spawning stock biomass in the absence of fishing, given the parameter estimates of the stock assessment model. Multiple methods can be used to specify what component of the time series is used for a reference point. In this case a dynamic B_0 40-10 HCR is implemented with a 35-year moving window to calculate unfished biomass. This dynamic unfished biomass rule essentially estimates the size that the spawning stock biomass would have been in a given year in the absence of fishing, then averages these values over the most recent 35 years (y – 35 to y – 1), allowing for the HCR to change slowly. Thirty-five years are approximately 2-generation times for sablefish (DFO 2014) and represents ages commonly seen in data collections for the California Current (Johnson et al. 2016).

Performance Metrics

Performance metrics are meant to 1) evaluate potential future trends in the sablefish stock and fishery given persistence of the SL-recruitment relationship, and 2) assess the ability of the current and alternative HCRs to maintain the stock near the target reference point of 40% B_0, prevent the stock from falling below the 25% B_0 reference point (resulting in an overfished declaration), and the 10% B_0 reference point (resulting in fishery closure). Note that in the case applying the dynamic unfished biomass HCR the reference points are permitted to change over time, based on the average of unfished biomass for the most recent 35 years. Specific performance metrics include:

1. Projected time series of spawning biomass, stock depletion, catches.
2. The distribution of estimated unfished biomass and unfished recruitment.
3. The year that the relative spawning biomass (stock depletion) declines below 1) the target stock size and 2) the stock size at which the fishery would be closed.
4. The proportion of the time that historical (defined as 1970 to 2014) and projected (defined as 2015-2060) spawning biomass is below the true (operating model) 25% (limit reference point) and 10% (fishery closure point) levels of B_0 (from the reference run).
5. Comparison of distributions of historical and projected spawning biomass and recruitment.

Results

Future SL deviations relative to the global mean from the 11 CGMs largely fall within the range of the historical observed deviations (Figures 2 and 3). However, the range of variability in the projected ensemble mean is less that that observed historically. Additionally, prior to approximately 2040 the ensemble mean SL deviation is higher than zero, indicating less favorable conditions for sablefish recruitment, while after approximately 2040 the ensemble mean SL deviation is below zero, indicating more favorable conditions for sablefish recruitment. Three models project California Current SL deviations at the end of the projection period to be greater than the long-term mean, with eight models projecting SL deviations lower than the long term mean. A majority of the GCMs suggest that after about 2040 there will be a slight trend towards generally lower SL deviations, with an increasing frequency of low SL deviations outside of the range of the historical observations.

Projected catches based on the application of the 40-10 HCR generally trend downward through approximately 2040, then stabilizing during 2040 to 2060, as SLs shift lower towards values more favorable for sablefish recruitment (Figure 4). On average, catches during the last 20 years of the projection period are lower than recent 2000 through 2014 catches, which generally ranged between 4000 and 6000 mt, similar to catches taken during the late 1960s and early 1970s. On average, catches during the last few decades of the projection period range between 2000 mt and 3000 mt. Projections suggest that catches will decline below the 2000 to 2014 minimum anywhere between the early 2020s and 2050s before stabilizing. One GCM, IPSL.CM5A.MR SL, suggests a marked increase in catches at the end of the projection period, driven by a strong trend towards lower SLs favorable for sablefish recruitment. Application of the dynamic B_0 40-10 HCR shows similar patterns to the catches set by the 40-10 HCR. However, the dynamic B_0 40-10 HCR sets catches slightly lower than the 40-10 HCR early in the projection period, resulting in stabilizing catches at slightly higher levels in comparison to the 40-10 HCR. The dynamic B_0 40-10 HCR results in larger catches from the middle to the end of the projection period than those obtained when applying the 40-10 HCR. The range of catches removed by both control rules are similar to removals taken from the sablefish stock during the late 1930s through early 1960s. Given a stock that is at the target stock size, on average catches would be specified at just over 4,000 mt, with slightly lower catches using the 40-10 HCR and slightly higher catches under the dynamic B_0 40-10 HCR (Table 1).

The baseline no-fishing HCR suggests an increasing stock, and stock status, throughout the projection period (Table 1), with the IPSL.CM5A.MR SL providing the most optimistic projection (Figures 5 and 6). Projections of spawning biomass and relative spawning biomass applying both the 40-10 and dynamic B_o 40-10 HCRs show stock declines followed by stabilizing trends, with the exception of the IPSL.CM5A.MR GCM SL projections that produce a strong stock increase (Figures 5 and 6). The 40-10 HCR results in the stock falling below the estimated 25% of unfished spawning biomass level for the first time during the late 2020s, while applying the dynamic B_0 40-10 HCR results in a decline below this reference point for the first time during the late 2030s. On average, the dynamic B_0 40-10 HCR results in slightly higher spawning stock size and status in comparison to the 40-10 HCR (Table 1) due to lower average catches.

The estimated distributions of the unfished biomass reference point, B_0 across all three HCRs are relatively narrow; many are similar to the B_0 estimate from the reference model (Figure 7). Average estimates across all GCMs (and across all years) are 115,782 mt, 115,911 mt, and 118,906 mt for the no-fishing, 40-10, and dynamic B_0 40-10 HCRs, respectively (Table 1). Note that the values for B_0 differ because each GCM run integrates sea level data from the 1925 through 2060. The no-catch scenario shows four GCMs with B_0 modes lower than the base, one GCM similar to the base, and six GCMs higher than the base. The 40-10 HCR show GCMs with tighter B_0 distributions, most with modes similar to the reference model. Compared to the no-fishing HCR, the 40-10 HCR shows more GCMs with modes shifted higher than the base model, except for the CCSM4 GCM, which suggests a B_o distribution shifted lower than the base model. The dynamic B_0 40-10 HCR results in two GCMs with B_0 distributions shifted lower than the reference model, four GCMs that are similar to the base model, and five GCMs shifted higher than the base model. The IPSL.CM5A.MR SL projection results in B_o distributions with the highest mode and widest distribution of B_o for all three HCRs.

The distributions of log-unfished recruitment (Figure 8) show wider distributions than those for B_0 across all three HCRs (Figures 7 and 8). Average estimates across all GCMs are 9.008, 8.960, and 9.150 for the no catch, 40-10, and dynamic B_0 40-10 HCRs, respectively (Table 1). Again, note that the values for log-unfished recruitment differ because each GCM run integrates sea level data from the 1925 through 2060. The no-fishing HCR results in five GCMs with log-unfished recruitment distributions lower than the base model and six GCMs higher than the base. The 40-10 HCR shows a wider spread of log-unfished recruitment distributions across GCMs than the no-fishing HCR Compared to the reference model these distributions are shifted lower for four GCMs, similarly for two GCMs, and higher for five GCMs. The dynamic B_0 40-10 HCR results in five GCMs with distributions of log-unfished recruitment shifted lower than the reference model, and six GCMs shifted higher. The CCSM4 and IPSL.CM4A.MR models bound the lower and upper ends of the distributions of log-unfished recruitment, respectively, for the 40-10 and B_0 dynamic HCRs.

