Gulf of Alaska Pacific Cod assessment developments for 2019

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Introduction

For the September Plan Team we developed 4 new data and 10 new model configurations (Table 1 and Fig. 1). The naming convention follows a year-data-model convention (i.e., first two digits are year, followed by 2-digit data and model configuration index). The data index descriptions are:

11. reducing the range of the age data 0-20+ to ages 0 =10+
12. updating the sea surface temperature anomaly index to the most recent version from the CFSR and using the period 1981-2012 (previously the data were standardized from 1977-2018),
13. including the age data prior 2007 (previously these were omitted due to age-determination issues), and
14. addition of the IPHC longline survey index with its 2018 size composition data.

The model configuration descriptions (and index) are:

- 44. 2018 Council's recommended model
- 44a. IPHC Longline survey index data added
- 44b. aging error included
- 47. all available conditional age at length data included
- 48a. changing from size to age-based selectivity and freeing growth parameters,
- 48b. aging bias as observed in the re-read of otoliths used in Stark (2007)
- 48c. aging bias – pre-2007 parameters set free, 2007+ set at 0
- 48d. aging bias – pre-2007 set at 48c values, 2007+ parameters set free.
- 49. scaling recruitment to the marine heatwave index (MHWI), and
- 50. adding nodes to natural mortality to allow age varying *M* and scaling each of these age varying *M*s to the MHWI.

Note, model configurations 49 and 50 are exploratory. The following sections describe the model specifications, rationale, and results.

Table 1. Description of data configurations and models presented in this document

Model	Description
Model 18.10.44	2018 Council's recommended model
Model 18.11.44	Same as 18.10.44 except plus group at age 10
Model 19.11.44	Same as 18.11.44 except data updated and all recent data included
Model 19.12.44	Same as 19.11.44 except 10cm CFSR June temperatures are updated to latest with anomaly defined by 1981-2012 average
Model 19.14.44a	19.12.44 with IPHC longline survey index and length data
Model 19.14.44b	19.14.44a with the addition of aging error
Model 19.14.47	19.14.44 with all available age data included and aging error - without bias
Model 19.14.48a	19.14.47 with age-based selectivity and growth parameters fit freely
Model 19.14.48b	19.14.48a with the model aging bias for data prior to 2007 based on Stark (2007) re-aging and 2007+ fit freely with uninformative priors
Model 19.14.48c	19.14.48a with the model aging bias fit freely for pre-2007 with uninformative priors and 2007 to present bias set to 0
Model 19.14.48d	19.14.48c with 2007 to present aging bias parameters fit freely
Model 19.14.49	19.14.48d with recruitment scaled to the fourth root of the MHWI
Model 19.14.50	19.14.48d with Natural mortality by age and time scaled to the MHWI

Reducing the age plus group from 20+ to 10+ (Model 18.10.44 vs 18.11.44)

Only a few age 11+ cod have been observed (4 of 917 aged with the oldest fish aged at 12) in the Gulf of Alaska since 2007. As with most fish species, age determination uncertainty increases with age. In 2018 the samples used for the Stark (2007) analysis were re-read using the most recent aging criteria. Although there had been 3 fish aged greater than 10 in the original read, the re-read showed no fish greater than age 10. For these reasons we explored reducing the range of the age data 0-20+ to ages 0=10+.

The fits to the data for Models 18.10.44 and 18.11.44 are nearly indistinguishable. Relative to Model 18.10.44, Model 18.11.44 estimates of higher natural mortality and lower of both survey catchabilities (Table 2). The impacts were minor in the estimates of ending year spawning biomass (Fig. 2) and reference points.

Addition of new composition data (Model 18.11.44 vs Model 19.11.44)

For the September Plan Team meeting the data drawn for the new models include fisheries data through 31 December 2018 (Fig. 3). In addition the length composition data for the 1984 and 1987 survey were included as were newly available fisheries age data for 2010 and 2011 (Fig. 4). The multinomial sample weight on the 2009 bottom trawl survey had been down-weighted to 10 in previous years from 100, this is no longer the case. The effect of these data changes on the model results can be seen in the differences between model 18.11.44 and 19.11.44 (Fig. 2 and Table 3). The largest impact was a decrease in the natural mortality estimate from 0.51 to 0.48. Since there was a data change a direct comparison of likelihoods is inappropriate. For all further models described below (19.11-14.xx) the new dataset will be used.

Sea surface temperature estimation change (Model 19.11.44 vs. Model 19.12.44)

The sea surface temperatures used in this year's models are derived from the Climate Forecast System Reanalysis (CFSR) bottom temperatures for the central GOA. CFSR is the latest version of the National Centers for Environmental Prediction (NCEP) climate reanalysis (Saha *et al.* 2010). To make the index the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations in the central Gulf of Alaska between 145°W and 160°W longitude. The co-located CFSR oceanic temperature profiles were linearly interpolated to obtain the centers of gravity of temperatures at the depths occupied by Pacific cod at 10 cm to 100 cm at 10 cm intervals as determined from the AFSC bottom trawl survey. All co-located grid points for the month of June were then averaged to get the time series of CFSR temperatures over the period of 1979-2018. Previously the assessment model used the full time series anomaly, for Models 19.12-14.xx, the anomalies were calculated using 1982-2012 as the baseline (Fig. 5). This is not the same as the time series used in the Ecosystem Status Report (Zador *et al.* 2017) to calculate the marine heatwave index (MHWI).

In Model 19.12.44, the 10cm temperature index is used to fit the AFSC longline survey index as described in Barbeaux *et al.* (2017). Pacific cod tend to move deeper and become more available to the survey when bottom temperatures are warmer. The change from last year to this year was minor and makes only a small improvement to the fits to the survey indices (-1.78 LL). This improvement to the fit also resulted in an increase in the natural mortality estimate to 0.49 from 0.48. See Table 3 and Figure 6 for changes to spawning biomass and recruitment attributable to this update.

Addition of IPHC survey index and size composition (Model 19.12.44 vs Model19.14.44a)

The IPHC survey was introduced in last year's assessment but not used in the model. Models 19.14.44-50 add these data (Fig. 7). The IPHC survey differs from the AFSC longline survey in gear configuration and sampling design, but catches substantial numbers of Pacific cod. More information on this survey can be found in Soderlund et al. (2009). A major difference between the AFSC and IPHC longline surveys is that the IPHC survey samples the shelf consistently from ~ 10-500 meters, whereas the AFSC survey samples the slope and select gullies from 150-1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey may catch smaller and younger Pacific cod than the AFSC Longline survey. On the other hand, the IPHC uses larger hooks (16/0 versus 13/0) than the AFSC longline survey which may prevent very small Pacific cod from getting hooked. IPHC relative population number's (RPN) were calculated using the same methods as the AFSC longline survey index, except that different strata are used. Stratum areas (km^2) from the AFSC trawl survey were used for calculating the IPHC RPNs. Length data on Gulf of Alaska Pacific cod started being collected during the 2018 survey season and became available in October 2018.

The trends in the IPHC survey index matches that observed in the AFSC bottom trawl survey. Model results with the addition of these data are very similar to the model without these data (Fig. 6 and Table 3). As the models have different data there can be no direct comparison of full model likelihoods, however for the components that are the same we can examine relative model fits (Table 6). Relative to Model 19.12.44, Model 19.14.44a fits to both the trawl survey and AFSC longline survey index fits are slightly worse (+0.21 and +1.61) as are the length and age composition fits. The degradation of fits with the addition of a new dataset is expected, the degree of the degradation in the fits are very small overall (+7.38 LL) for the data that are common. In addition, the IPHC longline data provide an annual index, unlike the biannual AFSC bottom trawl survey, and represents the entire shelf, unlike the AFSC longline survey which is restricted to deeper depths.

Addition of aging error (Model 19.14.44a vs Model19.14.44b)

Aging error was included in Models 19.14.44b-50 (Fig. 8). This was developed from age reader agreement testing results for otoliths read from the 2007-2017 bottom trawl surveys. In Stock Synthesis aging error can be parameterized using two parameters; one specifying the standard deviation at minimum age and the second specifying standard deviation at the maximum age with a linear interpolation between the two. From the age reader versus tester validation the standard deviation at age 1 is 0.57 and at age 10 is 1.16.

The addition of aging error in Model 19.14.44b decreased estimated natural mortality (from 0.51 to 0.48), increased unfished spawning biomass estimates, and decreased R_0 (Table 3). The overall model fits are nearly indistiguishable by eye. The main impact to the model fit was a poorer fit to the conditional length-at-age composition data. The resulting trends in female spawning biomass are nearly the same (Fig. 9). Retrospective analysis (Table 4 and Fig. 10) reveal the Mohn's ρ and Woods Hole ρ were both small similar to Model 19.14.44a, however the distribution of spawning stock biomass timeseries were tighter with a decrease in the RMSE from 0.236 to 0.126 for Model 19.14.44a to 44b.

Addition of Pre-2007 ages (Model 19.14.44b vs Model 19.14.47)

In 2018 we identified aging bias for data prior to 2007. In the 2018 model we excluded all age data aged prior to 2007. For Models 19.14.47-50 we added the pre-2007 conditional length-at-age data back into the models. Model 19.14.47 includes these data with no other changes from Model 19.14.44b. Adding these age data back in the model made little difference in model results (Table 3 and Fig. 11). Parameter estimates across the model stayed the same. This would be expected as the priors on the growth parameters were highly constrained in this model.

