Appendix 2.1 Gulf of Alaska Pacific cod assessment models for Plan Team consideration, September 2021

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Introduction

In this document the authors present a series of bridged models and seek advice on which models the Plan Team would like presented in November. The authors would also like advice on what objective model selection criteria the Plan Team would suggest be presented to aid in model evaluation and selection for November.

For this year we explored five changes to the model from the 2020 reference model (Model 19.1, Barbeaux *et al.* 2020) that resulted in nine bridged models (Table 1). First we looked at the inclusion of a beach seine age-0 index of abundance to the model; second, we examined environmental links on growth, natural mortality, and recruitment; third we examined changing the natural mortality block to 2015-2020; and finally we examined tuning the indices input standard error to the RMSE and tuning composition data using the Francis method. The addition of the age-0 beach seine data as a recruitment index was provided as an improvement to help inform recruitment estimates. Previous models used to manage this stock have had few data to inform abundance at ages younger than 3. The set of environmentally linked models demonstrated issues with fitting these links in single species stock assessment models and the difficulty in model selection where improvements are minimal. The tuned models were presented to demonstrate the sensitivity of the models to differences in data weighting.

Adding environmental links to the base model adds complexity to the models and makes assumptions about the processes that impact the annual variability of the stock that may not yet be well established in the literature. The improvements to the tactical model in all cases were at best minor while changes to the management advice resulting from the models were in some cases substantial. The authors wish to continue to work on these models and present a set of these for November, but are reluctant to recommend any of them for management of the stock at this time.

Environmental Data

Laurel and Litzow age-0 index

Beach seine sampling of age-0 cod was conducted at two Kodiak Island bays during 2006-2021 and an expanded survey was conducted during 2018-21 at 13 additional bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (n = 3 - 9 fixed stations per bay, 95 total stations). Sampling occured during July and August (days of year 184-240), within two hours of a minus tide at the long-term Kodiak sites, and within three hours of a low tide at the expanded survey sites. At all sites, a 36 m long, negatively buoyant beach seine was deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Wings on the seine (13 mm mesh) were 1 m deep at the ends and 2.25 m in the middle with a 5 mm delta mesh cod end bag. The seine wings were attached to 25 m ropes for deployment and retrieval from shore. The seine was set parallel to and ~ 25 m, making the effective sampling area ~ 900 m^2 of bottom habitat.

A model-based index of annual catch per unit effort (CPUE) for age-0 cod was used to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the *brms* package (Carpenter et al. 2017, Buerkner 2017, R Core Team 2021). The beach seine age-0 CPUE index showed the large 2012 year class and subsequent drop in CPUE for 2013-2016, larger recruitment in 2017 and 2018, a drop again in 2019, and then large 2020 year class (Table 2). The most recent bottom trawl survey included in Model 19.1 was 2019, however Pacific cod don’t fully recruit into this survey until approximately age-3. Therefore Model 19.1 would not have much information informing year classes after 2016. The 2006 through 2016 recruitment deviations from Model 19.1 correlate positively with the log CPUE of the beach seine index with an R^2 of 0.67.

CFSR bottom temperature indices

The Climate Forecast System Reanalysis (CFSR) was the latest version of the National Centers for Environmental Prediction (NCEP) climate reanalysis. The oceanic component of CFSR included the Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 4 (MOM4) with an iterative sea-ice (Saha et al., 2010). It used 40 levels in the vertical with a 10-meter resolution from surface down to about 262 meters. The zonal resolution was 0.5° and a meridional resolution of 0.25° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 0.5° poleward of 30°S and 30°N.

To make the index the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations. The co-located CFSR oceanic temperature profiles were then linearly interpolated to obtain the temperatures at the depths centers of gravity for 10 cm and 40 cm Pacific cod as determined from the AFSC bottom trawl survey. All co-located grid points were then averaged to get the time series of CFSR temperatures over the period of 1979-2020 (Table 3).

Sum of annual marine heatwave cumulative intensity index (MHCI)

The daily sea surface temperatures for 1 January 1981 through 31 December 2020 were retrieved from the NOAA High-resolution Blended Analysis Data database (National Oceanic and Atmospheric Administration, 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300 m in depth. The overall daily mean sea surface temperatures were then calculated for the entire region. These daily mean sea surface temperatures data were processed through the R package *heatwaveR* (Schlegel and Smit, 2018) to obtain the marine heatwave cumulative intensity (MHCI; Hobday et al., 2016) value where we defined a heatwave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the 1 January 1982 through 31 December 2012 time series. The MHCI were then summed for each year to create an annual index of MHCI, summed for each year for the months of January through March, November, and December to create an annual winter index of MHCI, and summed for February and March to create an annual spawning index of MHCI (Table 3).

Model Configurations

Except where noted below, the models presented were configured the same as Model 19.1 from Barbeaux et al. (2020), the reference model used to set management advice. All ecosystem-link parameters presented were fit with uninformative uniform priors.

AFSC longline survey catchability

For the base model an ecosystem-linked covariate on AFSC longline survey catchability has been in use since 2017 (Barbeaux et al., 2016) and will continue to be used in all of the models used in this study. Annual catchability, Q_y, was modeled using a multiplicative link as:

$$log\left(\mathrm{Q_y}\right) = \log(\overline{\mathrm{Q}})\mathrm{e}^{\alpha \mathrm{f}_{Jy}},$$

where $\bar{Q}$ was the mean catchability for the AFSC longline survey for 1977 through 2020, α was the ecosystem link parameter fit with an uninformative prior, and f_{Jy} was the June CFSR bottom temperature anomaly in the Central GOA in year y.

Growth

For the base model (19.1), 21.1a, 21.1b, and 21.1c length at age, L_a, were modeled as three parameter von Bertalanffy growth models with length in June, L_1, maximum asymptotic length, L_2, and growth rate, k, as:

$$\mathrm{L_a} = \mathrm{L_2} - (\mathrm{L_2} - \mathrm{L_1})\mathrm{e}^{-\mathrm{ak}},$$

where a was age.

For the ecosystem-linked models 21.1d, 21.1e, 21.1f, 21.5a and 21.5b length at age for each year, L_{ay}, were modeled as six parameter von Bertalanffy growth modeled with annual water temperature covariates on L_1, L_2, and k as:

$$\mathrm{L_{ay}} = \mathrm{L_{2y}} - \left(\mathrm{L_{2y}} - \mathrm{L_{1y}}\right)\mathrm{e}^{-\mathrm{ak}\left(\mathrm{e}^{\varphi \mathrm{f_{Jy}}}\right)}$$

$$L_{1y} = \bar{L}_1 e^{\left(\gamma \frac{\mathrm{e}^{\left(0.2494+0.3216\left(\bar{t}+f_{Jy}\right)-0.0069\left(\bar{t}+f_{Jy}\right)^2-0.0004\left(\bar{t}+f_{Jy}\right)^3\right)}}{e^{\left(0.2494+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3\right)}}\right)}$$

$$L_{2y} = \bar{L}_2 e^{\upsilon f_{Jy}}$$

where f_{Jy} was the June bottom temperature anomaly in the Central GOA (described above) in year y, γ was the temperature anomaly link parameters for L_1 and an index of the ratio of the annual June temperature, $\bar{t} + f_{Jy}$, dependent juvenile growth (Laurel *et al.* 2015) for a given year over the growth in June for the mean temperature for 1982-2012, $\bar{t}$, υ was the temperature anomaly link parameter for L_2, and φ the temperature anomaly link parameter for *k*.

Natural mortality

Natural mortality in the base Model 19.1, and Models 21.1a, 21.1b, and 21.1d were fit for two time blocks, 2014-2016 and all other years, as a single non-varying parameter for all ages for each block. Natural mortality in Model 21.1c, 21.1e, and 21.1g was annually varying with a linear ecosystem-link parameter, η, which scaled the non-heatwave year natural mortality, $\widehat{M}$, using the annual central GOA marine heatwave cumulative index (I_{Ay}) as:

$$\mathrm{M_y} = \widehat{M} + \eta l_y$$

$$l_y = \lambda / \left(1 + e^{-\varsigma(I_{Ay} - \psi)}\right)$$

A logistic curve was used to convert the index forcing M to asymptote at higher index values (Table 3). Here the shape of the logistic curve including the asymptote, λ, slope, ς, and inflection point in °C days, ψ, was determined within the model iteratively and the parameters resulting in the lowest negative log-likelihood were selected for projections. The best fit model had λ at 0.65, $\varsigma = 0.005$ and $\psi = 400$ resulting in increased natural mortality estimates for years with positive I_{Ay} values. Note the maximum annual marine heatwave index value in the time series was 631°C-days in 2016, well below future projected values.

For Models 21.5a and 21.5c natural mortality were fit for two time blocks, 2015-2021 and all other years, as a single non-varying parameter for all ages for each block with uninformative priors.

Recruitment

In the base Model 19.1, Model 21.1a, and Model 21.1b recruitment by year, R_y, were modeled as:

$$\mathrm{R_y} = \left(\mathrm{R_0 e^{\vartheta}}\right)\mathrm{e}^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}\text{, if } \mathrm{y} \geq 1977 \rightarrow \vartheta = 0\text{, where } \widetilde{\mathrm{R}}_\mathrm{y} = \mathrm{N}\left(0;\ \sigma_\mathrm{R}^2\right),$$

$\mathrm{R_0}$ was the unfished equilibrium recruitment, $\widetilde{\mathrm{R}}_\mathrm{y}$ was the lognormal recruitment deviation for year y, σ_R^2 was the standard deviation among recruitment deviations in log space and was fixed at 0.44, and b_y was a bias adjustment fraction applied during year, y (Methot Jr and Taylor, 2011). To account for an environmental regime change in 1977 (Anderson and Piatt, 1999) the parameter ϑ was fit for recruitment allowing for a change in R_0 prior to the regime change in 1977. Projections in the base model post-2017 assumed average recruitment for 1977-2017 for R_y.