The historical distributions of spawning biomass for the reference model and all HCRs show the greatest density falling above the 40% B_0 reference point, with a small proportion of the density in the precautionary zone between 40% B_0 and 25% B_0 (Figure 9). Notably, the projection period distributions for spawning biomass and recruitment are tighter than those from the historical period, with fewer strong but infrequent recruitment events to translate into higher levels of recruitment and spawning biomass **(this will likely change in revised model runs)** (Figures 9 and 10). Only the

IPSL.CM5A.MR GCM shows distributions of spawning biomass more similar to those from the historical period. In comparison to the historical distributions of spawning biomass, the no fishing HCR shows higher levels of spawning biomass during the projection periods across all GCMs, with little density falling in the precautionary zone. Application of the 40-10 HCR into the projection period results in a majority of the spawning biomass falling above the target reference point (40% B_0) in only one GCM, IPSL.CM5A.MR (Figure 9). All other GCMs show a majority of the distribution of project spawning biomasses in the precautionary zone (Figure 9). Application of the dynamic B_0 40-10 HCR during the projection period results in spawning biomass distributions that are, similar to or shifted higher than distributions from the projections under the 40-10 HCR.

During the projection period the sablefish stock does not decline below the 10% of the estimated unfished spawning biomass, the point at which the fishery is closed, under either HCR (static and dynamic B_0 40-10 HCR) given recruitment that is weakly driven by the SLs projected by each of the GCMs. Applying the 40-10 HCR during the projection period results in spawning biomass declines below the 25% B_0 (limit reference point) under SL conditions forecast by five of the GCMs during 10% to 70% of the projection years (Figure 11). Projections using the 40-10 HCR with six GCMs remain above the 25% B_0 reference point during the full projection period. Only one GCM SL projection results in the sablefish stock declining below the limit reference point of 25% of the unfished spawning biomass when applying the dynamic B_0 40-HCR for less than 20% of the projection years (Figure 11). Averaging across all GCMs the dynamic B_0 40-10 HCR keeps the stock above the limit reference point most of the time (Table 1).

Discussion

This work presents a first approach to MSE for sablefish off the U.S. west coast under potential future climate conditions, building directly on research linking SL to sablefish recruitment success in the California Current (Schirripa and Colbert 2006). The focus of this MSE is the impact of variability in the IPCC GCM SL forecasts on California Current sablefish recruitment, rather than the variability within the stock assessment model. Projected SLs from the CMIP5 GCMs suggest that future sablefish recruitment is likely to fall within the range of past observations but may be less variable **(this will likely change in revised model runs)** and is likely to exhibit decadal trends that result in recruitment levels that persist at lower levels (through about 2040) followed somewhat higher levels (from about 2040 through 2060). While the results of this study through approximately 2040 agree with a qualitative study that suggested northern CC sablefish would exhibit decreased year-class success with reduced spring productivity and copepod production for larvae (King et al. 2011), the results from approximately 2040 forward suggest increased year class success. The current GCMs seem to capture long-term trends in SL but suggest less natural variability. Decreased variability in SL could be partially related to a weaker ENSO, but warrants further investigation. The lower variance in the GCM SL projections, in comparison to historical values, suggests a lack of occasional large recruitments during the projection period that could sustain the population at higher levels due to the decreased variability in sea level. Indeed, in upwelling systems such as the CC longevity, coupled with high fecundity and periodic strong year classes (periodic strategists (Winemiller and Rose 1992, Winemiller 2005), are mechanisms expected to maintain sablefish biomass (King et al. 2000, King and McFarlane 2003, and Schirripa and Colbert 2006) at levels higher than estimated in this study. The periodic strategist life history type effectively allows fish stocks to withstand many years of poor recruitment by taking advantage of inter-annual variability that periodically favors strong recruitment (Winemiller and Rose 1992, Winemiller 2005).

Two model groups appear, out of the 11 GCMs. The first group suggests an overall decrease in productivity due to decreases in wind forcing, upwelling strength, and boreal copepod community leading to lower catches (higher SL resulting in lower recruitment). The second group suggests increases in productivity, likely due to increasing in deep water, nitrogen rich, upwelling (Rykaczewski and Dunne 2010) leading to an increase in productivity (lower sea level resulting in higher recruitment). A majority of the GCMs suggest that after about 2040 there will be a slight trend towards generally lower SLs, with an increasing frequency of low SLs outside of the range of the historical observations. Lower sea levels suggest more favorable conditions for sablefish in the northern California Current. Analyses of potential oceanographic changes in the CC due to climate change suggest only moderate oceanographic changes: mild surface warming accompanied by relatively minor increases in upwelling-favorable winds in northern portions of the CCS, with natural variability overshadowing climate signals for many important metrics (Overland and Wang, 2007; Wang et al., 2010). These results agree with the basic findings of Mote and Mantua (2002) that drastic changes in upwelling are unlikely over the next few decades, but are at odds with Bakun (1990) and Snyder et al. (2003), who posited that upwelling was liable to strengthen.

This MSE suggests that although spawning biomass and catches decline, and then stabilize, into the future under both the current 40-10 HCR, with static reference points, and the alternative dynamic B0 40-10 HCR, that both HCRs maintain the sablefish stock above the stock size that causes a fishery closure, as intended. However, using the 40-10 HCR triggers stock rebuilding plans more frequently that the dynamic B0 40-10 HCR, suggesting that the dynamic B0 HCR is more robust to potential future climate change due to the ability to track decadal scale changes in productivity.

While the dynamic B_0 HCR appears favorable given long-term shifts in productivity due to environment, it could be risk prone in cases where fishing pressure is causing biomass declines, allowing higher catches at low stock sizes due to reference points shifting lower through time. In practice, presenting a combination of both static and dynamic B_0 reference points to fishery managers is recommended. Note that this MSE does not model the stock rebuilding process triggered when the stock drops below the 25% B0 limit reference point. The improved performance of the dynamic B0 HCR aligns with the previous suggestion that management strategies need to consider the decadal-scale dynamics in sablefish year class success and their longevity (King et al. 2001).

One of the utilities of understanding the potential long-term impacts of climate change is in the ability to plan strategically for likely future changes, and the identification of potential climate adaptation strategies. Societal adaptations to projected declines in population size and catches could include: 1) adapting to a smaller fishery by developing markets for higher quality and priced product, 2) implementation of a dynamic control rule that further incorporates changes in stock productivity, 3) farm raised all female sablefish (Norman-López et al. 2013, Luckenback et al. 2017). Additionally, Norman-López et al. (2013) recommend evaluating the resilience of the fishery supply chain to likely declines in catch, with the goal of building community resilience to potential change. Given the potentially negative impacts to sablefish productivity, it is imperative to maintain monitoring programs that allow for tracking of potential non-stationarity in biological responses to long term climate forcing.

Sablefish is a multiple boundary-straddling stock managed independently and under distinct closed stock assumptions by PFMC, DFO-BC, and the NPFMC, none of which have a routine mechanism for exchange of information. However, sablefish are a single NE Pacific population (Jasonowicz 2017), the management of which would benefit from a collaborative research effort that includes a stock-wide stock assessment and modeling framework. Stock-wide research is particularly important due to decadal scale declines in both stock size and recruitment for NE Pacific sablefish. This MSE is based solely on a modification of the current PFMC stock assessment model implemented for management in the CC. A separate MSE for British Columbia sablefish also assumed a closed stock in spite of the contrary evidence (Cox and Kronlund 2008). Future MSEs for sablefish should encompass the whole NE Pacific stock. In fact, the PFMC passed a motion during 2015 requesting that federal scientists “initiate a comprehensive review of the status of the sablefish stock throughout its range, including Canada and Alaska”. Ideally, this effort should involve both research scientists and industry stakeholder. Data-based management procedures, in combination with periodic stock assessment modeling, are appealing to fishery stakeholders for setting catch limits, due to simplicity, transparency, and the ability to both meet long-term precautionary management objectives, and to provide information about trade-offs associated with alternative fishery management procedures (Cox and Kronlund 2008).