Addition of age-based selectivity and freeing of growth parameters (Model 19.14.47 vs Model 19.14.48a)

To make the Bering Sea and Gulf of Alaska cod models more comparable and prepare for the addition of aging bias we chose to present models with age-based selectivity and uniform priors for all three von Bertalanffy growth parameters. For this model L_∞ increases from 99.462 cm to 112.070 cm and the estimate of K changed from 0.172 to 0.147 (Table 3 and Fig. 12). Selectivity was courser (Fig. 13) and fits to the size composition data were worse while fits to the age-at-length data were better in the model with age-based selectivity. The only substantial change to selectivity curve is that trawl and longline fishery selectivity in the pre-1990 fits become dome-shaped instead of asymptotic. The number of model parameters estimated was also reduced with age-based selectivity from 200 to 182. Overall Model 19.14.48a had a better fit to the data than Model19.14.47. Model results show nearly identical estimates of natural mortality (0.476 vs. 0.473; Table 3), however bottom trawl survey catchability changes from 0.97 to 1.01. The recruitment and spawning biomass time series differ somewhat in the 1980s (Fig. 11) due to the change in the fisheries selectivity curves.

Addition of aging bias (Model 19.14.48a - 19.14.48d)

Aging bias was added to Models19.14.48b, 48c, and 48d. Within Stock Synthesis the option to fit a vector of aging bias with a starting age, starting bias, and bias at the maximum age. The aging bias estimates are then linearly interpreted between the two parameters. For all models the starting age was fixed at 3. In Model 19.14.48b the pre-2007 time block bias at the maximum age (10) was fixed at 1.25 and at the minimum age (3) at 0.95. For the 2007 to present time block the two parameters were fit with uninformative priors. The pre-2007 bias parameter values of 1.25 and 0.95 were used to emulate the results of re-reading otoliths from Stark (2007) (Table 5 and Fig. 14). In the re-read of the Stark (2007) otoliths a positive bias was observed showing readers over-aging fish. This bias is thought to have been corrected for otoliths age post-2007.

For Model 19.14.48c aging bias was estimated in the model for the pre-2007 time block and 2007-present was assumed to be bias free and parameters fixed at 0. We conducted a likelihood profile to assess how well these parameters were estimated (Fig. 15). For model 19.14.48d we fixed the pre-2007 age bias parameters to those fit in Model 19.14.48c and fit the two 2007+ parameters with uninformative priors.

Fixing pre-2007 ageing bias parameters to the re-read Stark (2007) values in Model 19.14.48b lead to a poorly fit model (+62.81 LL) compared to the unbiased model (Table 3). The fit was poorer across all composition likelihood components while there was a slight improvement in fit to the index (-0.41). In addition, the forced bias suggests a best model fit with an increased estimate of natural mortality (M=0.57) and decrease estimate of bottom trawl catchability ($Q_{AFSC\ trawl}$ = 0.896). Natural mortality in this model is at the extreme high end of its prior distribution. Although the recruitment estimate increases due to the change in M and Q the trends in both recruitment and spawning biomass remain the same as previous models (Fig. 16). Although the Mohn's ρ and Woods Hole ρ remain small (Table 4), the RMSE increases substantially indicating low bias but a decrease in the precision in the overall spawning biomass time series (Fig. 10).

Model 19.14.48c fit a small positive age bias for pre-2007 data with the minimum age bias parameter at 0.387 (σ=0.055) and maximum parameter at 0.177 (σ=0.159; Table 4 and Fig. 14). This model provides an improvement in model fit (-32.61) over 48a across all likelihood categories except survey length composition (Table 6) where there was a marginal (<+1 LL) degradation. The change in fit to the age and length composition data were minimal and not distinguishable by eye. Natural mortality changed by +0.006, AFSC bottom trawl survey catchability by -0.042, and ln(R_0) by +0.047 (Table 3). The retrospective bias remains low with Mohn's ρ = -0.006, Woods Hole ρ = 0.072, and the RMSE at 0.155 (Table 4 and Fig. 10), similar to Model 19.14.48a. The largest difference in Model 19.14.48a and 48b is in the estimate of unfished spawning biomass and early recruitment where Model 48b estimates slightly higher recruitment in the late 1970s and early 80s. This results in a higher spawning biomass in Model 48b 1978-1993 (Fig. 16).

Model 19.14.48d fit a small age bias for 2007+ age data which starts nearly neutral for age 3 but then changes to a negative bias for older fish with the minimum age bias parameter at 0.135 (σ=0.038) and maximum parameter at -0.792 (σ=0.114; Table 4 and Fig. 14). This model provides and improved fit to the data over Model 19.14.48c (-20.97 LL). The new bias correction improves fit to all age composition, all length composition except the trawl fishery and AFSC longline survey length composition, and both the AFSC trawl survey and IPHC longline survey indices (Table 6). The change in fit between Model 19.14.48c and 19.14.48d is not easily distinguished by eye. The retrospective analysis shows that the retrospective bias remains small in this model similar to Model 19.14.48c (Table 4). There is a substantial reduction in the estimate of natural mortality down to 0.432 while AFSC trawl survey catchability remains similar to Model 19.14.48b at 0.966 (the same as model 19.14.47; Table 3). The ln(R0) is the lowest of all the models explored at 12.862. The change in natural mortality results in an decrease in recruitment to compensate, but the trend remains the same as Model 19.14.48c and the trend in spawning biomass remains nearly the same (Fig. 16). The unfished spawning biomass for Model19.14.48d was 259,000t while model 19.14.48c was 253,000 t a 2% change (Table3).

Ancillary data to inform which aging bias correction is best is unavailable. The data, as seen through the lens of our model, suggest a minimal positive bias in the pre-2007 data and minimal negative bias in the 2007+ data. However, if the re-read of the Stark (2007) data are correct, our model may somehow otherwise be mis-specified. The only other study that provides clarity is Kastelle *et al.* (2017) which suggested a minor positive aging bias in relation to oxygen isotope ($\delta^{18}O$) analysis, the otoliths from this paper were read between 2005 and 2011. However this study was conducted on only 40 otoliths and the age range was limited to ages 2-5.

Recruitment scaled to the cube root of the MHWI (Model 19.14.47d vs Model19.14.49)

As an exploratory model we scale R_0 with the cube root of the marine heat wave index (MHWI). We hypothesize that very high temperatures should result in lower recruitment, which has been observed in lower CPUE of Pacific cod larvae in ichthyoplankton surveys during warmer years (Barbeaux et. al. 2017). A direct relationship with temperature has not been found, however Laurel *et al.* (2011) suggest that the juvenile Pacific cod have a narrow thermal tolerance range. Therefore, a MHWI could be incorporated into the model using a threshold temperature model. We use the cube root to buffer the extreme highs observed in the 2014-2016 GOA marine heatwave. Using the actual temperature anomalies or MHWI produces a model fit approximately the same as Model 19.14.48d (± 1 LL), using the cube root of the MHWI produces a model fit marginally better (-8.35 LL). The improvement in fit is ~2LL for each likelihood component. Parameter estimates are nearly identical with M +0.06, $Q_{AFSCtrawl}$ -0.015, and R_0 +0.243 (Table 3). Unfished spawning biomass increased by 58,000t from 259,000t to 317,201t from Model 19.14.48d to 19.14.49. Recruitment changes from Model 19.14.48d with increased recruits in years prior to 2010 and decrease in recruitment since 2013. The spawning biomass was higher pre-2012 and is diverging lower in 2017 and 2018 as would be expected given differences in recruitment (Fig. 18). The improvement to the model from Model 19.14.48d is marginal, but is an improvement gauging by AIC (5719.44 vs 5710.74).

Age-specific annually varying natural mortality scaled to the WMHCI (Model 19.14.47b vs Model19.14.50)

An alternative exploration (Model 19.14.50) allows age specific natural mortality to be estimated over time and age with five nodes (ages 1, 3, 5, 7, and 9) with linear interpolation between each node. Natural mortality is also scaled to the winter marine heatwave cumulative index (WMHCI) for ages 1, 3, and 5. Models were explored allowing natural mortality at ages 7 and 9 to scale with different temperature indices. Doing so did not improve model fits to the data. This model was fit with age varying M and the time block during the 2014-2016 heatwave (instead of fitting to the WMHCI) had a -31.86 change in negative log likelihood with the WMHCI scaling. A model exploration which used the bottom temperature anomaly instead of the WMHCI resulted in an increase in the negative log likelihood of 6.64. Natural mortality was fixed at 1.0 for age 0 fish, but in warmer than normal years exceeds 1.0 with the extreme in 2016 of 1.63 for age 1's (Table 7 and Fig. 19). The lowest natural mortality was 0.36 for age 7. Average natural mortality for ages 3-8 for all years was 0.46 and for the marine heatwave years (2014-2016) was 0.61. For all years, natural mortality increased after age 7 resulting in a U-shaped natural mortality, suggesting senescence. Research supporting senescence in Pacific cod (*Gadus morhua*) is limited. However, Atlantic cod studies have suggested senescence may occur in that related species (Rideout and Burton 2000).

Another difference from Model19.14.48d is the scaled increase in natural mortality observed during the 2014-2016 heatwave. Model 19.14.48d has the same M for the entire time period while Model 19.14.50 has a peak in M in 2016. In addition, in Model 19.14.48d all age classes are affected by the higher M while in Model 19.14.50 only the age 1-6 are impacted. This impacts estimates of recruitment where the 2003-2011 year class strength is relatively lower (Fig. 19) than in Model 19.14.48d. The Model19.14.50 recruitment pattern leads to much lower estimates of spawning biomass in the most recent years (Fig. 20) and a less steep decline following the marine heatwave. Both models however result in the current status of the stock to be the lowest in the time series in 2019.

Note that we wish to explore a combination of Model 19.14.49 and 19.14.50 for November which could be used for a more realistic realization of the future status of the stock in the face of climate change if a rebuilding plan becomes necessary.

Summary

Figure 1 shows substantial uncertainty remains in the pre-1985 estimates. This uncertainty is the largest factor in variation in reference value estimates among models. All of the models and data configurations have the following in common:

- that GOA Pacific cod are currently at historic low abundance with low recruitment during the 2014-2016 heatwave
- that the stock will be very near or below $B_{20\%}$ in 2020., and

- conditions will improve after 2019 due to the assumed average recruitment for 2017 and 2018.