The ecosystem-linked recruitment (R_y) in models 21.1d, 21.1e, 21.1g, 21.5a, and 21.5c were modeled as Beverton-Holt relationships with parameter (ω) which scaled the unfished equilibrium recruitment, $\mathrm{R_0}$, using the annual spawning Central GOA marine heatwave cumulative index (I_y; described below) as:

$$\mathrm{R_y} = \frac{4\mathrm{h}\left(e^{\vartheta + \ln\left(\mathrm{R_0} e^{\omega \mathrm{I}_{Sy}^{\frac{1}{3}}}\right)}\right)\mathrm{SB}_y}{\mathrm{SB_0(1-h)+SB_y(5h-1)}} e^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}\text{, if } \mathrm{y} \geq 1977 \rightarrow \vartheta = 0\text{, where } \widetilde{\mathrm{R}}_\mathrm{Y} = \mathrm{N}\left(0;\ \sigma_\mathrm{R}^2\right),$$

h was the steepness parameter, SB_0 was the unfished equilibrium spawning biomass (corresponding to R_0), and SB_y was the spawning biomass at the start of the spawning season during year y.

Where h=1, the formula reduces to $\mathrm{R_y} = e^{\vartheta + \ln\left(\mathrm{R_0} e^{\omega I_{Sy}^{\frac{1}{3}}}\right)} e^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}$.

Model tuning

For all models except Model 21.1g and 21.5c the models remained at the base configuration with no additional tuning. For these two models the index input variances were tuned to the RMSE and the length and age composition sample size tuned using the Francis TA1.8 method (Francis 2011).

Results

Beach seine index

The inclusion of the age-0 beach seine index in Model 21.1a resulted in a poorer fit for the majority of data components compared to Model 19.1 (Table 4); however, there was a reduction in the objective function for recruitment (Table 5). Comparisons of overall likelihood and marginal likelihoods were not possible given the inclusion of a new dataset/likelihood component. As one would expect the variance estimates for recruitment deviations for the years in which index data were available were lower than in the model without the beach seine index (Table 6). For 2006-2020 the mean CV for Model 19.1 was 0.25 and for Model 21.1a, with the beach seine age-0 index, was 0.19. The index root-mean-squared-standardized-residual (RMSSR) for the bottom trawl and longline survey showed a reduction in fit and the Effective N for age and length compositions for all components showed a slight degradation in fit from Model 19.1 to Model 21.1a.

Retrospective analysis showed both models had slight positive retrospective bias in the estimates of spawning stock biomass with the Mohn's ρ of 0.081 for Model 19.1 and 0.087 for Model 21.1a. The Woodshole ρ and RMSE for spawning stock biomass were also similar (Table 7) with only slight differences between the two configurations. The retrospective bias for both models was considered to be within acceptable bounds.

The largest change in model results between Model 19.1 and Model 21.1a was the increase in estimates for the 2017, 2018, and 2020 year classes and slight decrease in the 2019 year class estimate (Table 6 and Fig. 2) resulting in an overall increase in 2019-2020 estimates of spawning stock biomass (Table 8 and Fig. 2) and increase in projected 2021 and 2022 spawning biomass. This increasing abundance starting in 2017 due to fit to the age-0 index and inability of the model to compensate with changing M post-2016 resulted in the disagreement in Model 21.1a with the recent reduction in the longline survey abundance. Model 21.1a would recommend a ~200% increase in ABC for 2022. This large increase was mostly due to a drop in the estimated unfished spawning biomass with increases in recruitment (Table 5) and an increase in the projected spawning biomass for 2022 resulting in the spawning biomass ratio being above $B_{40\%}$ and no longer on the sloping portion of the control rule.

As Model 21.1a was configured there was disagreement between the age-0 beach seine index and all other data components. There were at least two possible reasons for this disparity 1) the beach seine survey doesn't capture the GOA-wide trend in age-0 abundance, and/or 2) Model 21.1a with natural mortality modeled across all ages with only a block for 2014-2016 does not adequately capture survival variability between age-0 and age-3. Attempts this year at fitting annually varying age-specific M failed as there was a lack of information for the younger age classes as these younger fish were not consistently caught in the fisheries or surveys. For the remainder of the models presented we assumed that the beach seine survey index captures the trend in GOA age-0 Pacific cod abundance.

Environmentally-linked models

The three new environmental links on growth, natural mortality, and recruitment made improvements to the overall model fits over Model 21.1a as measured by full likelihood and full AIC. However the marginal likelihood (Thorson *et al.* 2019) in some cases suggested some of the changes were not true model improvements. Most of the changes made by the inclusion of the environmental links were minor in terms of fit, but some would result in substantial changes in management advice from the base model. Although the residual plots were not provided due to the volume of possible plots, they were assessed by the authors and can be made available on request for any model. For all the age and length composition data there were no severe trends in the residuals and it was very difficult to ascertain differences in model fits visually as differences were subtle. For all models presented there were no parameters near bounds and the likelihoods appeared well defined with the gradient of the objective function at less than 10e-4. All models were examined by "jittering" starting parameters by 10% over 50 runs to evaluate if models had converged to local minima. All models evaluated were deemed adequate.

Model21.1b: SST-linked growth
The parameterization and fit of the SST-linked growth in Model 21.1b resulted in the model estimating faster growth in warm years and slower growth in cold years (Fig 3). The parameters appeared to be well fit with small gradients and CVs between 0.23 and 0.28. SST-linked growth was most impactful in the age-0 fish creating a cohort effect on length in the model (Fig. 3). The addition of sea surface temperature links to growth in Model 21.1b resulted in an improvement in both length and age composition fits for likelihood and effective N, and a slight improvement to the bottom trawl survey (Table 4), but a larger degradation in the fit to the longline and beach seine survey indices with increases in likelihood and RMSSR. There was an overall improvement in AIC from Model 21.1a, however the marginal AIC suggests that the SST-linked growth was not a model improvement. Although the retrospective bias remained within acceptable bounds the analysis suggests a slight increase in positive retrospective bias from Model 21.1a in the spawning biomass estimates across all three measures (Table 7). Overall model results in terms of reference points and current biomass levels (Table 5 and Table 8) remained similar to Model 21.1a.

Model 21.1c: Annual heatwave linked natural mortality
Adding heatwave-linked natural mortality to the model made the greatest improvement to the objective function, AIC, and Marginal AIC over all of the single eco-linked changes from Model 21.1a. The environmental link parameter was well fit with low gradient and a CV of 0.10. Model 21.1c showed improvement over Model 21.1a in fits to the most recent drop in abundance in the longline survey (Fig. 4), in the trawl and longline fishery length composition data, and in the beach seine index. There was a slight degradation in fit to the other data components (Table 4 and Table 5), however the improvement of fit to the most recent longline survey estimates were greater than the combined negative impacts to fit to the other components. Including annual heatwave index-linked natural mortality in Model 21.1c (Fig. 5) results in natural mortality peaking during heatwave years with the highest in 2016 at 0.92 and second highest in 2019 at 0.81. The retrospective analysis showed the model within acceptable bounds with a slight increase in the Mohn's ρ, but a decrease in both the Woodshole ρ and retrospective RMSE compared to Model 21.1a.

Although the overall trend in abundance and recruitment were similar for most of the time series as were reference points between Models 21.1a and 21.1c, the management implications of the estimated drop in abundance for 2018-2020 and projections in Model 21.1c (Fig. 7) changed recommended harvest advice on ABC considerably from Model 21.1a and 21.1b with a -40% lower ABC in 2022. This difference resulted in an ABC nearer the Model 19.1 value (+23%). The difference from Model 21.1a was partly due to the 2022 Model 21.1c spawning biomass being estimated below $B_{40\%}$ (Table 5) and on the slope of the control rule.

Model 21.1d: Spawning heatwave index linked recruitment
The spawning heatwave index linked recruitment (Fig. 6) in Model 21.1d resulted in a slight improvement of fit compared to model 21.1a based on a lower overall objective function and AIC estimate, however there was an increase in the marginal AIC (Table 7). Minor improvements in the objective function can be attributed to fit to the bottom trawl and longline surveys and reduction in recruitment residuals. There were minor reductions in fit to all of the age and length composition data (Table 4). Retrospective bias remained positive for all measures with a slight improvement over Model

21.1a (Table 7). Estimates for unfished biomass were within 1% of the Model 21.1a values as were the recommended ABC for 2022.

Model 21.1e: All three environmental links

Inclusion of all three environmental links in Model 21.1e (Table 5) resulted in a better fit model in regards to the objective function and AIC, however the marginal AIC was higher than Model 21.1c with just heatwave-linked natural mortality. In addition, although still within generally acceptable bounds the retrospective analysis resulted in an increase in the positive bias in the model over all the other models examined for the Mohn's ρ and retrospective RMSE (Table 7). Gradients for the environmental link parameters were all relatively low (Table 9). The ω link parameter on R_0 was the least well defined with a CV of 0.38 and gradient of 0.0001. Compared to Model 21.1a, Model 21.1e improved fits to the longline and beach seine survey indices, the length and age composition data for all three fisheries, the bottom trawl survey age composition data, and the longline survey length composition data (Table 4). Recruitment residuals were improved over all of the other models assessed before tuning (Table 5).

For Model 21.1e the overall trend in abundance and recruitment were similar to the other Model 21.1 series (Fig. 1). Like model 21.1c, Model 21.1e had a drop in abundance for recent years (Fig. 7) and the projections with similar estimates of annually varying natural mortality. Model 21.1e unfished spawning biomass at 345,360 t was the lowest of the un-tuned Model 21.1 series, but was only -5% different from Model 21.1a and -6% from Model 21.1d, the highest of the series, and -16% from Model 19.1. The management implications of the estimated drop in abundance for 2018-2020 and projections in Model 21.1e (Fig. 7) changed recommended harvest advice on ABC considerably from Model 21.1a and 21.1b with a -45% lower ABC in 2022. The Model 21.1e ABC, like Model 21.1c ABC, was nearer the Model 19.1 value (+13%).