Increasingly skillful predictions of climate variables at scales useful to understanding and managing fisheries present opportunities for improved fishery management and industry operations, as well as new research avenues in fisheries science (Tommasi et al. 2017). However, taking advantage of these climate predictions requires continued data collection, and basic biological research and modeling studies that continue to strengthen mechanistic linkages between climate and fish population processes, allowing for improved prediction of ecosystem relevant climate variables at the regional scales at which fish population processes function and marine resource decisions are made (Tommasi et al. 2017). Specifically, future sablefish work should investigate the utility of forecasting using short term seasonal to annual climate model products, as well as engage with the PFMC, NPFMC, and DFO-BC to solicit feedback on subsequent iterations of this MSE. Currently, near-term sablefish forecasts rely upon average recruitment from the stock recruitment curve. However, recruitment is often far above or below the average, with large annual deviations around that curve. Using even the weak SL-recruitment relationship to inform whether near term recruitment is likely to be above or below the average would be informative for fishery managers.

Regional sea level, as used in this study, reflects the integrated effects of a variety of processes and represents a single overall measure of physical oceanographic conditions. Using specific regional environmental indices at spatio-temporal scales relevant to the sablefish life history results in greater ability to explain the variation around the stock-recruitment curve, 57% in the case of CC sablefish (Tolimieri et al. 2018). Indices with greater explanatory power are more likely to be useful in near term recruitment projections from stock assessment models and may be less likely to break down over time. The indices identified by Tolimieri et al. (2018) could inform future MSE development for sablefish both in the CC and the NE Pacific as well as for short term forecasting of recruitment. This study assumes that the SL-recruitment relationship is stationary, along with other potentially important ecological relationships. Future MSE may investigate the impact of such assumptions. Finally, research that can provide advice on technical stock assessment modeling issues such as how best to specify the stock-recruitment bias correction during model periods with environmental data (where, in this example, SL informs a recruitment estimate a single time) but without length and age composition data (where multiple observations through time inform recruitment estimates) would be beneficial to future studies. While the current implementation of the stock-recruitment bias correction in SS is implemented as a simple ramp (Methot and Taylor 2011), a more complex shape would most likely be an improvement when environmental data is used to hind-cast recruitment in the absence of age- and length-composition data.

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Tables

Table 1. Reference points and projection-period averages and standard deviations across all Global Climate Models for each Harvest Control Rule (HCR).

	No-Fishing		40-10 HCR		Dynamic Unfished Biomass 40-10 HCR	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Unfished recruitment (millions)	9.008	0.496	8.960	0.425	9.150	0.525
Unfished spawning biomass (mt)	115,782	6,733	115,911	5,146	118,906	6,879
Spawning biomass at 40% Unfished spawning biomass (mt)	46,313	2,693	46,364	2,059	47,562	2,752
Catch at 40% Unfished spawning biomass (mt)	4,283	252	4,289	208	4,386	268
Spawning Biomass at MSY (mt)	33,905	1,989	33,962	1,519	34,835	2,018
Catch at MSY (mt)	4,490	264	4,495	218	4,597	281
Spawning biomass 2015-2024 (mt)	52,132	6,013	41,748	3,582	44,286	4,046
Spawning biomass 2051-2060 (mt)	74,839	21,823	34,071	14,866	37,623	10,580
Ratio of biomass 2015-2024 to Unfished spawning biomass	45.0%	4.7%	36.0%	2.7%	37.2%	2.2%
Ratio of biomass 2051-2060 to Unfished spawning biomass	64.0%	13.9%	29.0%	10.8%	31.3%	7.0%

Figure Captions

Figure 1. Illustration of the MSE loop.

Figure 2. Mean normalized sea level data from the historical period (1925-2014) and the projection period (2015-2060) where the historical values are the spatio-temporal mean SL calculated as used in past stock assessments and the projected values are the ensemble mean SLs across the 11 GCMs (bold black line). Also plotted are the sea level from each individual GCM (grey lines), the minimum and maximum SLs from the historical period (horizontal dashed lines), the lower and upper 5% and 95% quantiles from the ensemble of 11 GCMs (light black lines), and the mean SL over the last 10 years of the projection period for each of the 11 GCMs (open circles are above the zero line, closed circles are below the zero line).

Figure 3. Individual mean normalized sea level from each individual GCM.

Figure 4. Catches resulting from application of the current 40-10 HCR (top panel) and the dynamic unfished biomass HCR (bottom panel).

Figure 5. Time series of spawning biomass from the no catch, 40-10 HCR, and dynamic unfished biomass 40-10 HCR.

Figure 6. Time series of stock depletion from the no catch, 40-10 HCR, and dynamic unfished biomass 40-10 HCR.

Figure 7. Distribution of unfished spawning biomass from the no catch, 40-10 HCR, and dynamic unfished biomass 40-10 HCR.

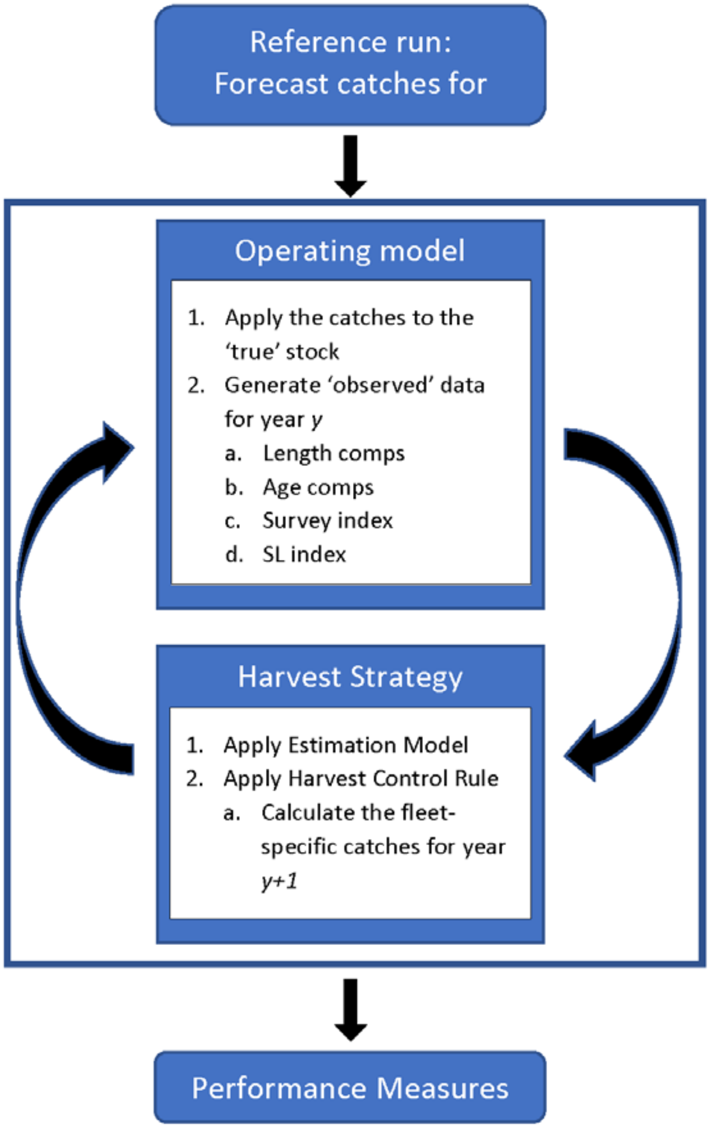
Figure 8. Distribution of log unfished recruitment from the no catch, 40-10 HCR, and dynamic unfished biomass 40-10 HCR.