Most of these models and data configurations are refinements from last year's model and as such, are relatively insubstantial. All models, except 19.14.48b, indicate that estimates of M and Q are close in approximation (Fig. 22). Including aging bias impacts model estimates significantly. Estimates on the magnitudes of the 2017-2019 year classes are limited and the 2019 survey data will be available soon. As such, reference points or stock status estimates are deferred to the forthcoming full assessment.

It is worth noting that if the 2019 survey estimates are below the previous estimates (2017 for bottom trawl survey, 2018 for AFSC and IPHC longline surveys), this would possibly indicate that the stock is below $B_{17.5\%}$ (overfished).

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Tables

Table 2. Parameters and key results from Model 18.10.44 and 18.11.44 changing the plus group from 20+ to 10+.

	Model 18.10.44		Model 18.11.44	
Parameters	**Value**	**σ**	**Value**	**σ**
Natural mortality (M)	0.505	0.022	0.519	0.023
Natural mortality 2014-2016 ($M_{14\text{-}16}$)	0.869	0.055	0.877	0.055
L_{inf}	99.460	0.015	99.460	0.015
VonBert K	0.173	0.002	0.173	0.002
CV young	3.137	0.271	3.385	0.270
CV old	10.332	0.383	9.917	0.360
LN(R_0)	13.463	0.205	13.541	0.208
Log $Q_{AFSC\ trawl}$	0.085	0.092	0.071	0.092
Log $Q_{AFSC\ longline}$	0.200	0.081	0.183	0.079
Environmental covariate on longline survey catchability	1.372	0.343	1.438	0.365
Results				
TOTAL likelihood	1872.33		1854.45	
Survey likelihood	-19.190		-19.050	
Length_comp_like	1259.08		1252.71	
Age_comp_like	727.613		716.382	
Parm_priors_like	1.696		1.739	
SSB_0 (10^3t)	205.429		204.041	

Table 3. Likelihoods, parameters, and key results for model evaluation

Label	Model 19.11.44	Model 19.12.44	Model 19.14.44a	Model 19.14.44b	Model 19.14.47	Model 19.14.48a	Model 19.14.48b	Model 19.14.48c	Model 19.14.48d	Model 19.14.49	Model 19.14.50
#parameters	197	197	200	200	200	182	184	184	186	187	190
Likelihoods											
TOTAL	2081.02	2080.71	2192.08	2418.49	2807.98	2727.30	2790.11	2694.69	2673.72	2667.95	2626.90
Survey	-13.76	-15.54	-17.99	-18.43	-17.53	-17.20	-17.61	-17.65	-17.17	-18.87	-13.07
Length_comp	1314.55	1314.55	1322.12	1327.88	1337.29	1417.59	1429.37	1414.17	1408.78	1406.99	1360.43
Age_comp	879.12	879.12	884.80	1108.29	1488.31	1334.33	1383.80	1304.89	1289.51	1291.21	1286.64
Parm_priors	1.68	1.81	1.78	1.20	1.19	0.81	1.53	0.87	0.57	0.57	2.32
Parameters											
LN(R_0)	13.174	13.274	13.38	13.164	13.166	13.089	13.574	13.136	12.862	13.111	14.49
M	0.480	0.490	0.506	0.477	0.476	0.473	0.571	0.479	0.432	0.439	
$M_{2014\text{-}2016}$	0.783	0.811	0.808	0.756	0.754	0.746	0.871	0.760	0.690	0.686	
$Q_{\text{AFSC trawl}}$	1.096	1.057	1.008	0.976	0.966	1.011	0.896	0.969	0.966	0.951	1.076
L_{inf}	99.46	99.461	99.461	99.461	99.462	112.070	115.745	111.810	107.639	107.696	111.359
VonBert K	0.161	0.161	0.162	0.171	0.172	0.147	0.150	0.150	0.157	0.157	0.148
SSB_0 (10^3t)	199.737	204.195	205.729	218.710	218.242	247.078	243.354	252.574	259.000	316.686	271.888

Table 4. Female spawning biomass retrospective results from new models with Mohne's ρ, Woods Hole ρ, and Root mean square error (RMSE) for each model.

Model	ρ	Woods Hole ρ	RMSE
Model19.12.44	0.166	0.083	0.150
Model19.14.44a	-0.051	-0.015	0.236
Model19.14.44b	0.037	0.062	0.126
Model19.14.47	0.022	0.063	0.125
Model19.14.48a	-0.013	0.080	0.147
Model19.14.48b	-0.048	-0.112	0.332
Model19.14.48c	-0.006	0.072	0.155
Model19.14.48d	-0.007	0.088	0.153
Model19.14.49	-0.005	0.048	0.114
Model19.14.50	0.180	0.091	0.155

Table 5. Aging bias parameters with standard deviations for those fit in the Model19.14.48 series.

	Model19.14.48a	Model19.14.48b	Model 19.14.48c	Model 19.14.48d
Starting age	3	3	3	3
Bias at start age pre-2007	0	0.95 (σ = NA)	0.387 (σ = 0.055)	0.387 (σ = NA)
Bias at maxage pre-2007	0	1.25 (σ = NA)	0.177 (σ = 0.159)	0.177 (σ = NA)
Bias at start age 2007+	0	0.263 (σ = 0.041)	0	0.135 (σ = 0.038)
Bias at maxage 2007+	0	0.193 (σ = 0.189)	0	-0.792 (σ = 0.114)
Standard deviation at start age	0.57	0.57	0.57	0.57
Standard deviation at maxage	1.16	1.16	1.16	1.16
-Loglikelihood	2727.45	2790.24	2694.87	2673.72

Table 6. Likelihood by fleet for each likelihood component.

Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv	IPHCLL	Model
Age_like	1488.31	249.93	316.93	227.61	693.85			Model19.14.47
Age_like	1334.33	227.11	275.57	212.22	619.42			Model19.14.48a
Age_like	1383.80	225.39	279.89	215.42	663.10			Model19.14.48b
Age_like	1304.89	226.14	276.68	212.81	589.26			Model19.14.48c
Age_like	1289.51	224.06	273.19	209.22	583.03			Model19.14.48d
Age_like	1291.21	224.21	273.63	209.87	583.51			Model19.14.49
Age_like	1286.64	224.68	271.60	207.71	582.65			Model19.14.50
Length_like	1337.29	379.99	281.85	287.92	178.20	201.74	7.60	Model19.14.47
Length_like	1417.59	403.56	277.23	297.23	220.07	209.75	9.75	Model19.14.48a
Length_like	1429.37	394.92	289.11	306.79	221.55	210.04	6.96	Model19.14.48b
Length_like	1414.17	401.66	275.24	298.59	221.47	208.09	9.13	Model19.14.48c
Length_like	1408.78	402.53	273.00	294.99	220.80	209.10	8.37	Model19.14.48d
Length_like	1406.99	402.95	271.84	294.99	220.43	208.63	8.15	Model19.14.49
Length_like	1360.43	386.51	266.26	284.67	212.37	205.19	5.43	Model19.14.50
Surv_like	-17.53				-5.04	-8.52	-3.98	Model19.14.47
Surv_like	-17.20				-7.70	-5.02	-4.49	Model19.14.48a
Surv_like	-17.61				-8.32	-3.24	-6.05	Model19.14.48b
Surv_like	-17.65				-8.06	-4.69	-4.90	Model19.14.48c
Surv_like	-17.17				-8.63	-2.71	-5.83	Model19.14.48d
Surv_like	-18.87				-9.80	-3.28	-5.79	Model19.14.49
Surv_like	-13.07				-1.75	-11.19	-0.12	Model19.14.50

Table 7. Natural mortality fit in Model 19.14.50 by age and year.

Year	1	2	3	4	5	6	7	8	9	10
1978	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1979	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1980	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1981	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1982	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1983	1.026	0.787	0.548	0.493	0.438	0.399	0.360	0.473	0.585	0.585
1984	1.050	0.814	0.578	0.508	0.438	0.399	0.360	0.473	0.585	0.585
1985	1.023	0.783	0.543	0.490	0.438	0.399	0.360	0.473	0.585	0.585
1986	1.014	0.773	0.531	0.484	0.438	0.399	0.360	0.473	0.585	0.585
1987	1.000	0.757	0.514	0.476	0.437	0.399	0.360	0.473	0.585	0.585
1988	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1989	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1990	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1991	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1992	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1993	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1994	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1995	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1996	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
1997	1.026	0.786	0.546	0.492	0.438	0.399	0.360	0.473	0.585	0.585
1998	1.218	1.026	0.834	0.638	0.441	0.401	0.360	0.473	0.585	0.585
1999	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2000	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2001	1.018	0.777	0.537	0.487	0.438	0.399	0.360	0.473	0.585	0.585
2002	1.062	0.829	0.596	0.517	0.439	0.399	0.360	0.473	0.585	0.585
2003	1.229	1.041	0.853	0.647	0.441	0.401	0.360	0.473	0.585	0.585
2004	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2005	1.006	0.764	0.521	0.479	0.438	0.399	0.360	0.473	0.585	0.585
2006	1.001	0.758	0.515	0.476	0.437	0.399	0.360	0.473	0.585	0.585
2007	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2008	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2009	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2010	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2011	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2012	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2013	0.993	0.749	0.505	0.471	0.437	0.399	0.360	0.473	0.585	0.585
2014	1.141	0.926	0.711	0.576	0.440	0.400	0.360	0.473	0.585	0.585
2015	1.360	1.227	1.094	0.768	0.443	0.402	0.360	0.473	0.585	0.585
2016	1.627	1.664	1.701	1.074	0.446	0.403	0.360	0.473	0.585	0.585
2017	1.030	0.791	0.552	0.495	0.438	0.399	0.360	0.473	0.585	0.585
2018	1.090	0.862	0.635	0.537	0.439	0.400	0.360	0.473	0.585	0.585