Expanding the natural mortality block to 2015-2020

Like Model 21.1e, Model 21.5a had environmental links on recruitment and growth, but unlike Model 21.1e the mortality block first used in Model 19.1 was changed from 2014-2016 to 2015-2020 after iteratively testing combinations of M blocks (Fig. 5). Compared to Model 21.1e, Model 21.5a improved fits to all age composition data and all length composition data except the longline survey length composition and length composition data as well as the longline and beach seine surveys over Model 21.1e while degrading the fit to the bottom trawl survey index. The AIC and marginal AIC were the lowest of all un-tuned models examined for this analysis. Environmentally linked parameter estimates (Table 9) were well estimated with low gradients and relatively low CVs. The estimate for natural mortality for 1978-2014 was the lowest of all the models evaluated at 0.40 and an estimate of M for 2015-2020 at 0.72. Both the bottom trawl and base longline catchability were high for Model 21.5a at 1.359 and 1.413, respectively. The α parameter linking the longline survey catchability to the CFSR surface temperatures was substantially lower than the other non-tuned models from between 0.8 and 1.0 down to 0.5 suggesting less influence of temperature on the longline survey index estimates (Table 9). The retrospective analysis on SSB suggested an increase in the Woodshole ρ and retrospective RMSE over all other models examined (Table 7), but a slight decrease in the Mohn's ρ compared to Model 21.1e, but still higher than other un-tuned models examined. The increased natural mortality in 2015-2020 improved the fit to the large drop in abundance estimated in the longline survey over the last 5 years while degrading the fit to the increasing biomass estimate from the 2019 bottom trawl survey (Fig. 9) making it the worst fit model to this dataset of all examined. While improving the fit to the beach seine survey Model 21.5a increased residuals to estimated recruitment over Model 21.1e.

The trends in spawning biomass and recruitment mirrored the other models examined, however with the lower estimates for natural mortality and higher estimates for catchability the recruitment estimates were lower than other models as were the biomass estimates. Like the other models examined in this document Model 21.5a estimated that the lowest spawning biomass occurred in 2020 (Table 8), however spawning biomass in Model 21.5a was estimated to be below $B_{12\%}$ in 2020 and 2021 and to remain below $B_{20\%}$ through 2022, which would substantially change management advice for this stock compared to the other un-tuned models.

Tuning the models

With the addition of the age-0 index we once again looked into model tuning and the use of the Dirichlet multinomial to handle data weighting for the length and age composition as recommended in Thorson et al. (2019). As in previous attempts with the GOA Pacific cod model, the model fits resulted in the $\ln(\theta)$ parameters with values >15. In addition when implemented in Stock Synthesis the Dirichlet multinomial option led the models to be highly unstable and sensitivity, jitter, and retrospective runs often failed to converge making it difficult to evaluate the models even with the theta parameters fixed. In this document we chose to run two model configurations (Model 21.1g and 21.5c) with the indices tuned to the Index RMSE and the age and length composition sample sizes tuned using the Francis A1.8 method as implemented in R4SS. These models corresponded with the un-tuned models 21.1e and 21.5a.

Due to differences in the multinomial sample sizes the overall likelihoods between Model 21.1g and 21.5c cannot be compared nor can they be compared with the other models presented. For both tuned models there was a reduced weight on all three survey indices with an increase in variance for all three indices and a reduction in all age and length composition sample sizes (Table 10). However once tuned these models ended up placing more weight on the indices as can be seen in the reduction of the RMSSR for all three (Table 5) to near or below 1.0. The effective sample size in both tuned models were substantially lower than the un-tuned models as would be expected with the lower input sample size. The increase in variance and drop in input sample size placed less weight on the data components and allowed the model to adhere more closely to structural assumptions such as those provided for recruitment. The model then expended less in reducing recruitment residuals where the assumptions conflicted with data. Due to the higher variance for the longline survey index in both tuned models, the environmental link parameter on catchability (α) was substantially lower (0.382 and 0.295 for Model 21.1g and Model 21.5c) than the un-tuned models (between 0.8 and 1.0 for the Model 21.1 series and 0.5 for Model 21.5a), resulting in models with less variability in the longline survey index with sea surface temperature. Similarly, the temperature growth link parameters (φ, γ, and υ) were lower in the tuned models resulting in lower annual variability in growth overall (Table 9).

One issue in the tuned models was a large increase in the catchability for both the bottom trawl and longline surveys (Table 5). Inflating catchability allowed for an overall lower abundance making it easier to fit to the large recent drop in the longline abundance. The larger catchabilities also allowed for lower recruitment with smaller deviations from the spawner-recruit relationship.

Tuning increased the positive retrospective bias for Model 21.1g over the other 21.1 series models. For Model 21.5c, however, the retrospective bias was substantially reduced with a slightly negative bias for Mohn’s ρ and Woodshole ρ and lower retrospective RMSE for the spawning biomass estimates making Model 21.5c the best model in terms of least retrospective bias (Table 7 and Fig. 11). Having RMSSR lower than 1.0 for most of the indices may indicate overfitting of the indices in these models and an additional iteration on tuning the input variance warranted.

Discussion

The inclusion of the age-0 beach seine index provided an anchor point for the models and resulted in an improvement in estimates of recruitment with lower recruitment residuals and a reduction in recruitment variability and variability in reference points. However this improvement came at a cost to the fits to the other data components. For the 21.1 and 21.5 series of models we needed to assume the beach seine index captured the overall trend in GOA age-0 Pacific cod abundance. We know that the other survey and fishery data included in this assessment provide poor estimates of young fish between ages 0 and 3. Therefore the degradation in model fit to the other survey indices and composition data we believe identifies model misspecification. This is likely due to the current set of models not having age-varying natural mortality and the likeliness of age-varying natural mortality being time varying. Models should be further explored that do include time and age-varying natural mortality. Attempts this year to develop such models found that fitting both of these in a single model was problematic and led to unlikely results with large differences in natural mortality between adjacent ages.

The exploration of ecosystem-linked models in this document highlight the difficulty in developing environmental links for tactical management advice. Here we saw marginal changes in measured model fit to the data that then produced a wide range of management advice depending on which environmental relationships were included. In the case of the models presented we can examine the partial impacts of increasing temperature and probability of a severe heatwave events, both of which were trending with climate change. Because we have opposing impacts on spawning biomass (faster growth, lower recruitment, and higher natural mortality with increasing temperature), including only one relationship may be problematic where data become scarce and in projections where they may drive estimates in a particular direction. Laboratory studies provide one means of examining the relationships and parameterizing the models; however, interactions within the ecosystem make these relationships less certain. In single species models the uncertainty in the relationships among ecosystem components when environmental conditions exceed the range of those observed in the past is not quantifiable.

It should be noted that when tuning a model, one is shifting weights of the data components in a model and changing the balance between the data components and model structure, including prior assumptions. In the series of models presented in this document, tuning of the model resulted in down-weighting all of the data components by adding variance to the indices and reducing sample size in the composition data. In broad terms the data down-weighting resulted in the model placing more emphasis on model assumptions and structure instead of data, particularly for recruitment. In addition the inflation of catchability in the tuned models was problematic and would lead me to disregard these model configurations.

Overall the variability in model results due to inclusion of different environmental links without a clear objective means of determining which configuration provides the best management advice was problematic. Retrospective analysis with time varying parameters was difficult to interpret particularly where there were time blocks and environmental linked relationships within the retrospective time period assessed. Likelihood and AIC measures were not useful for comparing models with different data components or different data weightings.

References

Barbeaux. S. J., A’mar, T., and Palsson, W. 2016. Assessment of the Pacific cod stock in the Gulf of Alaska. In Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 175-324. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Barbeaux. S. J., B. Ferris, W. Palsson, I. Spies, M. Wang, and S. Zador. 2020. Assessment of the Pacific cod stock in the Gulf of Alaska. In Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68: 1124-1138. https://doi.org/10.1139/f2011-025

Laurel, B., M. Spencer, P. Iseri, and L. Copeman. 2016a. Temperature-dependent growth and behavior of juvenile Arctic cod (*Boreogadus saida*) and co-occurring North Pacific gadids. Polar Biology 39:1127-1135.

Laurel, B. J., B. A. Knoth, and C. H. Ryer. 2016b. Growth, mortality, and recruitment signals in age-0 gadids settling in coastal Gulf of Alaska. ICES Journal of Marine Science 73:2227-2237.

Thorson, J.T., Johnson, K.F., Methot, R.D. and Taylor, I.G., 2017. Model-based estimates of effective sample size in stock assessment models using the Dirichlet-multinomial distribution. Fisheries Research, 192, pp.84-93.

Tables

Table 1 - Models developed for September 2021

Model name	Data changes from 2020	Model changes from 2020	Description
Model 19.1	None	None	Reference model from 2020
Model 21.1a	Laurel/Litzow larval index	Model 19.1	Addition of the age-0 index from the Kodiak Beach seine surveys conducted by Laurel and Litzow.
Model 21.1b	Laurel/Litzow larval index	Model 21.1a with Temp.-linked growth	SST-linked growth in model
Model 21.1c	Laurel/Litzow larval index	Model 21.1a with heatwave-linked natural mortality	Heatwave-linked natural mortality
Model 21.1d	Laurel/Litzow larval index	Model 21.1a with heatwave-linked recruitment	Heatwave-linked recruitment in model
Model 21.1e	Laurel/Litzow larval index	Model 21.1a with Temp.-linked growth, and heatwave-linked recruitment and mortality.	All environmental links turned on
Model 21.1g	Laurel/Litzow larval index	Model 21.1e with index tuned to RMSE and length composition tuned using the Francis method	Model 21.1e tuned
Model 21.5a	Laurel/Litzow larval index	Model 21.1e with extended M block 2015- 2020	Extended heatwave M to include 2015-2020 instead of environmental link
Model 21.5c	Laurel/Litzow larval index	Model 21.35a with index tuned to RMSE and length composition tuned using the Francis method	Model 21.5a tuned

Table 2 - Age-0 beach seine index CPUE (fish per set) and standard error and Model 19.1 age-0 recruitment in billions (10^9).

Year	CPUE (#/set)	SE	age-0 (1×10^9)
2006	86.34	0.41	0.687
2007	6.22	0.46	0.443
2008	20.45	0.44	0.652
2009	21.98	0.59	0.392
2010	6.53	0.54	0.507
2011	22.14	0.46	0.655
2012	117.77	0.44	1.215
2013	6.73	0.48	0.638
2014	5.95	0.58	0.211
2015	0.77	0.95	0.260
2016	1.30	0.55	0.168
2017	52.18	0.41	0.246
2018	84.85	0.31	0.390
2019	1.52	0.62	0.399
2020	117.81	0.35	0.464

Table 3 - Environmental indices used in reviewed 2021 models.