Figure 9. Spawning biomass distributions versus management targets including, the target sock size (40% of unfished spawning biomass, the green line), stock size at which a rebuilding plan would be required (25% of unfished spawning biomass, the yellow line), and stock size at which the fishery would be closed (10% of unfished spawning biomass, the red line). Panels show the historical distributions (upper row), projected distributions (lower row), and the three HCRs, no fishing (left column), 40-10 HCR (middle column), and dynamic unfished biomass HCR (right column). The GCMs are given across the x axis.

Figure 10. Recruitment distributions for each CGM (x axes). Panels show the historical distributions (upper row), projected distributions (lower row), and the three HCRs, no fishing (left column), 40-10 HCR (middle column), and dynamic unfished biomass HCR (right column). The black horizontal line is the reference model median recruitment.

Figure 11. Proportion of years below the limit reference point of 25% of the estimated unfished spawning biomass for the 40-10 HCR (left panel) and the dynamic unfished biomass 40-10 HCR (right panel).

Figures



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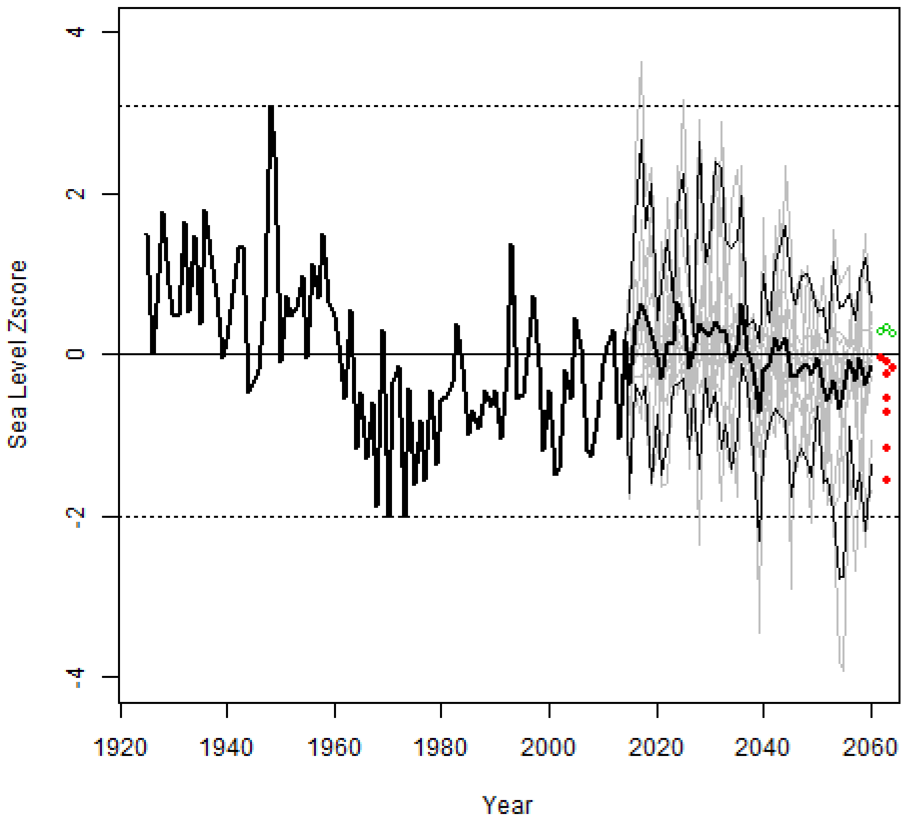
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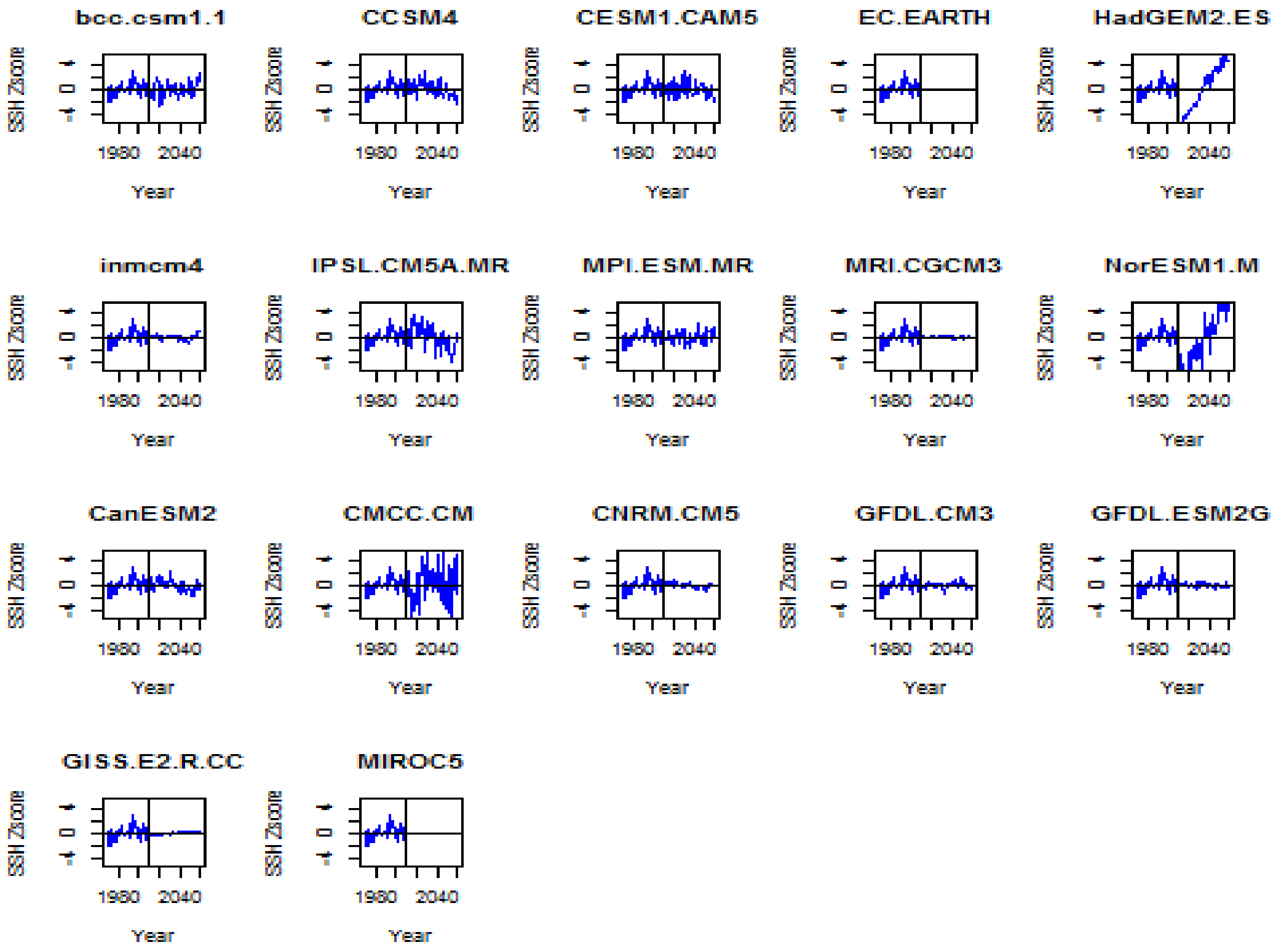
2
0
-2
-4
1920
1940
1960
1980
2000
2020
2040
2060
Year