Figures

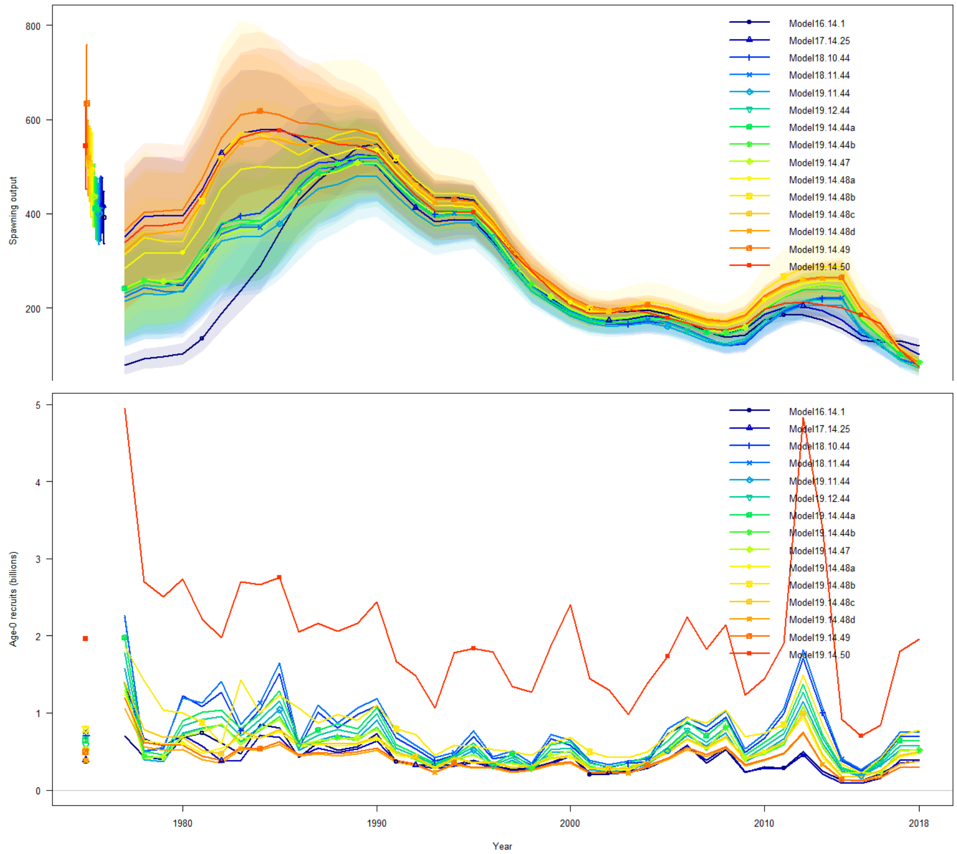

Figure 1. Spawning biomass (upper) and age-o recruits (lower) for all models. Two additional models, Model16.14.1 and Model 17.14.25 (the 2016 and 2017 Council accepted models) are include as the author's models for 2016 and 2017 with this year's data.

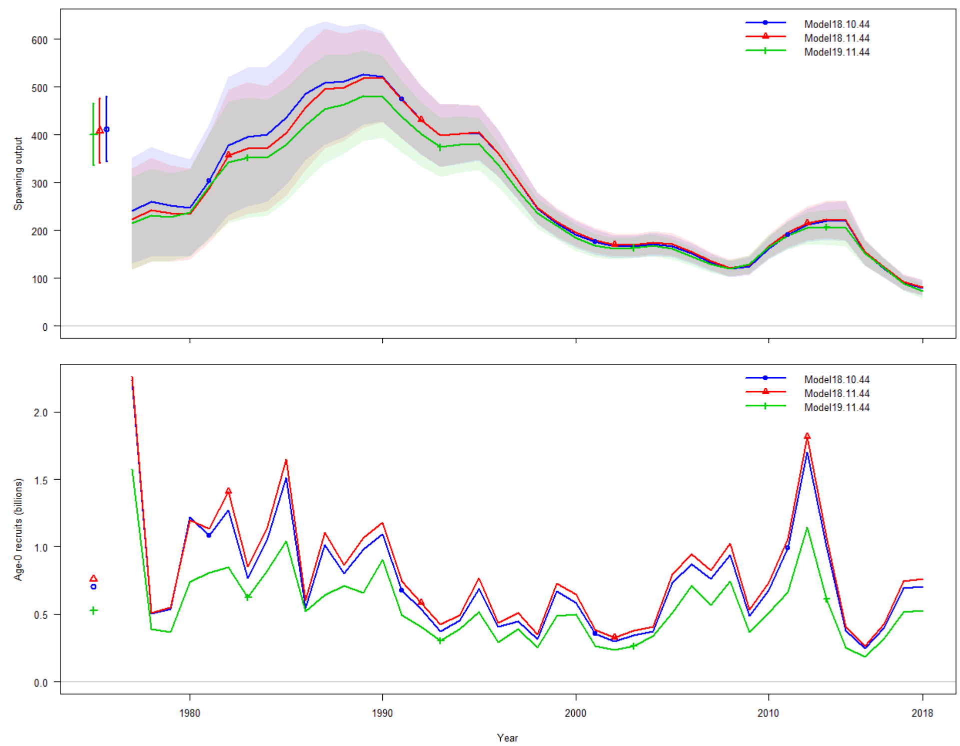

Figure 2. Spawning biomass (upper) and age-o recruits (lower) for models 18.10.44, 18.11.44, and 19.11.44.

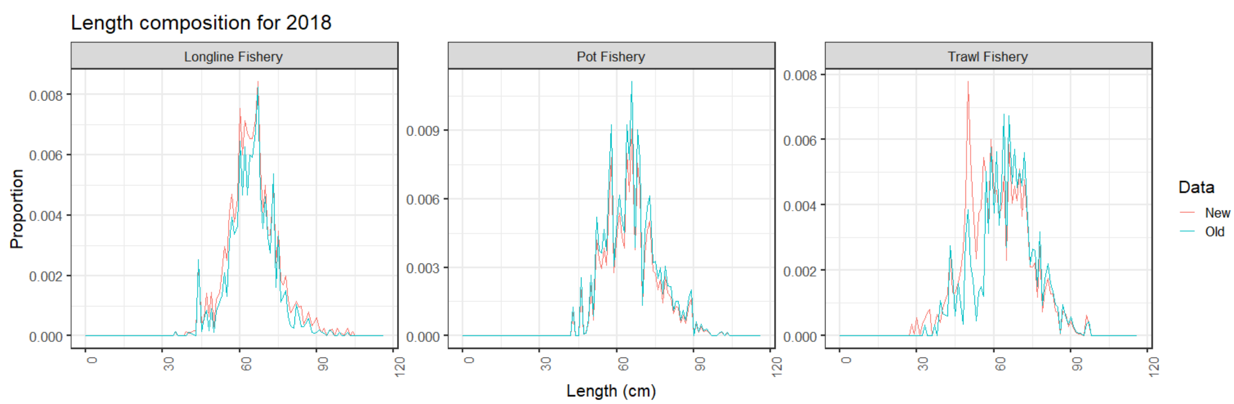

Figure 3. Length composition for 2018 from last year's model (Old) and updated (new) for each fishery.

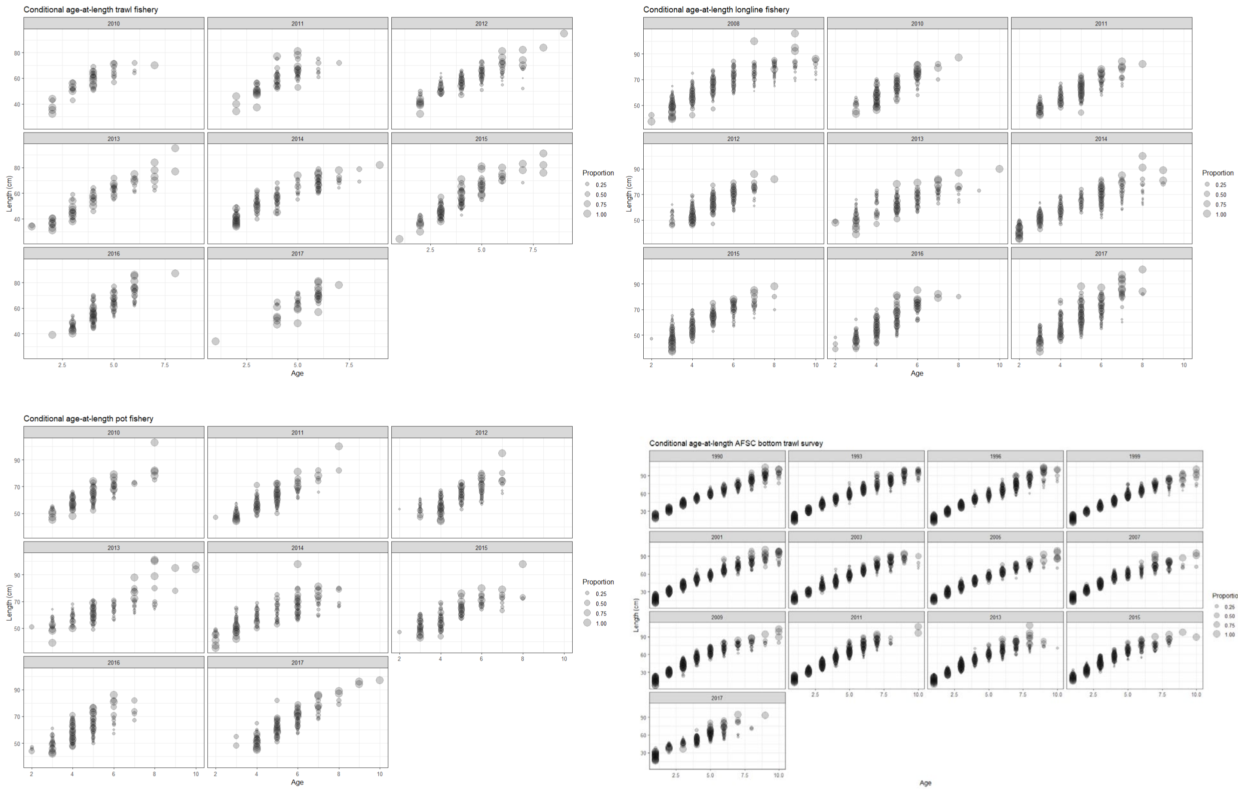

Figure 4. Conditional length-at-age for fisheries and surveys for new models. 2010 and 2011 for the fisheries are newly available since December 2018.