Year	CFSR SST Anomaly (°C)	Annual heatwave index (°C-days)	Spawning heatwave index (°C-days)	Larval growth index	Asymptotic heatwave index
1977	0.00	0.00	0.00	1.00	0.077
1978	0.00	0.00	0.00	1.00	0.077
1979	0.33	0.00	0.00	1.08	0.077
1980	0.45	0.00	0.00	1.11	0.077
1981	1.14	0.00	0.00	1.28	0.077
1982	-0.58	0.00	0.00	0.87	0.077
1983	0.53	31.88	1.68	1.13	0.089
1984	0.15	88.21	0.00	1.04	0.113
1985	0.00	24.61	2.70	1.00	0.086
1986	0.15	16.35	0.00	1.04	0.083
1987	0.72	5.58	0.00	1.18	0.079
1988	0.12	0.00	0.00	1.03	0.077
1989	-0.53	0.00	0.00	0.88	0.077
1990	-0.46	8.72	0.00	0.90	0.081
1991	-0.19	0.00	0.00	0.96	0.077
1992	0.32	0.00	0.00	1.08	0.077
1993	-0.05	19.10	0.00	0.99	0.084
1994	-0.10	0.00	0.00	0.98	0.077
1995	-0.54	0.00	0.00	0.88	0.077
1996	-0.08	0.00	0.00	0.98	0.077
1997	-0.01	142.05	0.00	1.00	0.140
1998	1.15	150.85	4.32	1.29	0.145
1999	-0.14	0.00	0.00	0.97	0.077
2000	-0.06	0.00	0.00	0.99	0.077
2001	0.40	46.91	2.25	1.10	0.095
2002	-0.37	51.27	0.00	0.92	0.097
2003	0.73	207.85	4.76	1.18	0.180
2004	0.03	117.65	0.00	1.01	0.127
2005	0.33	284.60	0.00	1.08	0.234
2006	0.05	35.14	0.00	1.01	0.090
2007	-0.44	0.00	0.00	0.90	0.077
2008	-0.25	0.00	0.00	0.94	0.077
2009	-0.92	0.00	0.00	0.80	0.077
2010	0.63	6.52	0.00	1.15	0.080
2011	-0.03	0.00	0.00	0.99	0.077
2012	-0.58	0.00	0.00	0.87	0.077
2013	-0.40	0.00	0.00	0.91	0.077
2014	0.16	283.02	0.00	1.04	0.233
2015	1.30	402.32	5.11	1.33	0.327
2016	1.13	630.87	5.38	1.28	0.494
2017	0.18	53.03	0.00	1.04	0.097
2018	0.53	128.50	0.00	1.13	0.133
2019	1.37	496.74	4.65	1.34	0.402
2020	-0.28	102.92	0.00	0.94	0.143

Table 4 - Likelihood components by fleet for models reviewed in 2021. Note that likelihoods for some models are not comparable due to differences in data (Model 19.1 survey ALL) or weighting (Models 21.1g and 21.5c).

LABEL	ALL	FSHTRAWL	FSHLL	FSHPOT	SRV	LLSRV	SEINE	MODEL
AGE_LIKE	1633.74	302.58	362.41	288.45	680.30			19.1
AGE_LIKE	1634.15	303.56	361.95	288.31	680.32			21.1a
AGE_LIKE	1625.46	302.40	358.74	285.91	678.40			21.1b
AGE_LIKE	1635.35	304.22	362.38	288.28	680.48			21.1c
AGE_LIKE	1634.62	303.61	361.98	288.32	680.71			21.1d
AGE_LIKE	1625.20	302.96	358.77	285.56	677.91			21.1e
AGE_LIKE	1562.15	295.63	342.96	276.29	647.27			21.1g
AGE_LIKE	1622.36	302.82	358.11	285.50	675.93			21.5a
AGE_LIKE	1562.75	295.88	343.21	276.65	647.01			21.5c
LENGTH_LIKE	1568.22	467.69	316.81	362.55	170.06	251.10		19.1
LENGTH_LIKE	1576.75	460.93	319.98	367.51	174.35	253.99		21.1a
LENGTH_LIKE	1573.39	462.68	321.19	363.61	176.50	249.41		21.1b
LENGTH_LIKE	1569.87	455.02	316.72	370.02	173.81	254.29		21.1c
LENGTH_LIKE	1577.55	460.64	319.48	368.42	175.40	253.61		21.1d
LENGTH_LIKE	1568.46	456.89	318.00	366.89	176.93	249.76		21.1e
LENGTH_LIKE	525.05	128.03	147.81	61.22	80.41	107.58		21.1g
LENGTH_LIKE	1561.77	455.25	316.78	362.68	176.14	250.92		21.5a
LENGTH_LIKE	521.18	126.74	144.14	62.55	82.25	105.50		21.5c
SURV_LIKE	-16.12				-10.64	-5.48		19.1
SURV_LIKE	-2.36				-7.00	0.49	4.15	21.1a
SURV_LIKE	-0.81				-7.94	2.54	4.59	21.1b
SURV_LIKE	-6.22				-3.20	-6.04	3.02	21.1c
SURV_LIKE	-4.09				-7.37	-0.92	4.20	21.1d
SURV_LIKE	-5.64				-4.02	-4.96	3.34	21.1e
SURV_LIKE	-32.74				-9.23	-21.99	-1.52	21.1g
SURV_LIKE	-11.09				2.89	-14.37	0.40	21.5a
SURV_LIKE	-34.89				-8.13	-25.07	-1.68	21.5c
LENGTH MEAN EFFN		788.6	1312.3	638.9	470.6	429.9		19.1
LENGTH MEAN EFFN		789.0	1314.4	630.2	468.0	420.0		21.1a
LENGTH MEAN EFFN		799.9	1393.7	641.8	450.1	431.6		21.1b
LENGTH MEAN EFFN		786.5	1313.6	633.9	467.5	416.3		21.1c
LENGTH MEAN EFFN		790.4	1318.1	627.3	468.2	422.4		21.1d
LENGTH MEAN EFFN		798.6	1402.7	642.6	449.3	429.4		21.1e
LENGTH MEAN EFFN		727.4	1136.7	622.0	445.5	439.7		21.1g
LENGTH MEAN EFFN		797.7	1440.5	646.6	449.1	431.9		21.5a
LENGTH MEAN EFFN		728.7	1165.2	626.3	446.7	441.0		21.5c
AGE MEAN EFFN		4.7	8.7	7.3	13.7			19.1
AGE MEAN EFFN		4.8	8.6	7.4	13.2			21.1a
AGE MEAN EFFN		4.8	8.9	7.8	12.2			21.1b
AGE MEAN EFFN		4.7	8.6	7.5	13.6			21.1c
AGE MEAN EFFN		4.7	8.6	7.4	13.6			21.1d
AGE MEAN EFFN		4.8	8.8	7.8	12.3			21.1e
AGE MEAN EFFN		5.2	9.4	8.9	12.8			21.1g
AGE MEAN EFFN		4.8	8.7	7.7	12.5			21.5a
AGE MEAN EFFN		5.2	9.3	8.9	12.7			21.5c

Table 5 - Likelihood components and derived quantities for models reviewed in 2021. For models with environmental links on M and models 21.5a and 21.5c the mortality estimates in brackets and greyed are the maximum and minimum estimates.

	Model 19.1	Model 21.1a	Model 21.1b	Model 21.1c	Model 21.1d	Model 21.1e	Model 21.1g	Model 21.5a	Model 21.5c
TOTAL_like	3190.02	3210.54	3202.85	3194.11	3205.07	3182.09	2039.62	3168.69	2036.43
Survey_like	-16.12	-2.36	-0.81	-6.22	-4.09	-5.64	-32.74	-11.09	-34.89
Length_comp_like	1568.22	1576.75	1573.39	1569.87	1577.55	1568.46	525.05	1561.77	521.18
Age_comp_like	1633.74	1634.15	1625.46	1635.35	1634.62	1625.20	1562.15	1622.36	1562.75
Recruitment	-5.50	-8.37	-5.60	-15.48	-12.34	-15.70	-20.48	-13.67	-18.47
InitEQ_Regime	1.48	1.45	1.90	2.03	1.59	2.67	1.17	2.13	1.30
Forecast_Recruitment	0.06	1.91	2.10	1.60	0.74	0.71	0.54	0.69	0.61
Parm_priors_like	1.59	0.47	0.01	0.47	0.47	0.01	0.00	0.01	0.00
Recr_Virgin_millions	463.71	472.99	406.78	495.07	544.07	485.41	444.55	324.79	310.91
SR_LN(R0)	13.05	13.07	12.92	13.11	13.21	13.09	13.00	12.69	12.65
SR_LN(R0)_ENV_mult					-0.0114	-0.0092	-0.0096	-0.0092	-0.0098
NatM (min M)	0.47	0.47	0.44	min(0.45)	0.47	min(0.44)	min(0.44)	min(0.40)	min(0.41)
NatM for 2014-2016 (max M)	0.82	0.75	0.75	max(0.92)	0.75	max(0.93)	max(0.85)	max(0.72)	max(0.68)
NatM central parameter				0.37		0.35	0.37		
NatM additive				1.12		1.17	0.98		
NatM mult. 2015-2020								0.57	0.51
L_at_Amin	12.09	12.09	7.00	12.08	12.08	6.67	5.67	6.66	5.59
L at Amin ENV mult.			0.56			0.61	0.71	0.61	0.73
L_at_Amax	99.46	99.46	99.46	99.46	99.46	99.46	99.46	99.46	99.46
L at Amax ENV mult.			0.11			0.11	0.10	0.11	0.10
VonBert K	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
VonBert K ENV mult			-0.16			-0.15	-0.13	-0.15	-0.12
Q bottom trawl index	1.16	1.16	1.23	1.10	1.15	1.16	1.43	1.36	1.61
SSB unfished 1000's t	413.55	365.05	361.74	347.33	368.36	345.36	318.94	310.79	300.36
SSB unfished CV	0.081	0.074	0.074	0.075	0.075	0.076	0.080	0.072	0.080
F_{MSY} (sum apical F)	0.668	0.753	0.678	0.795	0.761	0.729	0.753	0.639	0.636
2022 F_{ABC} (sum apical F)	0.448	0.753	0.678	0.620	0.761	0.549	0.648	0.292	0.344
SSBratio 2021	0.22	0.33	0.33	0.23	0.32	0.22	0.25	0.12	0.14
SSBratio 2022	0.28	0.43	0.43	0.32	0.41	0.31	0.35	0.19	0.23
Index root of mean squared standardized residuals (RMSSR)									
Bottom trawl survey	1.416	1.589	1.546	1.752	1.572	1.718	0.926	1.984	1.007
Longline survey	1.878	1.978	2.011	1.868	1.955	1.887	0.938	1.718	0.825
Beach seine survey	NA	1.408	1.429	1.353	1.410	1.369	0.920	1.217	0.908
Std.Dev(Ln(age-0)) 1978-2019	0.443	0.424	0.445	0.342	0.439	0.375	0.342	0.393	0.373

Table 6 - Age-0 recruitment in thousands of fish and coefficient of variation (CV) for assessed models.