Figure 2.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EC.EARTH
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NorESM1.M
CanESM2
CMCC.CM
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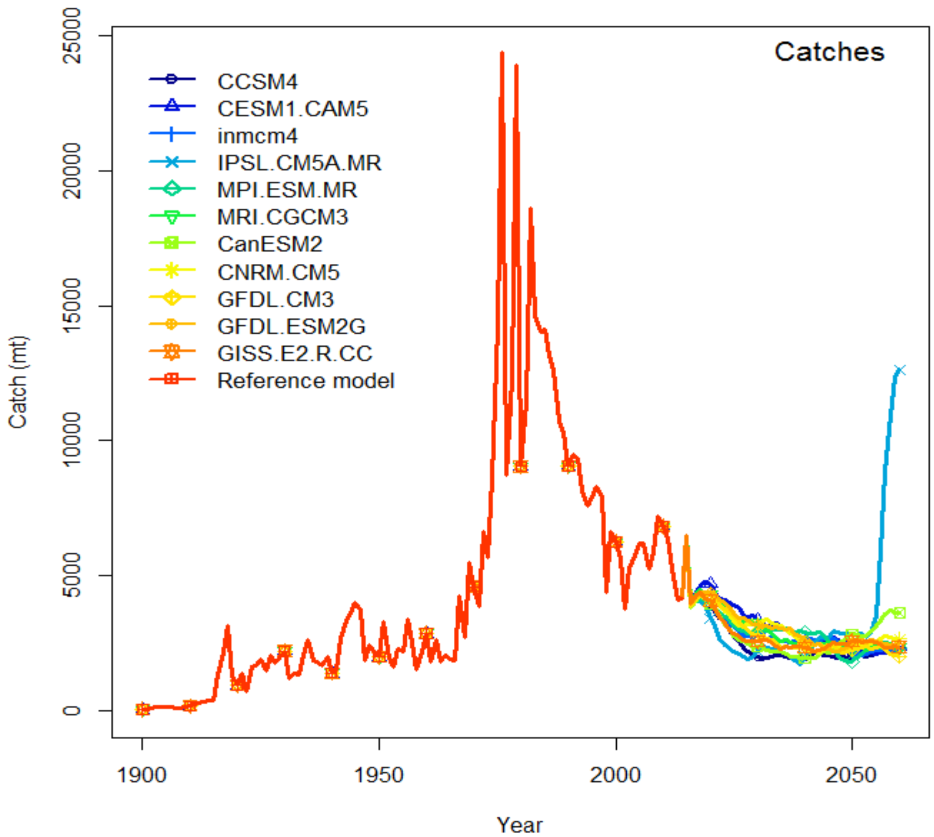
GFDL.ESM2G
GISS.E2.R.CC
MIROC5
SSH Zscore
Year
1980
2040

Figure 3.


Catches
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inmcm4
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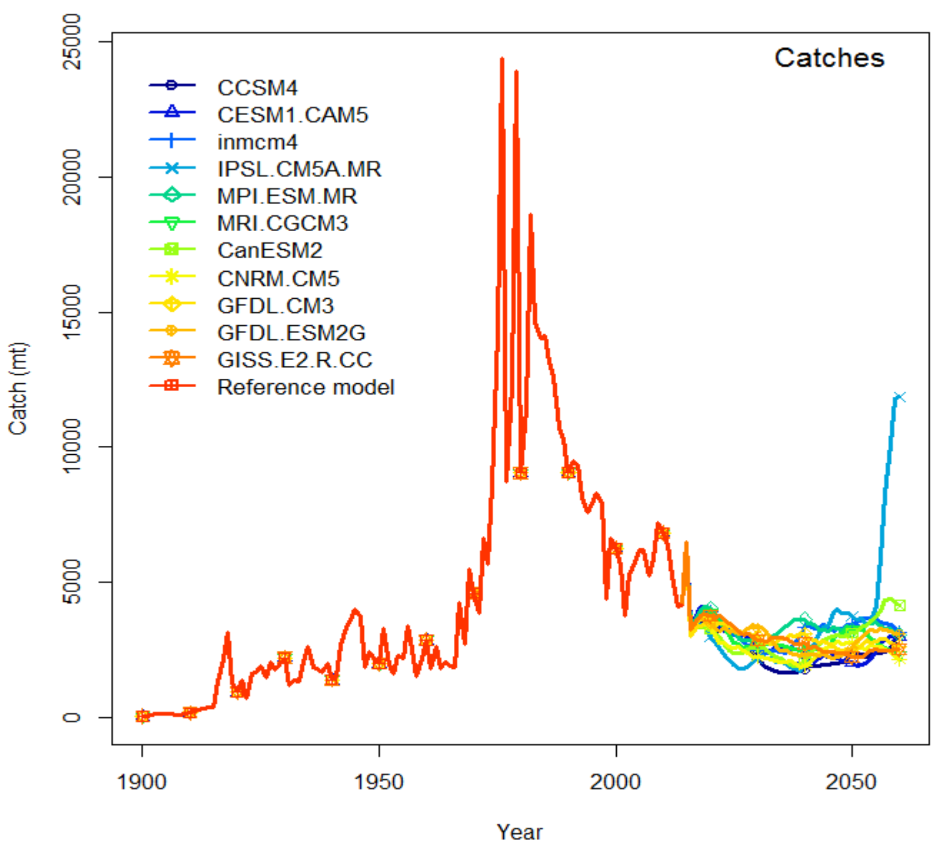
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
Reference model
Catch (mt)
0
5000
10000
15000
20000
25000
1900
1950
2000
2050
Year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CanESM2
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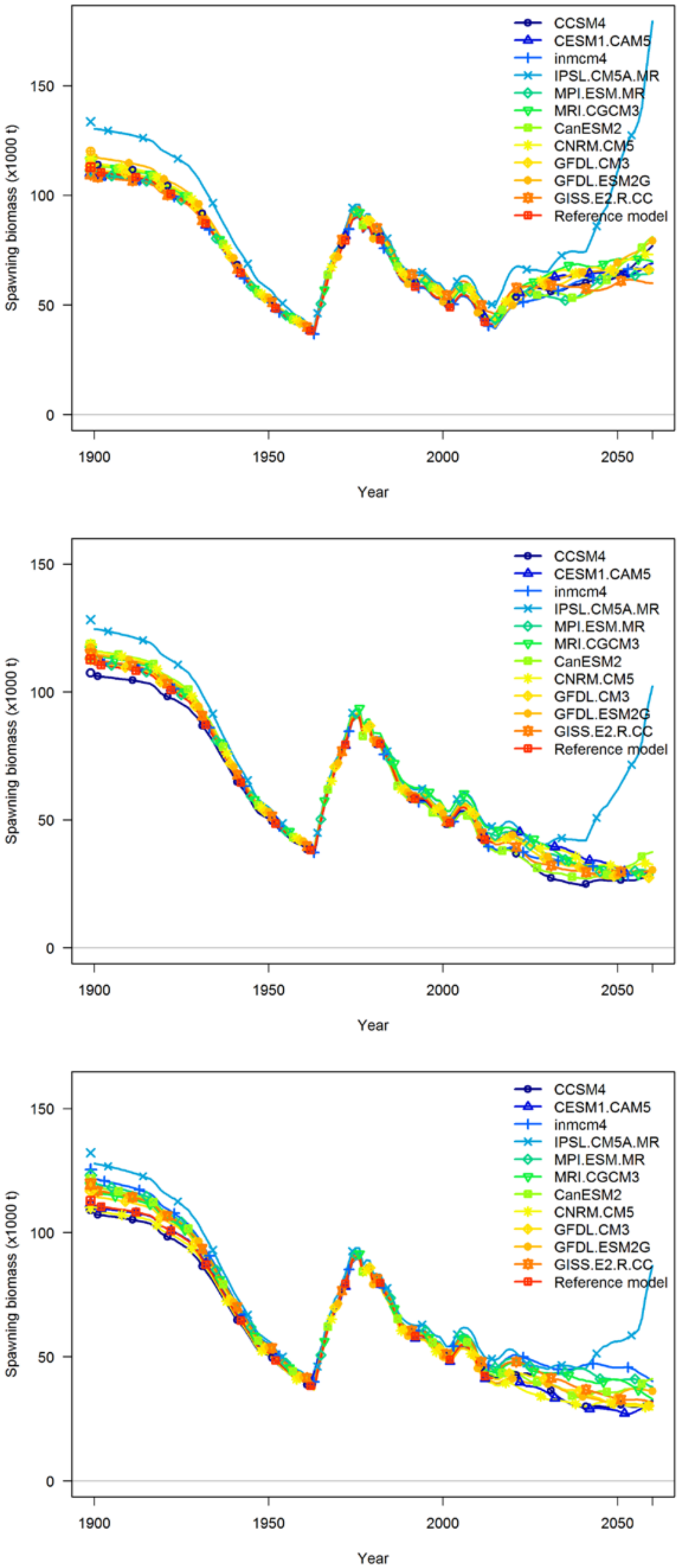
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
Reference model
Catch (mt)
0
5000
10000
15000
20000
25000
1900
1950
2000
2050
Year