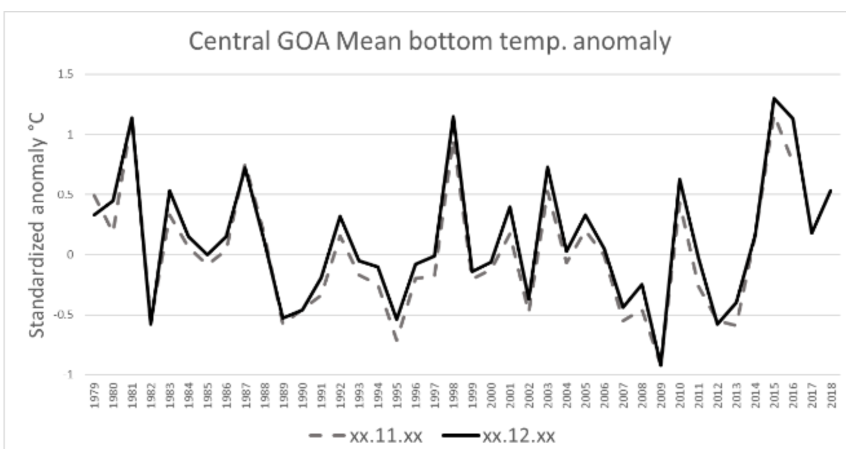

Figure 5. CFSR temperature anomaly for mean June temperature at depth for 10 cm Pacific cod for Models xx.11.xx and xx.12-14.xx.

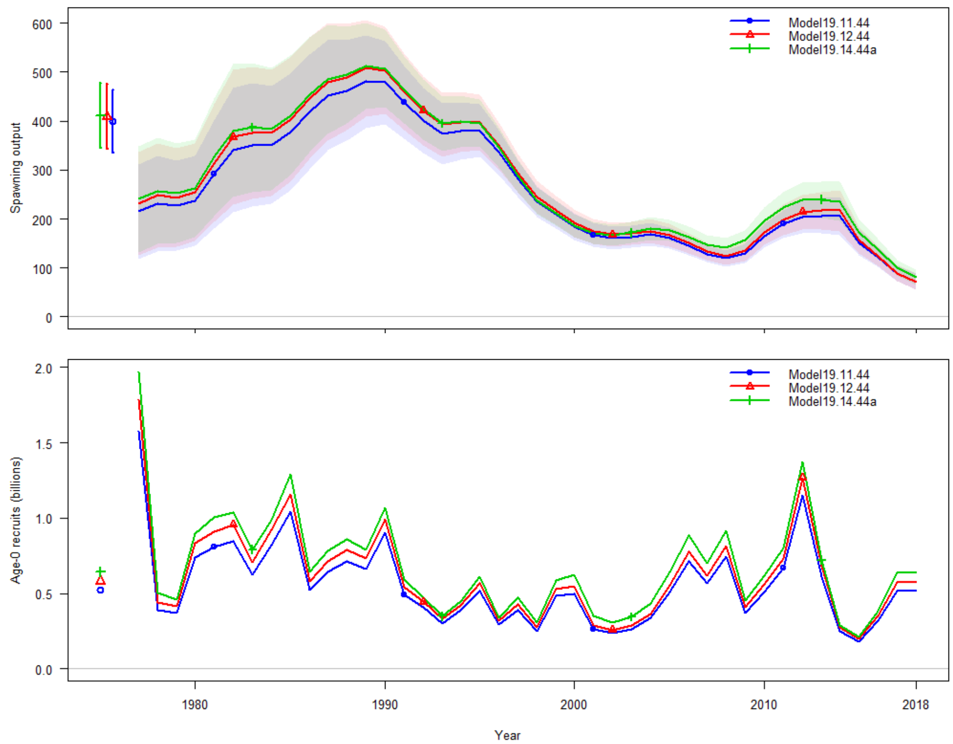

Figure 6. Spawning biomass (upper) and age-o recruits (lower) for models 19.11.44, 19.12.44, and 19.14.44a.

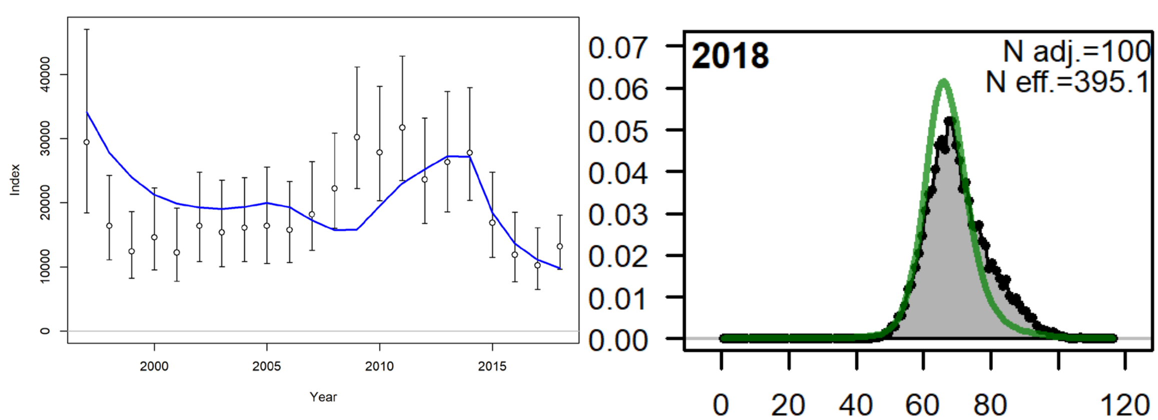

Figure 7. IPHC longline survey index RPN (left) and IPHC longline survey size composition data (right) with Model 19.14.44a fits for each (lines).

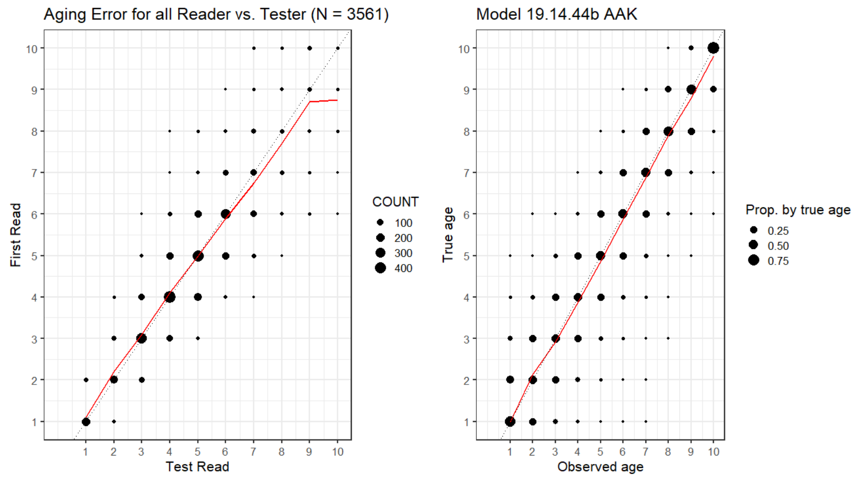

Figure 8. Aging error matrix from reader-tester validation (left) and as implemented in Models 19.14.44b-50 (right).

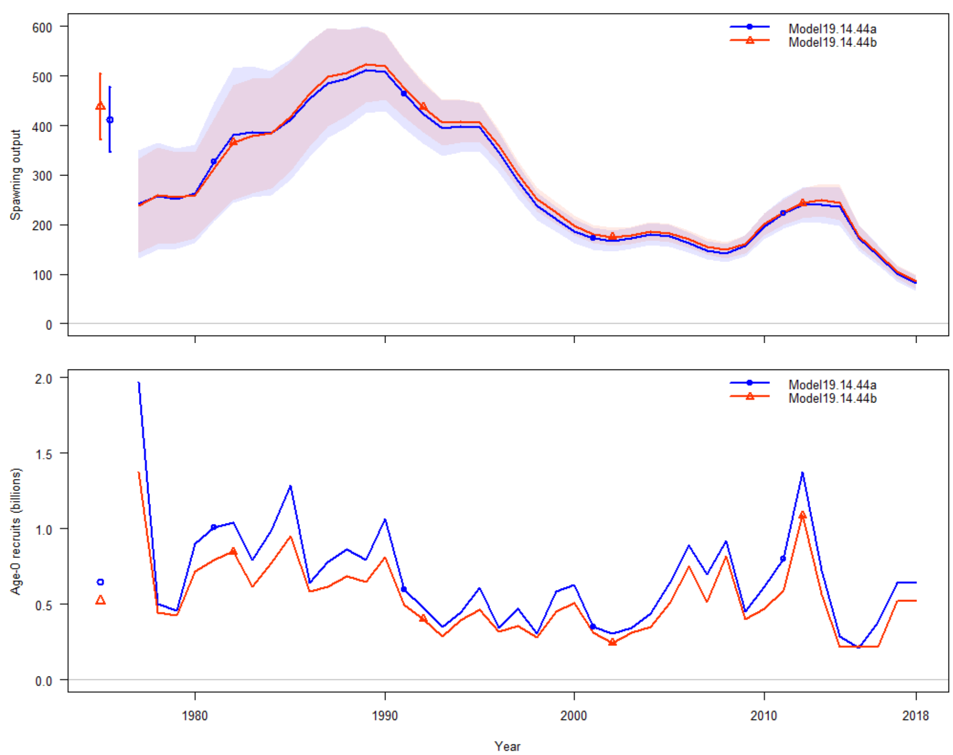

Figure 9. Spawning biomass (upper) and age-o recruits (lower) for models 19.14.44a and 19.14.44b with inclusion of aging error.