	Model 19.1		Model 21.1a		Model21.1b		Model21.1c		Model21.1d	
Year	Age-0	CV	Age-0	CV	Age-0	CV	Age-0	CV	Age-0	CV
1978	377,556	0.349	379,158	0.345	377,992	0.347	361,736	0.338	417,244	0.342
1979	369,733	0.319	376,339	0.314	373,381	0.317	359,789	0.308	410,868	0.311
1980	624,014	0.288	638,465	0.281	504,666	0.302	607,456	0.277	693,037	0.279
1981	689,951	0.268	698,292	0.262	659,821	0.253	667,217	0.258	752,084	0.259
1982	756,252	0.271	769,099	0.265	729,879	0.268	734,718	0.260	834,698	0.261
1983	538,912	0.310	540,797	0.307	407,980	0.325	520,729	0.299	536,447	0.312
1984	709,138	0.276	722,969	0.270	657,489	0.265	689,984	0.264	809,158	0.264
1985	886,695	0.238	892,515	0.234	799,968	0.231	833,058	0.230	889,248	0.237
1986	499,375	0.271	503,011	0.267	375,480	0.294	478,455	0.260	551,995	0.261
1987	588,083	0.227	595,309	0.222	491,730	0.223	562,530	0.219	618,762	0.219
1988	597,962	0.221	603,810	0.216	538,538	0.210	579,513	0.213	635,484	0.213
1989	632,229	0.217	639,776	0.212	596,082	0.207	621,659	0.209	671,344	0.208
1990	749,185	0.203	754,939	0.198	643,233	0.199	740,039	0.196	791,292	0.195
1991	444,758	0.224	446,710	0.220	346,336	0.230	449,242	0.218	469,281	0.217
1992	385,255	0.216	387,645	0.212	311,307	0.212	402,972	0.211	405,677	0.209
1993	309,854	0.219	313,010	0.215	256,693	0.214	337,543	0.215	327,972	0.212
1994	347,856	0.206	352,879	0.201	312,422	0.194	391,114	0.202	368,422	0.199
1995	438,067	0.187	440,732	0.182	380,762	0.180	503,708	0.184	461,184	0.179
1996	309,470	0.198	312,439	0.194	268,489	0.192	369,782	0.196	323,913	0.192
1997	293,505	0.196	294,918	0.191	231,693	0.200	363,125	0.195	314,388	0.189
1998	272,155	0.192	274,925	0.187	212,963	0.185	329,572	0.190	276,357	0.187
1999	366,527	0.181	370,574	0.177	351,062	0.169	436,357	0.178	391,163	0.174
2000	439,377	0.173	442,541	0.169	359,828	0.169	552,223	0.170	462,909	0.166
2001	250,745	0.192	250,536	0.189	236,532	0.179	335,654	0.190	254,341	0.188
2002	193,147	0.192	194,844	0.189	167,993	0.192	259,680	0.191	209,745	0.185
2003	244,348	0.176	245,085	0.172	212,052	0.169	321,670	0.174	245,080	0.172
2004	307,845	0.171	311,232	0.165	289,611	0.161	366,652	0.165	327,856	0.163
2005	420,358	0.167	410,764	0.161	346,196	0.160	454,397	0.159	424,567	0.158
2006	686,755	0.163	706,285	0.152	631,775	0.148	658,602	0.148	733,076	0.150
2007	443,195	0.178	404,280	0.165	356,507	0.164	379,898	0.159	417,934	0.164
2008	651,882	0.173	601,931	0.158	543,933	0.154	548,979	0.153	624,993	0.156
2009	391,813	0.195	397,704	0.172	334,628	0.176	373,756	0.164	409,121	0.170
2010	506,839	0.192	434,530	0.171	339,557	0.170	401,095	0.163	448,951	0.170
2011	655,108	0.202	567,604	0.175	513,133	0.172	536,803	0.165	583,773	0.174
2012	1,215,110	0.215	1,039,390	0.184	949,610	0.184	1,024,320	0.173	1,069,210	0.183
2013	638,080	0.248	468,547	0.208	433,984	0.209	495,858	0.196	479,472	0.207
2014	211,074	0.286	241,005	0.227	209,402	0.227	272,007	0.211	244,487	0.227
2015	260,163	0.247	240,750	0.220	165,092	0.234	306,902	0.219	237,647	0.220
2016	168,038	0.248	190,432	0.214	180,225	0.202	231,348	0.205	183,224	0.217
2017	246,044	0.235	438,126	0.194	377,592	0.196	475,888	0.182	439,743	0.194
2018	389,895	0.278	698,218	0.189	616,627	0.188	696,969	0.180	713,420	0.189
2019	399,011	0.401	253,131	0.259	213,060	0.260	268,197	0.239	226,550	0.273
2020	463,705	0.482	852,381	0.207	762,533	0.208	812,021	0.196	894,707	0.210
2006-2020 mean	488,447	0.249	502,288	0.193	441,844	0.193	498,843	0.183	513,754	0.193
1978-2020 mean	473,699	0.235	481,340	0.212	420,182	0.213	491,005	0.207	501,880	0.211

Table 6 Cont. - Age-0 recruitment in thousands of fish and coefficient of variation (CV) for assessed models.

	Model 21.1e		*Model 21.1g*		*Model 21.5a*		*Model21.5c*	
Year	*Age-0*	*CV*	*Age-0*	*CV*	*Age-0*	*CV*	*Age-0*	*CV*
1978	395,269	0.343	405,973	0.397	250,342	0.351	273,273	0.404
1979	385,344	0.316	366,576	0.373	237,661	0.331	244,589	0.384
1980	515,580	0.302	401,744	0.376	320,765	0.318	270,439	0.383
1981	683,986	0.255	518,978	0.338	433,580	0.275	353,499	0.347
1982	759,232	0.267	628,058	0.364	481,087	0.286	425,742	0.369
1983	394,972	0.328	350,884	0.416	259,739	0.338	242,584	0.413
1984	696,500	0.263	618,507	0.354	460,863	0.279	434,964	0.356
1985	759,515	0.235	571,253	0.342	534,252	0.249	417,468	0.342
1986	392,411	0.286	384,481	0.355	273,842	0.300	280,494	0.355
1987	487,543	0.223	463,544	0.302	347,065	0.236	343,380	0.302
1988	550,431	0.211	441,318	0.306	385,336	0.225	322,706	0.306
1989	615,420	0.208	575,463	0.293	423,790	0.224	415,443	0.292
1990	663,983	0.202	538,987	0.297	452,010	0.218	384,469	0.295
1991	368,196	0.231	338,298	0.317	247,678	0.243	239,031	0.313
1992	341,316	0.215	322,690	0.295	225,506	0.225	225,246	0.291
1993	293,828	0.217	305,766	0.289	187,902	0.226	208,267	0.285
1994	366,345	0.198	341,370	0.279	230,233	0.207	228,376	0.273
1995	461,980	0.186	399,468	0.271	277,983	0.194	259,289	0.262
1996	332,732	0.199	316,787	0.280	194,141	0.205	199,809	0.269
1997	308,514	0.206	271,199	0.296	173,363	0.211	165,041	0.281
1998	259,454	0.194	256,860	0.274	154,449	0.197	162,637	0.259
1999	444,120	0.175	378,239	0.266	263,873	0.182	238,206	0.251
2000	475,600	0.176	422,947	0.259	266,965	0.182	252,129	0.244
2001	332,943	0.186	265,022	0.271	175,222	0.192	152,467	0.256
2002	244,538	0.198	233,581	0.268	129,464	0.202	134,300	0.254
2003	286,522	0.177	244,064	0.252	155,503	0.181	144,368	0.237
2004	364,921	0.165	341,839	0.238	222,424	0.170	220,369	0.226
2005	401,823	0.162	358,779	0.235	262,307	0.169	246,100	0.226
2006	614,612	0.147	586,454	0.215	464,906	0.156	457,584	0.206
2007	347,100	0.161	349,904	0.228	266,598	0.167	272,617	0.218
2008	514,246	0.152	470,056	0.221	378,419	0.159	359,218	0.210
2009	320,417	0.171	290,948	0.239	230,732	0.175	217,718	0.226
2010	321,967	0.166	305,709	0.230	227,382	0.166	224,491	0.215
2011	494,854	0.167	478,024	0.232	336,251	0.164	343,155	0.213
2012	958,239	0.177	806,918	0.244	626,495	0.168	573,267	0.219
2013	468,120	0.202	373,191	0.266	319,211	0.187	273,128	0.241
2014	241,961	0.217	228,882	0.285	178,291	0.206	171,794	0.263
2015	205,189	0.240	178,631	0.308	165,812	0.232	144,272	0.290
2016	225,846	0.204	220,776	0.273	182,407	0.200	175,980	0.257
2017	418,118	0.188	461,615	0.255	347,844	0.188	366,859	0.243
2018	639,029	0.184	589,737	0.251	457,327	0.181	435,326	0.236
2019	212,764	0.251	208,246	0.312	160,661	0.241	157,075	0.297
2020	760,536	0.203	674,723	0.263	529,127	0.195	498,365	0.248
2006-2020 mean	449,533	0.189	414,921	0.255	324,764	0.186	311,390	0.239
1978-2020 mean	449,442	0.213	402,011	0.289	299,972	0.219	282,687	0.280

Table 7 - Negative log likelihood, Akaike information criterion (AIC), negative log marginal likelihood, marginal AIC, and retrospective values for 10-year peal for spawning stock biomass for models reviewed in 2021 showing Mohn's ρ, Woodshole ρ, and retrospective RMSE. Color coding is unique for each column with higher values in red, lower in green. Attributes are G = SST linked growth, Mh = annual heatwave-linked M, R = spawning heatwave-linked recruitment, M20 = 2015-2020 block M, and T = Index variance and composition sample sizes tuned.