Figure 4.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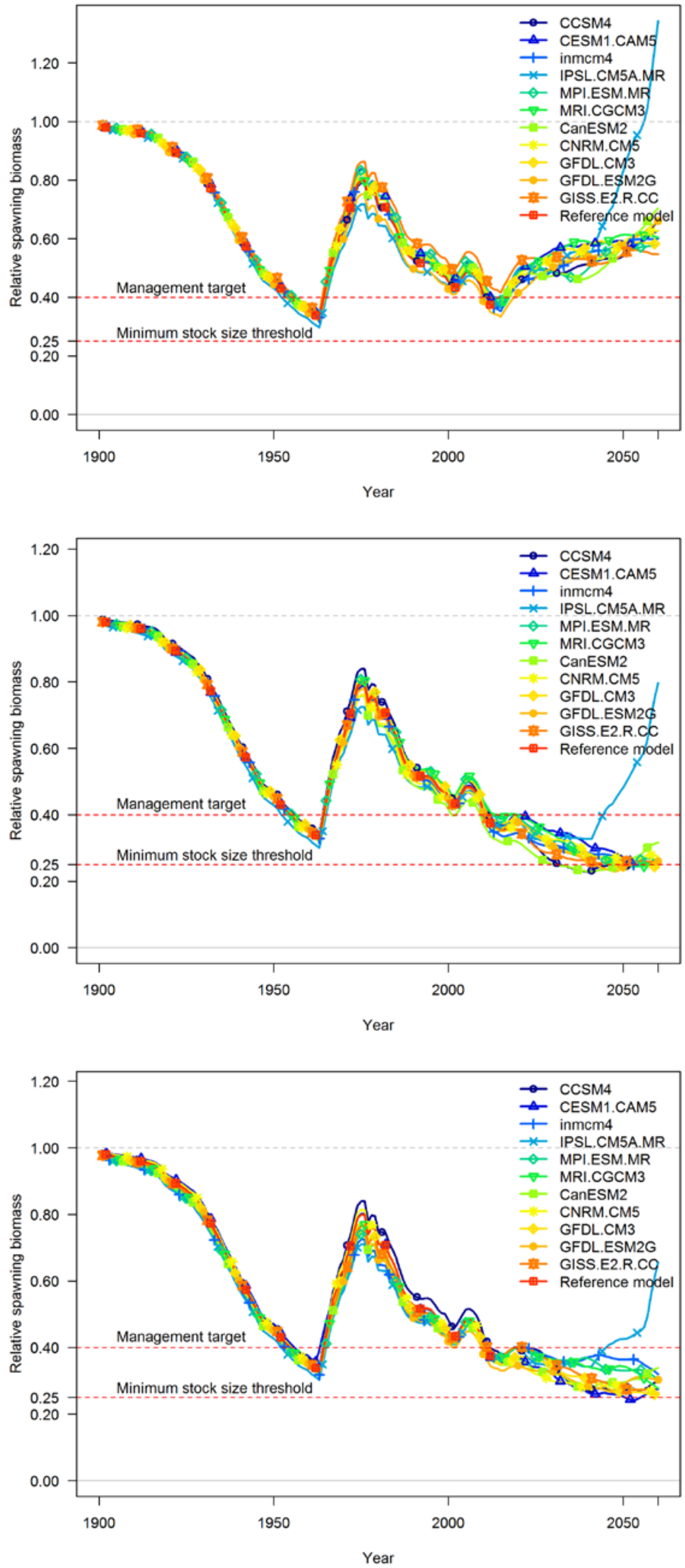
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
Reference model
Spawning biomass (x1000 t)
Year
0
50
100
150
1900
1950
2000
2050

Figure 5.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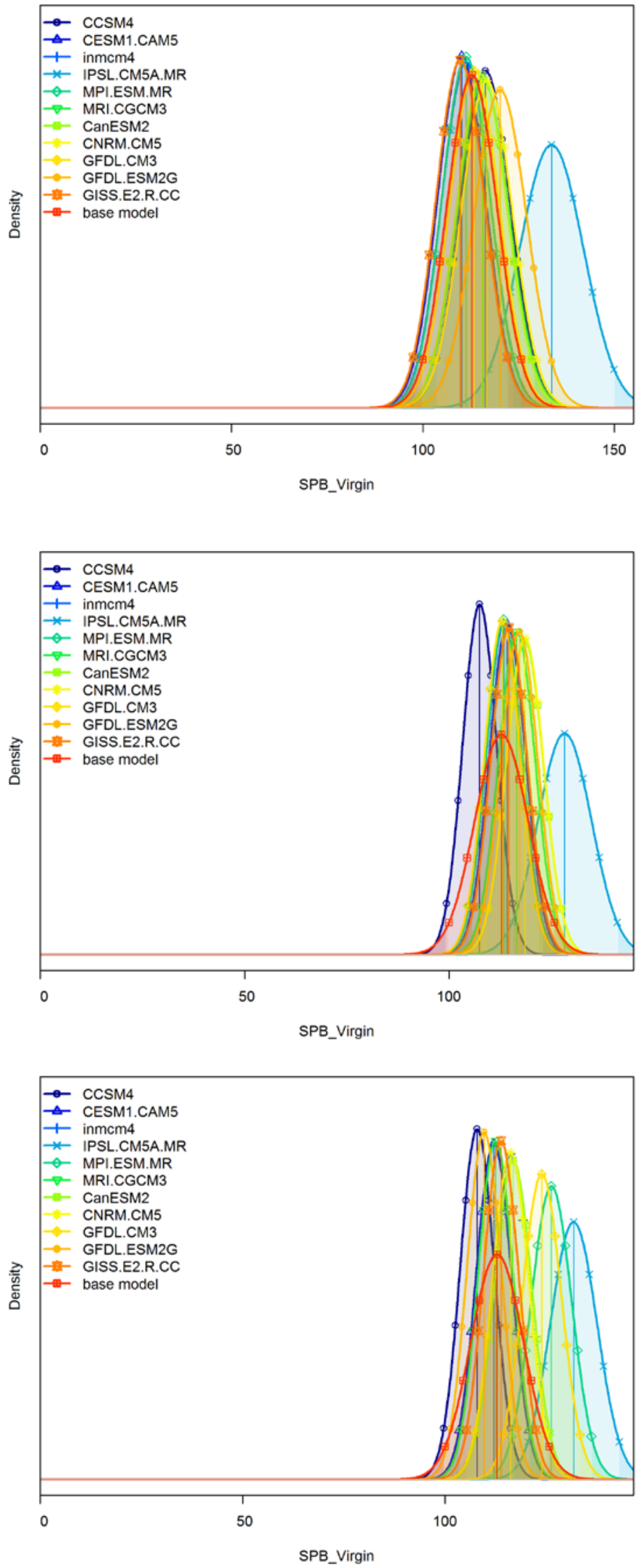
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
Reference model
Relative spawning biomass
Management target
Minimum stock size threshold
1.20
1.00
0.80
0.60
0.40
0.25
0.20
0.00
1900
1950
2000
2050
Year