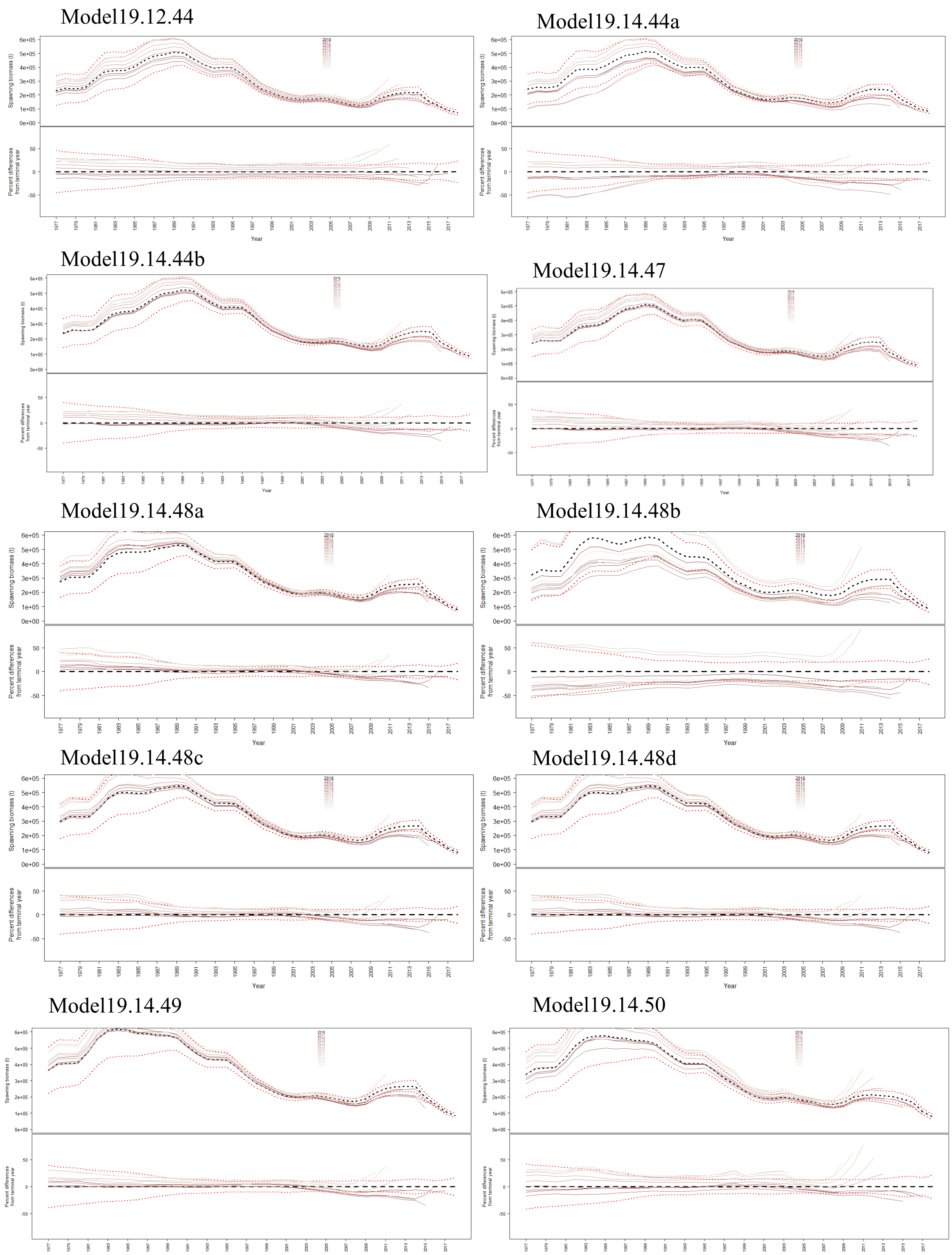

Figure 10. Retrospectives on female spawning biomass (top for each) and biomass percent different from final year (bottom for each) for all new models.

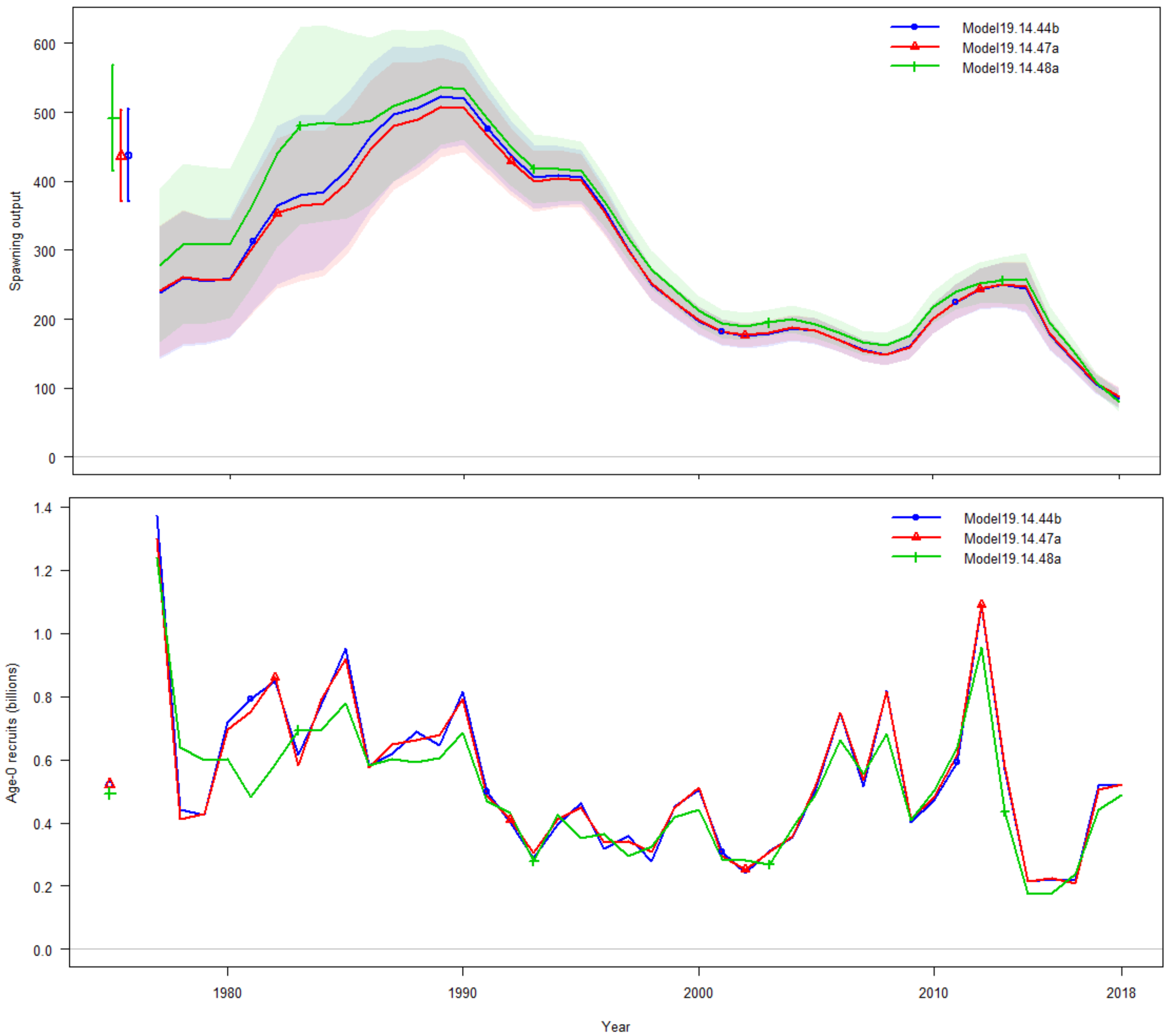

Figure 11. Spawning biomass (upper) and age-o recruits (lower) for models 19.14.44b, 19.14.47 with inclusion of aging error, and 19.14.48a with age-based selectivity and non-informative priors on growth.

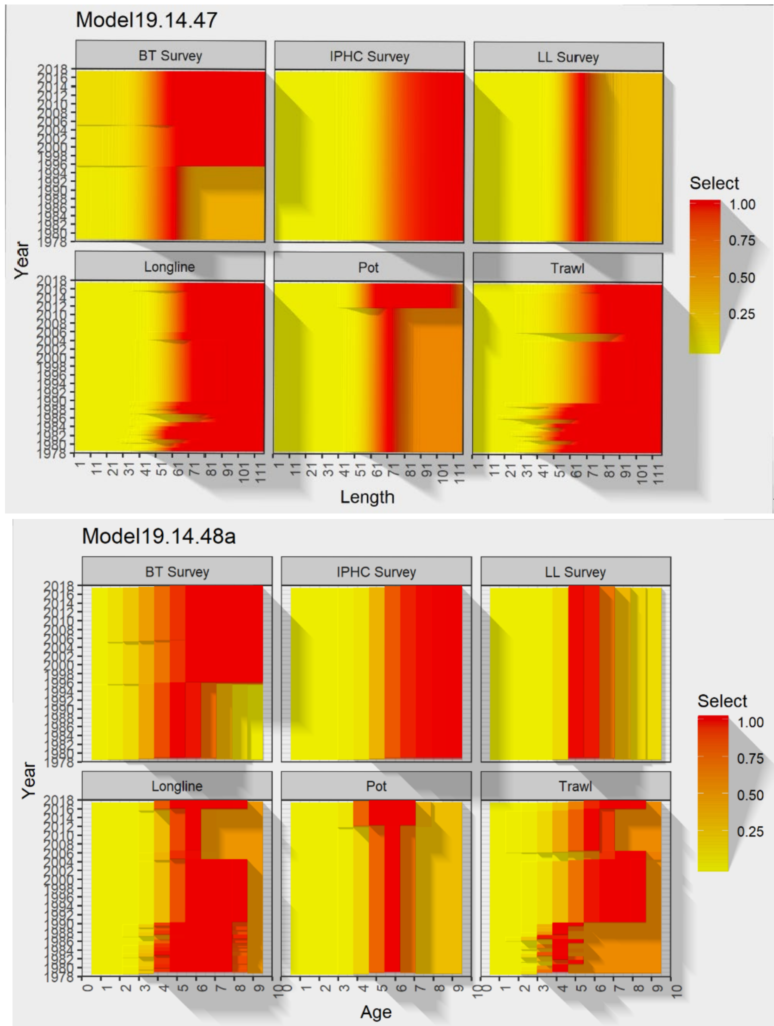

Figure 12. Length based selectivity for Model 19.14.47 (top) and age-based selectivity for Model 19.14.48 (bottom) series.