							Retrospective analysis (SSB)		
	Attributes	# Parameters	-Log likelihood	AIC	-Marginal log likelihood	Marginal AIC	ρ	Woodshole ρ	RMSE
Model 19.1		201	3,190.0	6,782.0	3,356.6	7,115.3	0.078	0.077	0.148
Model 21.1		202	3,210.5	6,825.1	3,368.7	7,139.3	0.087	0.071	0.162
Model 21.1b	G	204	3,202.8	6,813.7	3,372.1	7,152.3	0.129	0.080	0.178
Model 21.1c	Mh	201	3,194.1	6,790.2	3,352.2	7,106.4	0.101	0.063	0.159
Model 21.1d	R	203	3,205.1	6,816.1	3,368.7	7,141.5	0.086	0.067	0.145
Model 21.1e	G, R, Mh	205	3,182.1	6,774.2	3,356.3	7,122.6	0.164	0.072	0.183
Model 21.1g	G, R, Mh, T	205	2,039.6	4,489.2	2,149.1	4,708.2	0.164	0.120	0.198
Model 21.5a	G, R, M20	205	3,168.7	6,747.4	3,343.6	7,097.2	0.132	0.121	0.223
Model 21.5c	G, R, M20,T	205	2,036.4	4,482.9	2,149.8	4,709.5	-0.047	-0.015	0.078

Table 8 - Spawning biomass (SSB) in tons for models presented with coefficient of variation (CV).

	Model 19.1		*Model 21.1a*		*Model 21.1b*		*Model 21.1c*		*Model 21.1d*	
Year	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*
1978	239,697	0.209	247,661	0.203	234,602	0.202	240,390	0.206	265,263	0.206
1979	235,975	0.200	243,100	0.194	231,204	0.195	237,479	0.198	260,113	0.197
1980	240,527	0.191	246,978	0.185	239,307	0.185	242,276	0.188	264,244	0.187
1981	287,555	0.188	294,080	0.183	293,990	0.182	289,829	0.185	315,213	0.183
1982	333,569	0.184	340,448	0.179	364,284	0.178	339,561	0.181	364,838	0.180
1983	344,749	0.178	351,411	0.173	364,603	0.172	355,580	0.175	376,146	0.173
1984	347,180	0.173	353,440	0.168	383,529	0.166	357,296	0.168	377,812	0.167
1985	377,083	0.159	382,980	0.155	419,197	0.154	375,007	0.155	407,388	0.153
1986	422,196	0.142	427,757	0.138	457,103	0.137	417,136	0.137	451,838	0.136
1987	454,985	0.127	460,277	0.124	480,673	0.123	448,565	0.123	481,751	0.122
1988	466,017	0.114	470,623	0.111	505,793	0.112	459,994	0.110	489,655	0.109
1989	486,343	0.102	490,345	0.099	519,829	0.099	482,471	0.098	506,062	0.097
1990	486,461	0.092	489,978	0.089	492,421	0.089	487,076	0.089	502,450	0.088
1991	446,601	0.088	449,667	0.086	437,560	0.085	450,899	0.087	460,138	0.084
1992	410,158	0.086	412,946	0.084	397,392	0.084	419,881	0.085	422,082	0.082
1993	382,899	0.086	385,405	0.083	379,372	0.082	398,215	0.085	393,484	0.081
1994	388,969	0.081	391,230	0.078	382,088	0.077	407,402	0.080	399,183	0.077
1995	388,821	0.073	390,752	0.071	376,714	0.070	413,835	0.074	397,579	0.070
1996	345,532	0.070	347,113	0.068	323,908	0.069	376,731	0.071	353,005	0.067
1997	293,694	0.068	295,099	0.067	273,635	0.068	330,841	0.070	299,826	0.065
1998	247,246	0.069	248,599	0.067	229,602	0.069	269,814	0.070	252,560	0.066
1999	220,957	0.070	222,196	0.068	215,899	0.068	230,759	0.070	225,763	0.067
2000	194,687	0.073	195,821	0.071	185,549	0.071	209,989	0.073	199,068	0.069
2001	175,784	0.073	176,768	0.071	166,102	0.072	197,078	0.074	179,842	0.069
2002	167,020	0.070	167,881	0.068	161,370	0.068	191,560	0.071	170,359	0.067
2003	165,756	0.067	166,546	0.065	155,023	0.066	195,955	0.069	168,727	0.064
2004	166,849	0.067	167,552	0.065	162,136	0.065	186,357	0.066	169,945	0.064
2005	158,075	0.067	158,653	0.066	153,967	0.066	175,612	0.065	160,748	0.064
2006	141,916	0.066	142,365	0.065	141,699	0.065	136,755	0.061	144,081	0.064
2007	124,747	0.067	125,029	0.066	126,129	0.066	119,532	0.063	126,230	0.065
2008	116,691	0.071	116,683	0.069	114,917	0.067	112,403	0.066	117,659	0.068
2009	126,048	0.074	125,263	0.071	122,135	0.069	121,278	0.069	126,597	0.070
2010	164,317	0.072	162,984	0.068	149,085	0.068	158,925	0.066	164,762	0.066
2011	186,628	0.075	182,178	0.069	176,185	0.067	178,513	0.068	184,086	0.068
2012	198,720	0.082	188,101	0.074	182,205	0.072	185,023	0.073	190,017	0.073
2013	205,243	0.089	190,468	0.079	176,541	0.078	188,345	0.078	192,062	0.078
2014	213,549	0.098	192,761	0.084	176,462	0.086	191,957	0.082	193,864	0.084
2015	156,531	0.086	145,963	0.078	131,856	0.080	165,593	0.085	147,059	0.077
2016	125,791	0.079	123,232	0.075	115,357	0.073	147,985	0.083	124,512	0.074
2017	89,922	0.080	94,194	0.080	90,029	0.077	98,459	0.080	95,373	0.079
2018	71,880	0.100	77,567	0.096	72,754	0.095	81,840	0.094	78,264	0.095
2019	69,588	0.101	77,671	0.094	74,533	0.094	78,777	0.091	77,438	0.094
2020	69,263	0.109	82,742	0.097	83,838	0.097	57,944	0.100	81,096	0.097
1978-2020 mean	254,331	0.103	255,872	0.099	253,967	0.098	260,719	0.100	264,144	0.098

Table 8 Cont. - Spawning biomass (SSB) in tons for models presented with coefficient of variation (CV).

	Model 21.1cd		*Model 21.1e*		*Model 21.1g*		*Model 21.5a*		*Model 21.5c*	
Year	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV
1978	252,650	0.207	240,259	0.212	272,696	0.240	159,924	0.218	193,131	0.258
1979	249,397	0.198	238,047	0.205	265,215	0.234	159,149	0.212	189,158	0.254
1980	254,442	0.189	247,656	0.195	265,775	0.225	165,611	0.204	190,434	0.246
1981	304,840	0.184	307,043	0.190	301,502	0.217	204,890	0.202	216,954	0.238
1982	357,053	0.180	386,189	0.185	359,273	0.213	262,614	0.196	264,576	0.229
1983	373,479	0.174	390,960	0.178	354,935	0.206	269,157	0.190	266,805	0.221
1984	374,939	0.167	410,566	0.171	357,632	0.201	289,105	0.185	276,261	0.214
1985	392,432	0.153	432,416	0.157	360,737	0.186	324,366	0.171	295,569	0.197
1986	434,368	0.135	466,769	0.140	377,566	0.167	363,663	0.151	320,384	0.173
1987	464,061	0.121	486,995	0.126	388,733	0.150	390,650	0.135	338,603	0.153
1988	473,796	0.108	512,399	0.114	406,694	0.137	420,275	0.120	361,031	0.137
1989	494,007	0.096	527,121	0.102	414,118	0.122	439,583	0.106	372,635	0.120
1990	496,327	0.087	501,425	0.092	391,652	0.109	422,272	0.094	355,337	0.106
1991	458,706	0.084	448,277	0.089	347,064	0.107	377,254	0.091	314,875	0.103
1992	426,699	0.083	412,331	0.088	314,412	0.106	343,293	0.089	282,767	0.103
1993	404,222	0.082	400,338	0.087	300,893	0.107	328,001	0.088	266,318	0.104
1994	413,273	0.078	405,879	0.082	307,616	0.100	332,861	0.082	271,672	0.097
1995	418,785	0.071	406,302	0.076	310,736	0.091	332,552	0.075	273,589	0.087
1996	380,882	0.069	357,566	0.075	273,090	0.089	287,602	0.073	236,837	0.084
1997	334,002	0.068	312,180	0.074	239,497	0.089	244,169	0.071	202,634	0.083
1998	272,559	0.068	253,115	0.074	197,549	0.089	204,837	0.072	171,849	0.084
1999	233,359	0.067	227,788	0.072	180,998	0.086	193,687	0.069	164,116	0.082
2000	212,287	0.071	202,479	0.076	160,126	0.091	165,313	0.073	140,580	0.085
2001	199,167	0.072	188,992	0.078	150,122	0.092	147,858	0.074	127,055	0.086
2002	193,090	0.069	187,821	0.074	151,911	0.087	144,519	0.069	126,380	0.080
2003	197,137	0.067	185,962	0.073	149,904	0.084	138,718	0.068	120,905	0.076
2004	187,849	0.064	184,057	0.068	148,854	0.081	145,577	0.066	124,789	0.075
2005	176,854	0.063	173,813	0.067	138,144	0.080	138,088	0.066	115,608	0.076
2006	138,040	0.060	137,703	0.063	110,165	0.074	128,002	0.064	105,080	0.074
2007	120,464	0.061	121,760	0.064	96,026	0.075	114,076	0.064	92,709	0.074
2008	113,153	0.065	111,625	0.066	87,339	0.079	102,979	0.066	83,623	0.077
2009	122,263	0.067	119,405	0.068	93,947	0.083	107,779	0.068	88,541	0.080
2010	160,139	0.064	146,178	0.068	118,836	0.080	129,526	0.066	110,571	0.076
2011	179,657	0.066	173,528	0.067	143,042	0.076	151,603	0.062	131,697	0.070
2012	185,945	0.071	179,629	0.072	146,154	0.080	152,382	0.064	131,625	0.071
2013	188,812	0.076	173,979	0.079	138,857	0.086	142,737	0.068	121,909	0.074
2014	191,787	0.080	174,067	0.086	137,290	0.095	137,492	0.072	116,825	0.079
2015	165,518	0.083	149,549	0.090	119,158	0.102	135,963	0.082	114,577	0.096
2016	148,435	0.081	140,636	0.084	117,154	0.100	125,248	0.077	110,939	0.097
2017	99,600	0.078	96,023	0.080	85,734	0.110	104,598	0.076	96,421	0.105
2018	82,694	0.092	78,415	0.096	69,005	0.139	65,695	0.089	62,398	0.134
2019	79,042	0.089	76,258	0.093	69,397	0.139	49,064	0.094	49,205	0.155
2020	57,957	0.100	57,495	0.102	57,892	0.163	37,099	0.116	39,822	0.197
1978-2020 mean	266,609	0.098	265,837	0.102	220,406	0.123	211,159	0.103	186,902	0.123

Table 9 – Environmental link parameters, coefficient of variation, gradient by model for all models evaluated.