Figure 6.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inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
base model
Density
0
50
100
150
SPB_Virgin
CCSM4
CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
base model
Density
0
50
100
SPB_Virgin
CCSM4
CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
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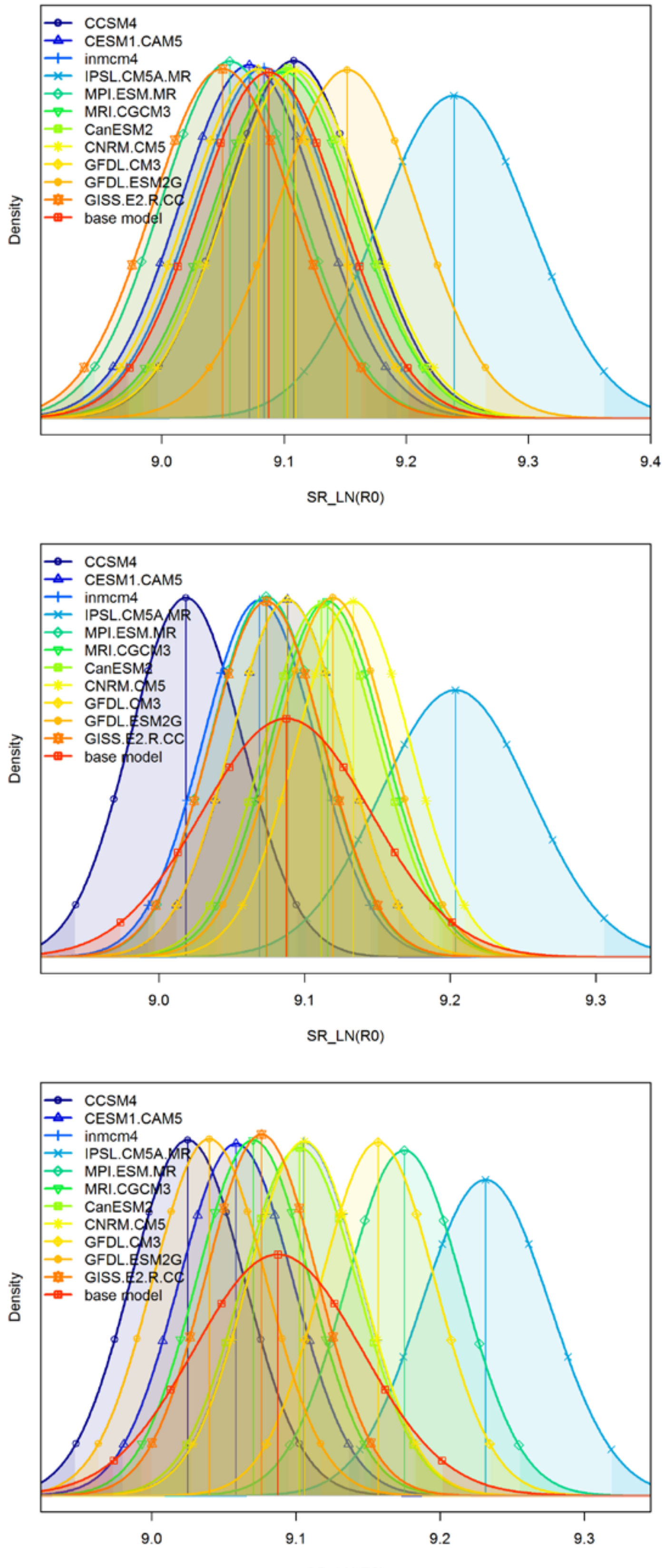
GFDL.ESM2G
GISS.E2.R.CC
base model
Density
0
50
100
SPB_Virgin

Figure 7.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GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
base model
Density
9.0
9.1
9.2
9.3
9.4
SR_LN(R0)
CCSM4
CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
base model
Density
9.0
9.1
9.2
9.3
SR_LN(R0)
CCSM4
CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
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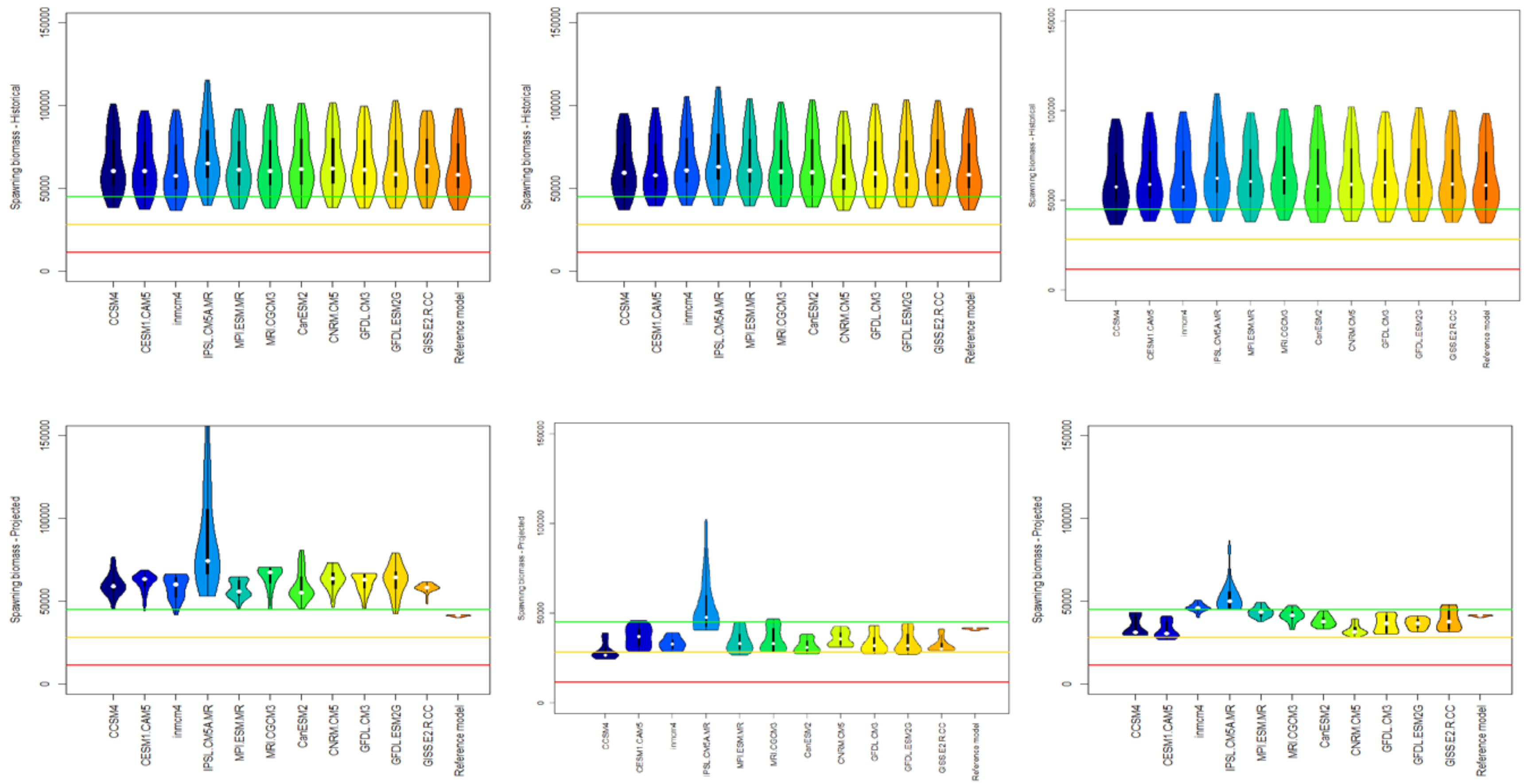
base model
Density
9.0
9.1
9.2
9.3
SR_LN(R0)