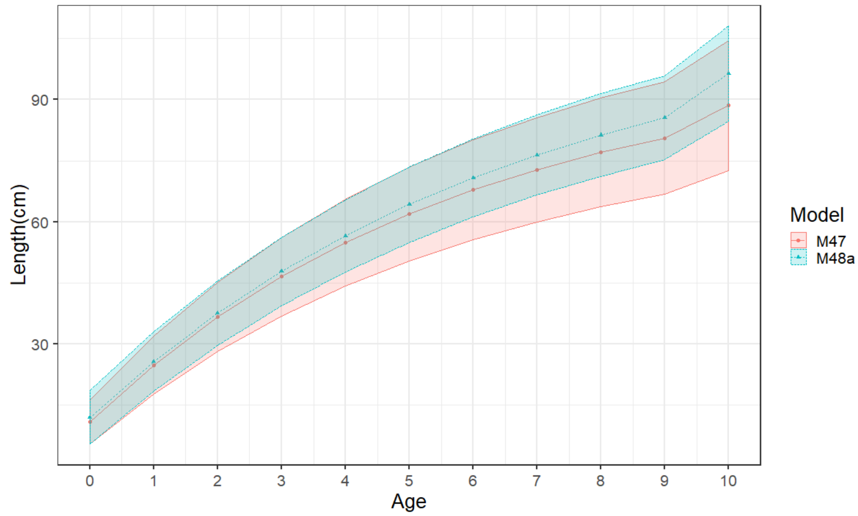

Figure 13. Growth curves for Models 19.14.47 and 48a.

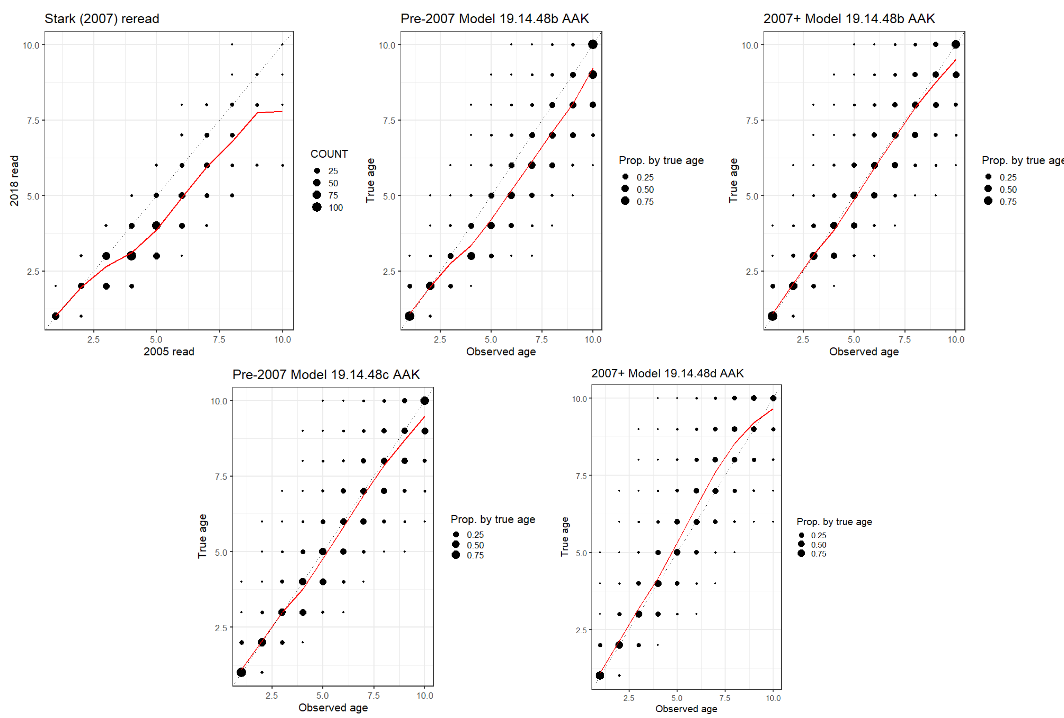

Figure 14. Reread of otoliths from Stark (2007) with the same otoliths read in 2005 (top left) and 2018 compared, age to age key for Model19.14.48b with pre-2007 age bias specified in model (top middle), age to age key for Model 19.14.48b with 2007+ age bias fit in model(top right), pre-2007 fit within Model19.14.48c where pre-2007 age bias parameters were freely fit in model and 2007+ fixed at 0 (bottom left), and age to age key for Model 19.14.48d for 2007+ age bias fit in model and pre-2007 age bias parameters specified at that fit in model 48c (bottom right). Dashed line is the 1:1 and the red line is the mean true age at observed age.

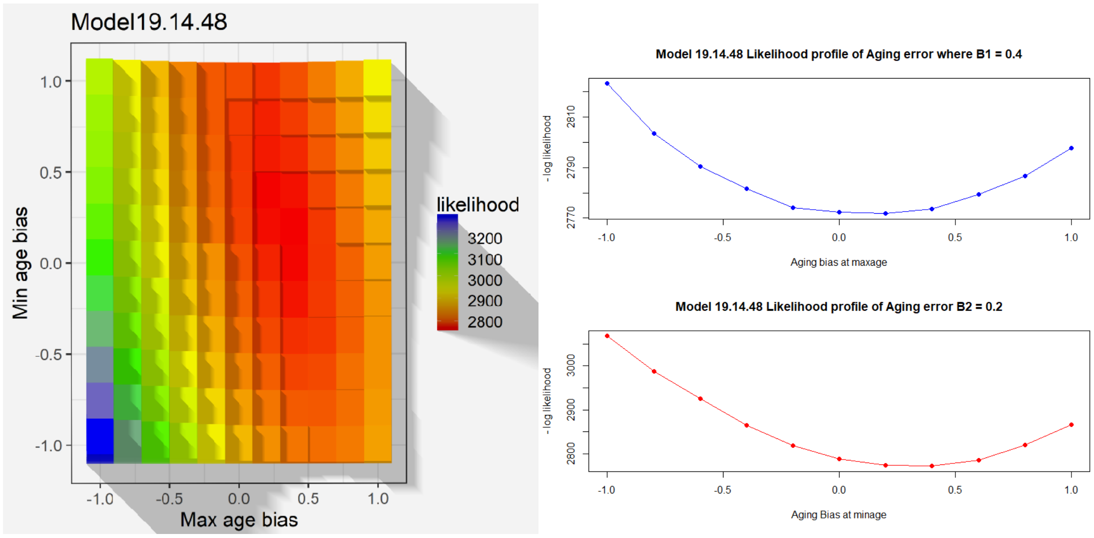

Figure 15. Likelihood provide over pre-2007 aging bias parameters B1 (aging bias at minimum age) and B2 (aging bias at maximum age).

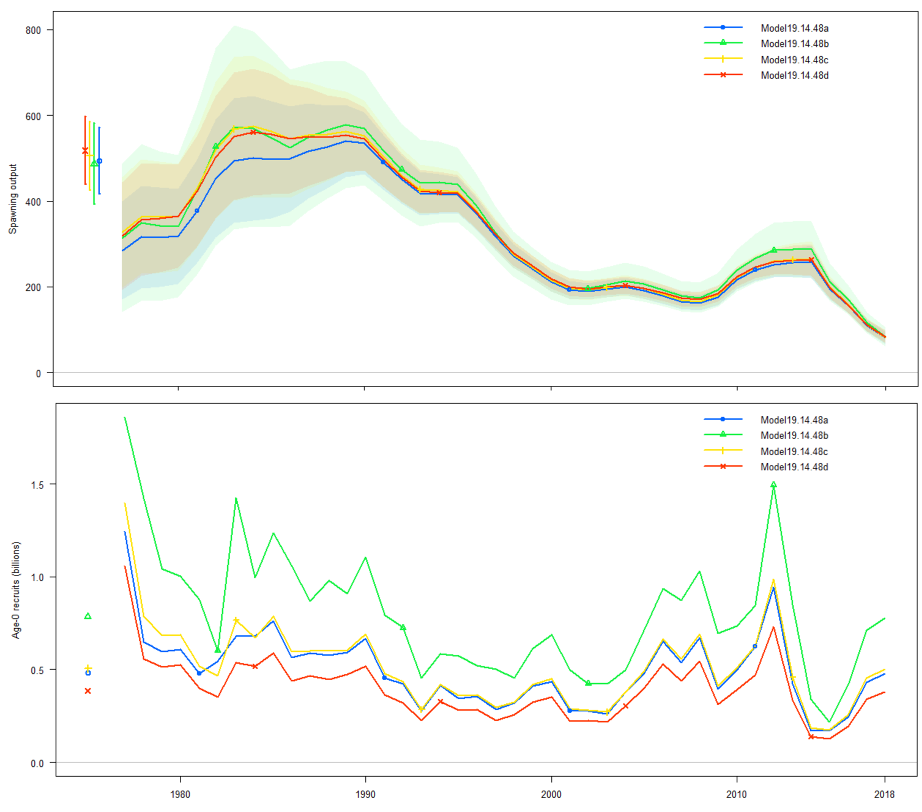

Figure 16. Spawning biomass (upper) and age-o recruits (lower) for models 19.14. 48a, 48b, 48c, and 48d comparing different options for ageing bias.