Environmental link		*Value*	*cv*	*Gradient*	*Model*
Catchability	Q - α	0.941	0.324	1.83E-07	19.1
Catchability	Q - α	0.926	0.340	-6.64E-07	21.1a
Catchability	Q - α	0.802	0.301	1.73E-06	21.1b
Catchability	Q - α	1.064	0.404	1.07E-05	21.1c
Catchability	Q - α	0.992	0.339	-4.74E-08	21.1d
Catchability	Q - α	0.953	0.370	1.61E-05	21.1e
Catchability	Q - α	0.382	0.730	-2.79E-05	21.1g
Catchability	Q - α	0.529	0.285	1.27E-07	21.5a
Catchability	Q - α	0.295	0.714	-2.93E-05	21.5c
Growth	K - φ	-0.159	0.276	-9.84E-06	21.1b
Growth	K - φ	-0.155	0.281	1.45E-05	21.1e
Growth	K - φ	-0.127	0.419	-8.71E-05	21.1g
Growth	K - φ	-0.146	0.292	1.26E-06	21.5a
Growth	K - φ	-0.124	0.428	-2.12E-04	21.5c
Growth	L1 - γ	0.559	0.231	2.68E-05	21.1b
Growth	L1 - γ	0.606	0.217	3.11E-05	21.1e
Growth	L1 - γ	0.714	0.217	-1.09E-04	21.1g
Growth	L1 - γ	0.613	0.211	2.41E-06	21.5a
Growth	L1 - γ	0.728	0.213	-9.99E-05	21.5c
Growth	L2 - υ	0.111	0.248	-1.98E-05	21.1b
Growth	L2 - υ	0.110	0.247	2.43E-05	21.1e
Growth	L2 - υ	0.097	0.352	-1.23E-04	21.1g
Growth	L2 - υ	0.109	0.245	1.98E-06	21.5a
Growth	L2 - υ	0.097	0.351	-4.01E-04	21.5c
Mortality	M - η	1.116	0.099	-4.50E-05	21.1c
Mortality	M - η	1.174	0.099	-6.01E-05	21.1e
Mortality	M - η	0.984	0.160	2.29E-04	21.1g
Mortality	M - η	0.572	0.078	-1.87E-06	21.5a
Mortality	M - η	0.508	0.134	-7.39E-06	21.5c
Recruitment	R0 - ω	-0.011	0.308	1.80E-05	21.1d
Recruitment	R0 - ω	-0.009	0.381	-1.14E-04	21.1e
Recruitment	R0 - ω	-0.010	0.384	-5.69E-03	21.1g
Recruitment	R0 - ω	-0.009	0.393	5.08E-05	21.5a
Recruitment	R0 - ω	-0.010	0.388	7.69E-03	21.5c

Table 10 – Tuning values for Model 21.1g and Model 21.5c

Component		Tuning	Model 21.1g	Model 21.5c
Index	Beach siene survey	add_to_survey_CV	0.100	0.100
	Bottom trawl survey	add_to_survey_CV	0.162	0.162
	Longline survey	add_to_survey_CV	0.171	0.171
Length	Trawl fishery	mult_by_lencomp_N	0.256	0.257
	Longline fishery	mult_by_lencomp_N	0.417	0.423
	Pot fishery	mult_by_lencomp_N	0.156	0.152
	Bottom trawl survey	mult_by_lencomp_N	0.432	0.420
	Longline survey	mult_by_lencomp_N	0.403	0.412
Age	Trawl fishery	mult_by_agecomp_N	0.511	0.532
	Longline fishery	mult_by_agecomp_N	0.572	0.577
	Pot Fishery	mult_by_agecomp_N	0.346	0.358
	Bottom trawl survey	mult_by_agecomp_N	0.196	0.192

Figures

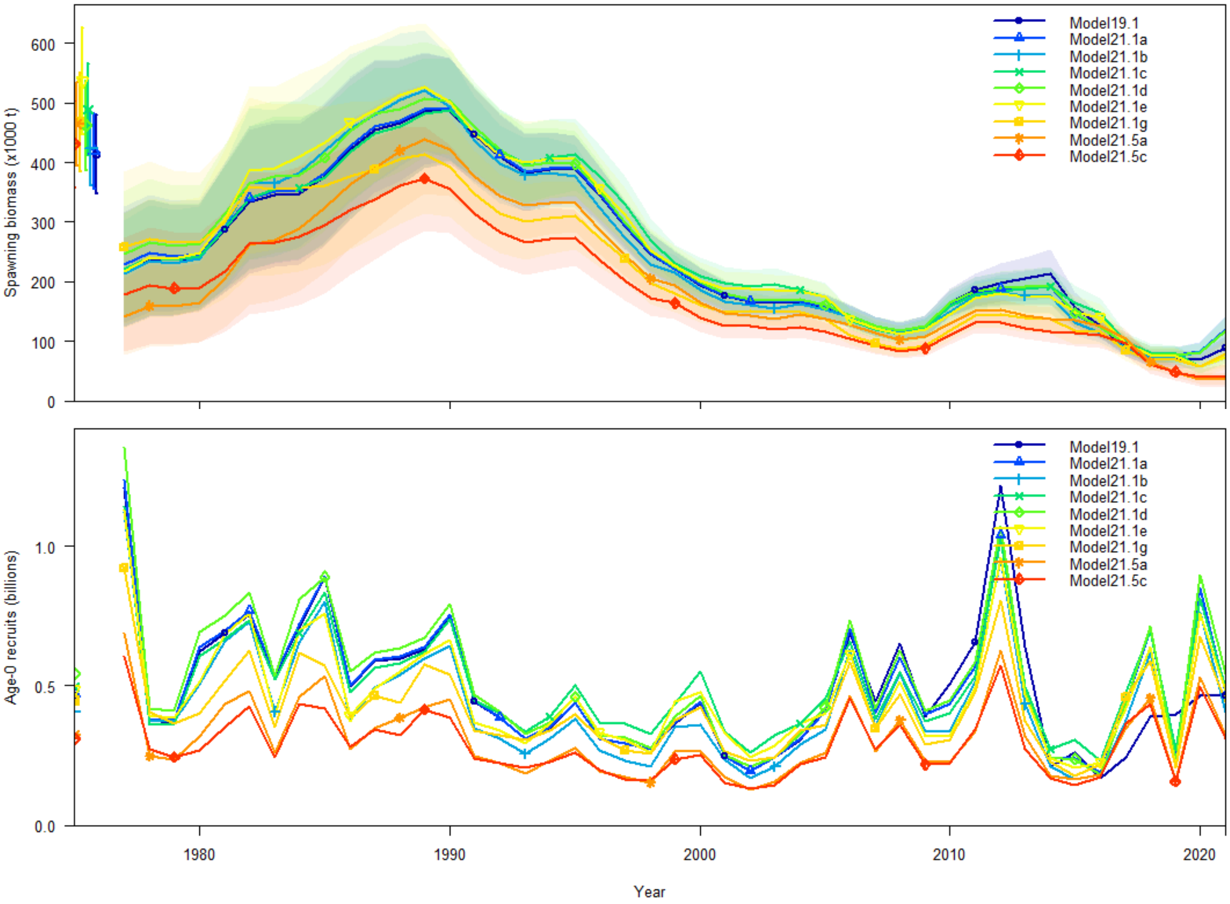

Figure 1 – (Top) spawning biomass (1000 t), and (Bottom) number of age-0 recruits (billions) for assessed models.

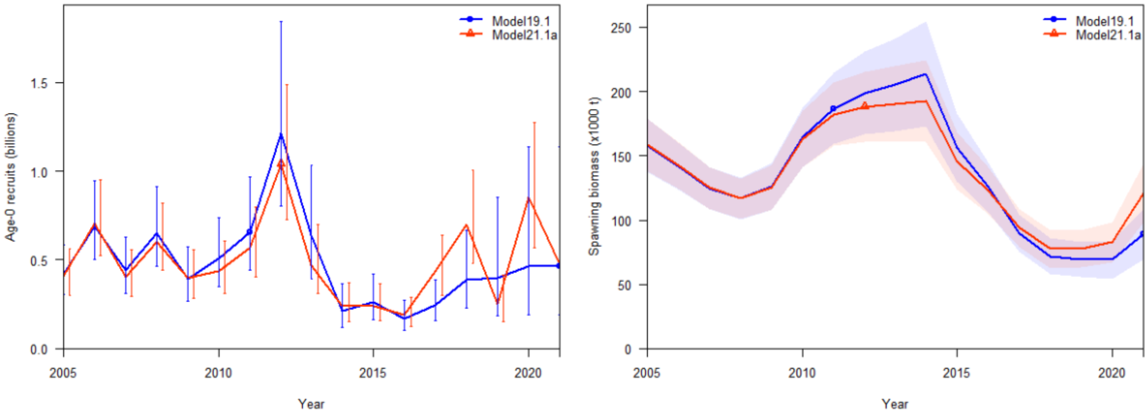

Figure 2 - (Left) estimate of the number of age-0 recruits for 2006-2021 and (Right) estimate of the 2006-2020 spawning biomass for the base model 19.1 and Model 21.1a with the inclusion of the age-0 beach seine index.