Figure 8.


Spawning biomass - Historical
Spawning biomass - Projected
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100000
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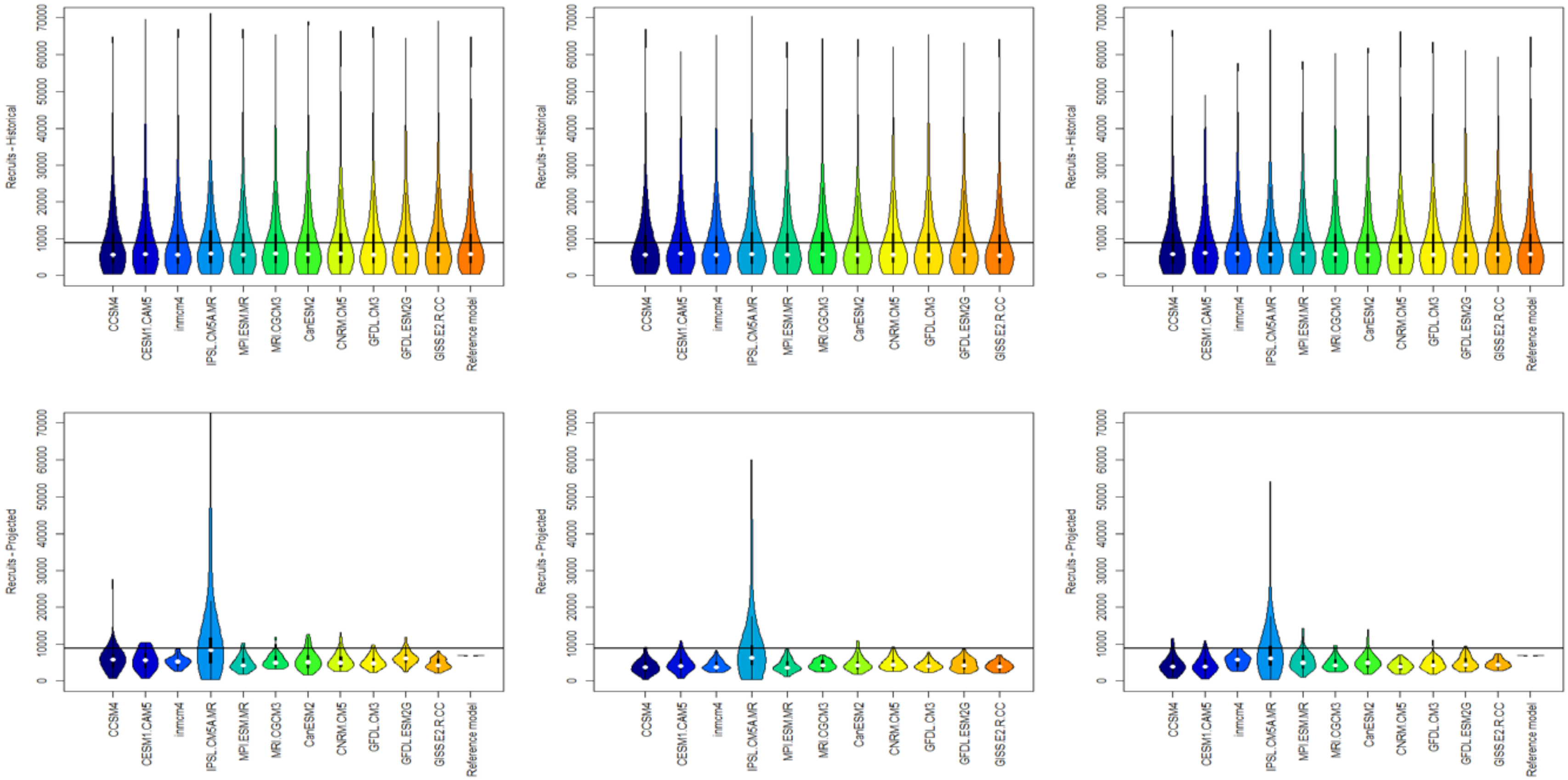
GISS.E2.R.CC
Reference model

Figure 9.


Recruits - Historical
Recruits - Projected
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60000
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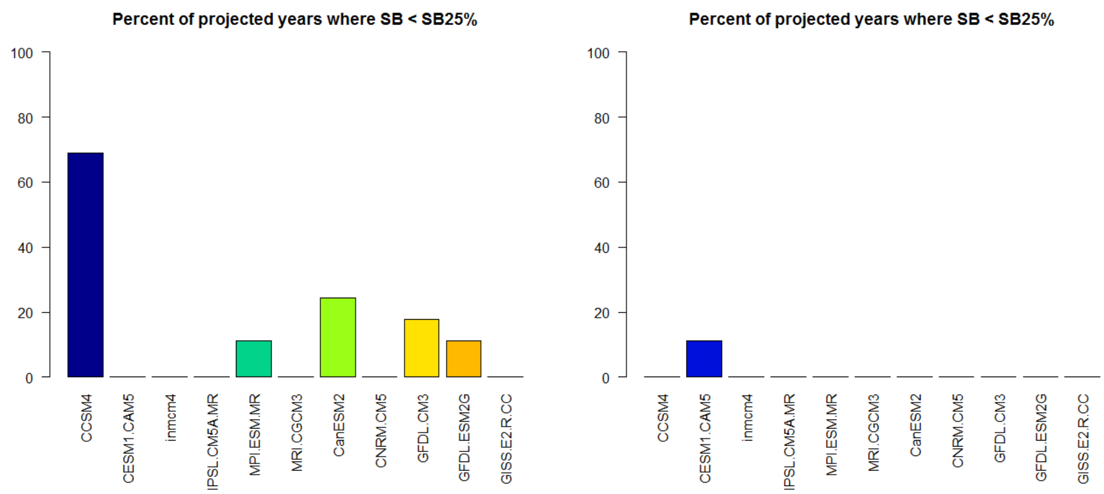
GISS.E2.R.CC
Reference model

Figure 10.


Percent of projected years where SB < SB25%
100
80
60
40
20
0
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CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC
Percent of projected years where SB < SB25%
100
80
60
40
20
0
CCSM4
CESM1.CAM5
inmcm4
IPSL.CM5A.MR
MPI.ESM.MR
MRI.CGCM3
CanESM2
CNRM.CM5
GFDL.CM3
GFDL.ESM2G
GISS.E2.R.CC

Figure 11.