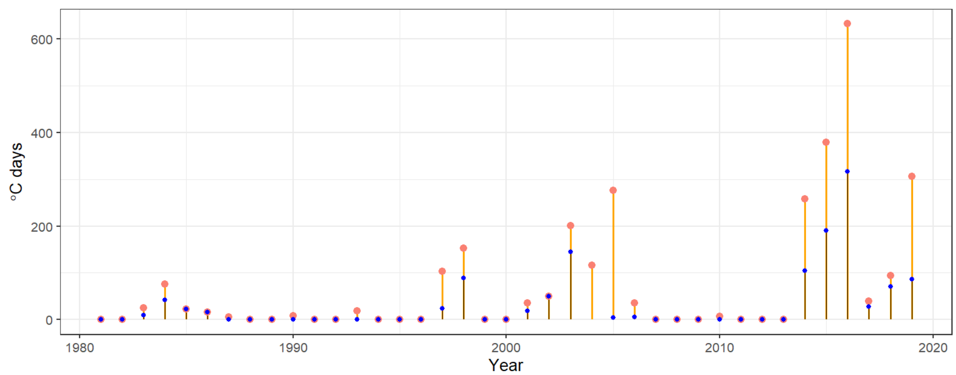

Figure 17. Marine heatwave index (orange) and winter marine heatwave index (blue) for the central GOA waters shallower than 300m.

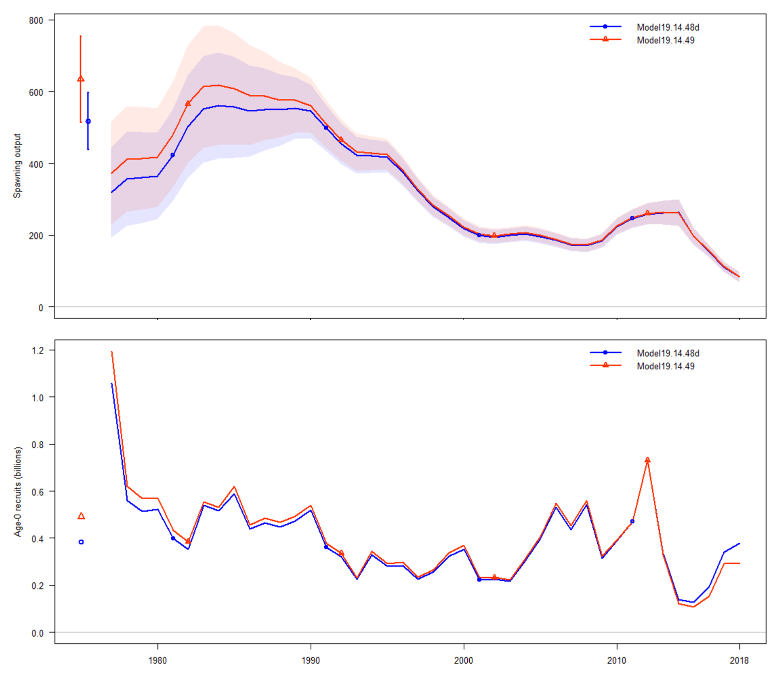

Figure 18. Spawning biomass (upper) and age-o recruits (lower) for models 19.14. 48d and 19.14.49.

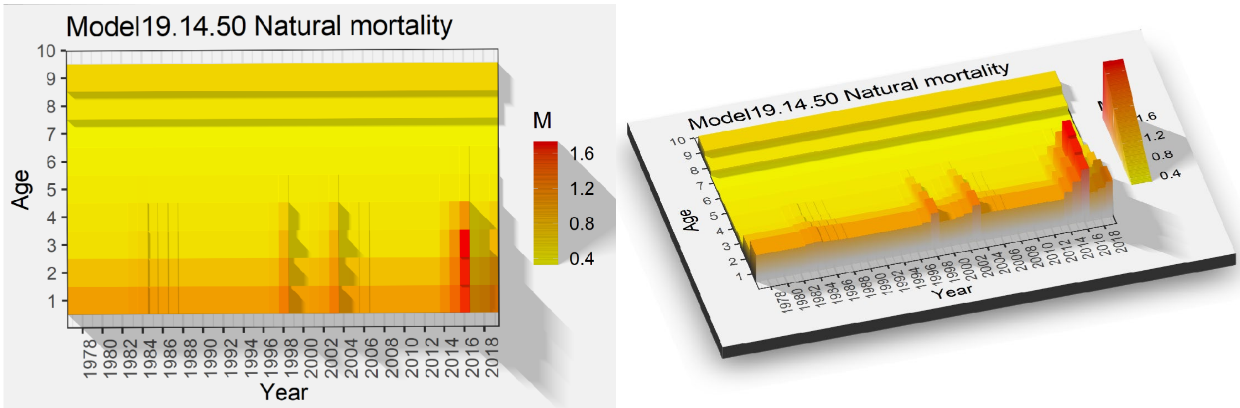

Figure 19. Natural mortality estimates for Model19.14.50.

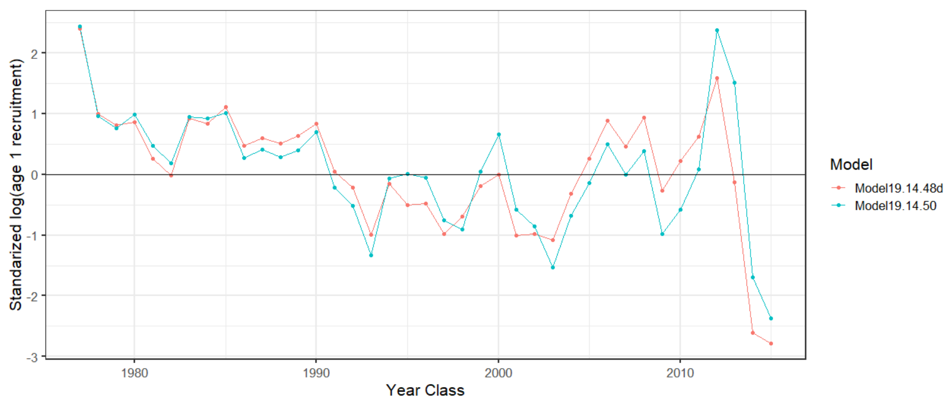

Figure 20. Standardized log age 1 recruitment for Model 19.14.48d and Model 19.14.50.

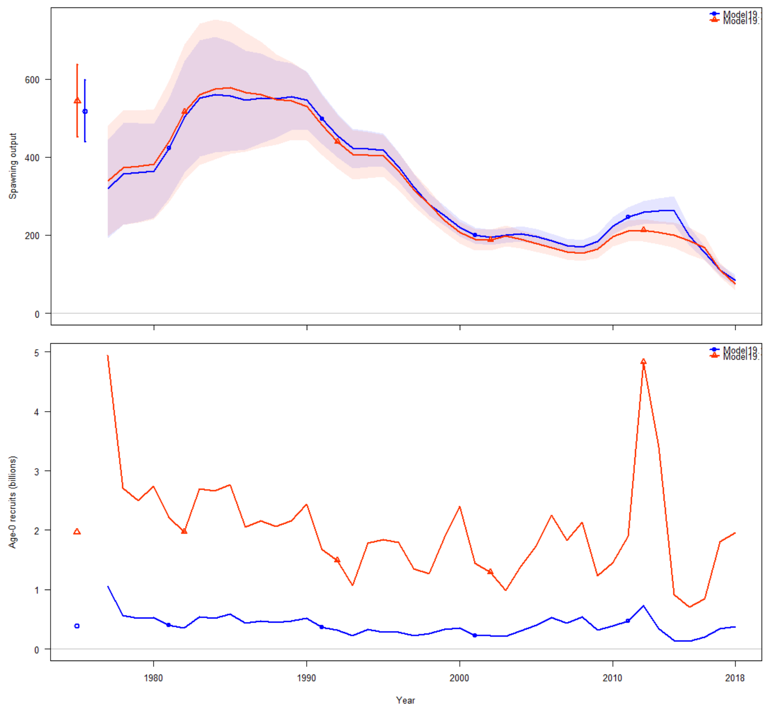

Figure 21. Spawning biomass (upper) and age-o recruits (lower) for models 19.14. 48d and 19.14.50.

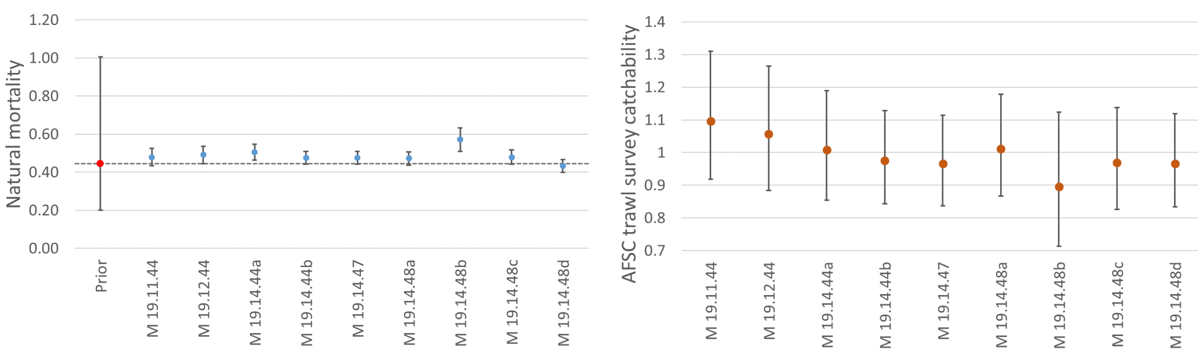

Figure 22. Natural mortality (left) and AFSC bottom trawl survey catchability estimates (right) with 95% confidence intervals from the inverted hessian approximation.