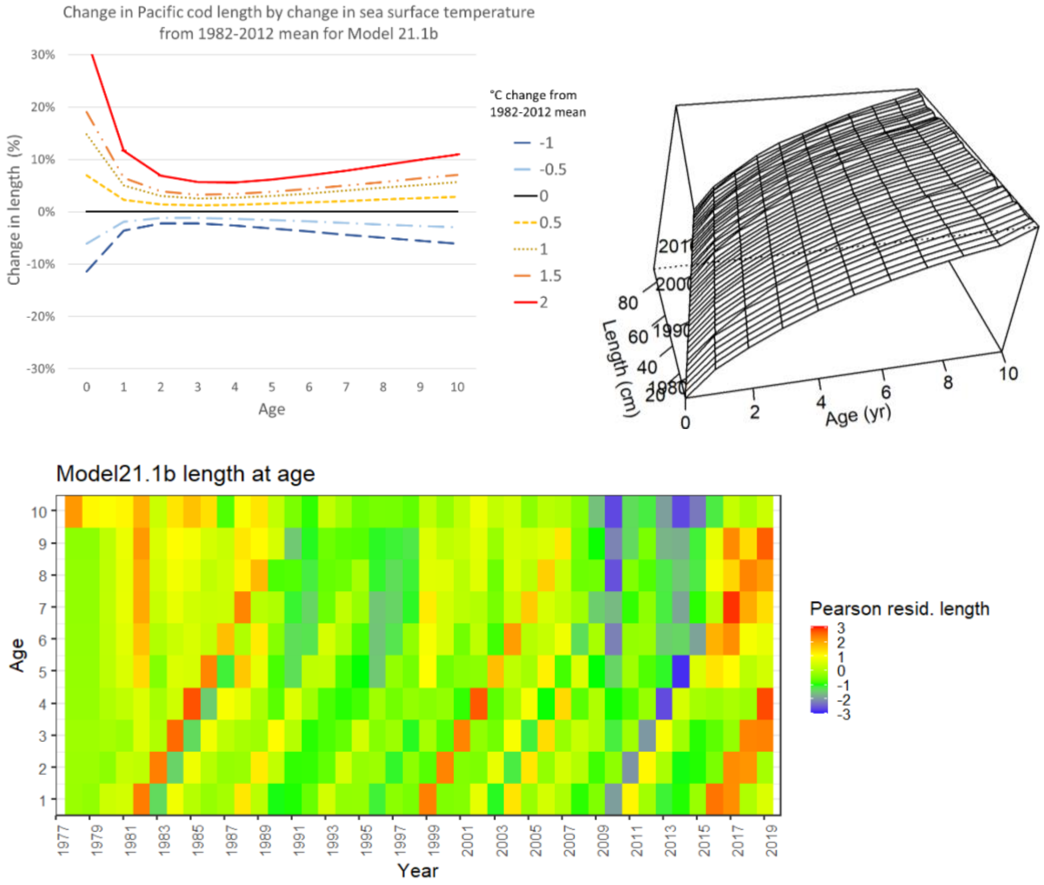

Figure 3 – For Model 21.1b (Top left) percent change in length from mean temperature by age, (Top right) Length at age over time for 1978-2020, and (bottom) Pearson residuals for length (cm) at age showing temperature effect on growth with larger Pacific cod originating in the warm years.

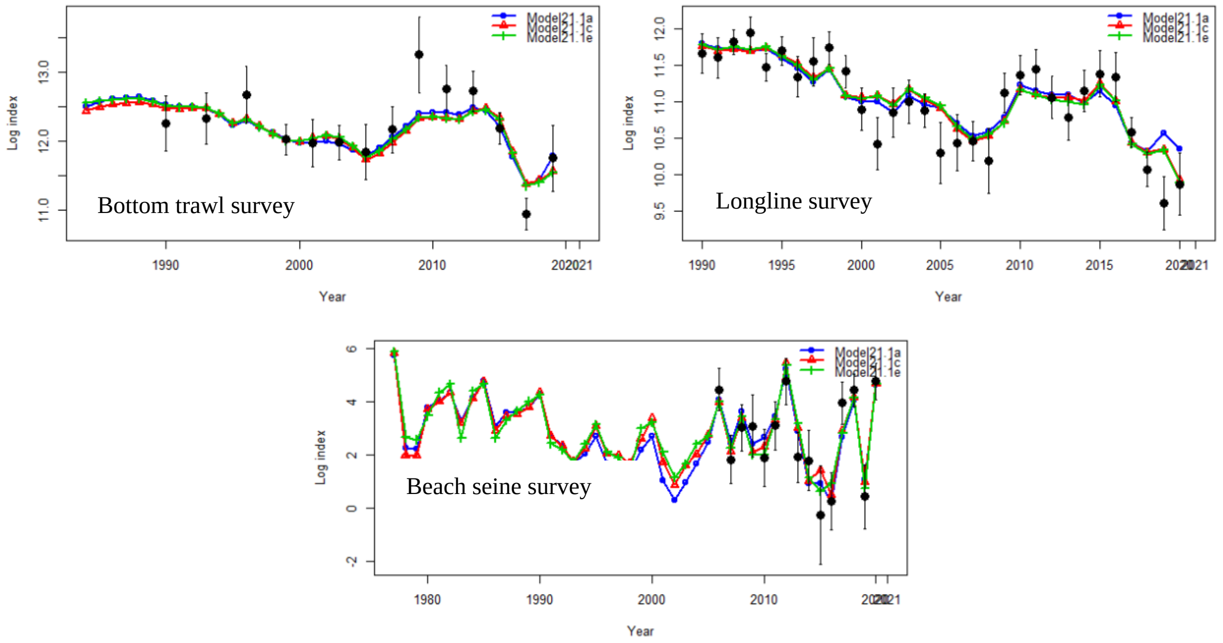

Figure 4 – Model fits to survey data for (Top left) Bottom trawl survey in tons, (Top left) Longline survey in relative population numbers, and Beach seine age-0 survey in fish per set for Model 21.1a (blue), Model 21.1c (red), and Model 21.1e (green).

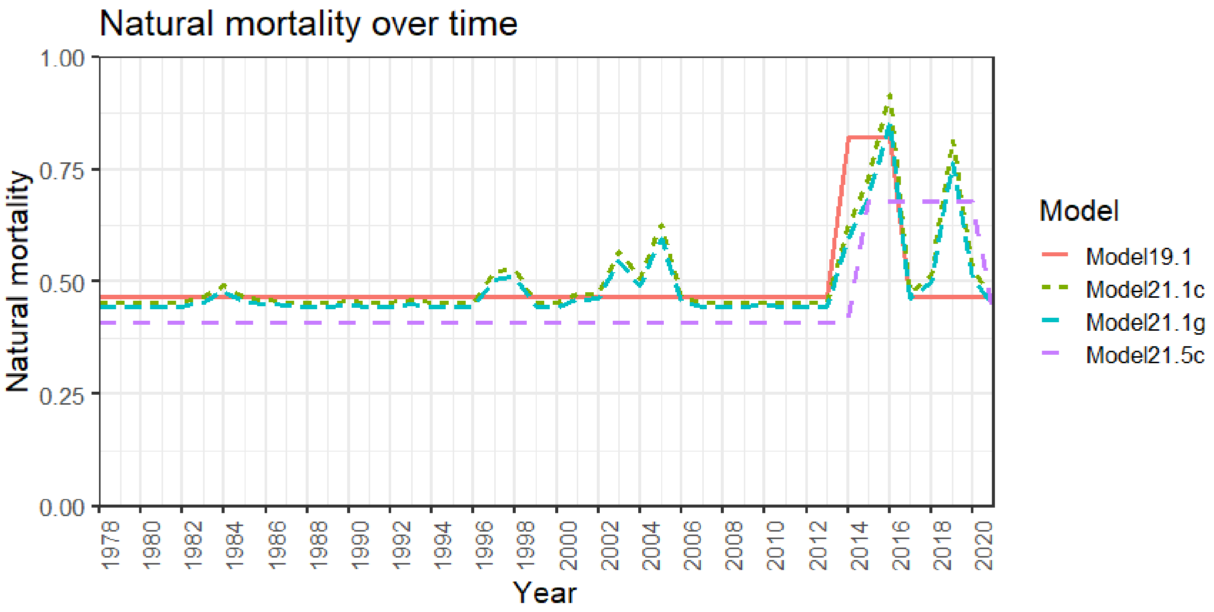

Figure 5 – Natural mortality over time for Models 19.1, 21.1c, 21.1g, and 21.5c.

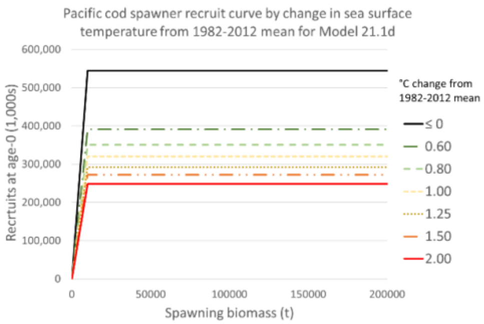

Figure 6 - Model 21.1d spawner-recruit relationship showing change over mean temperature driven by linking R_0 to the spawning heatwave index. We should note here that as GOA Pacific cod remain a tier 3 stock assessment, steepness was fixed at 1.0.

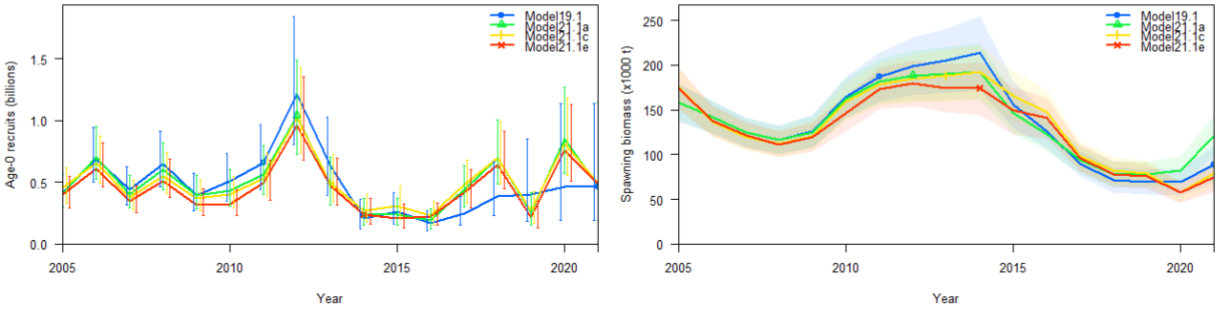

Figure 7 – (Left) Age-0 recruits and (Right) spawning biomass for 2005-2006 for Model 19.1, Model 21.1a, Model 21.1c, and Model 21.1e.

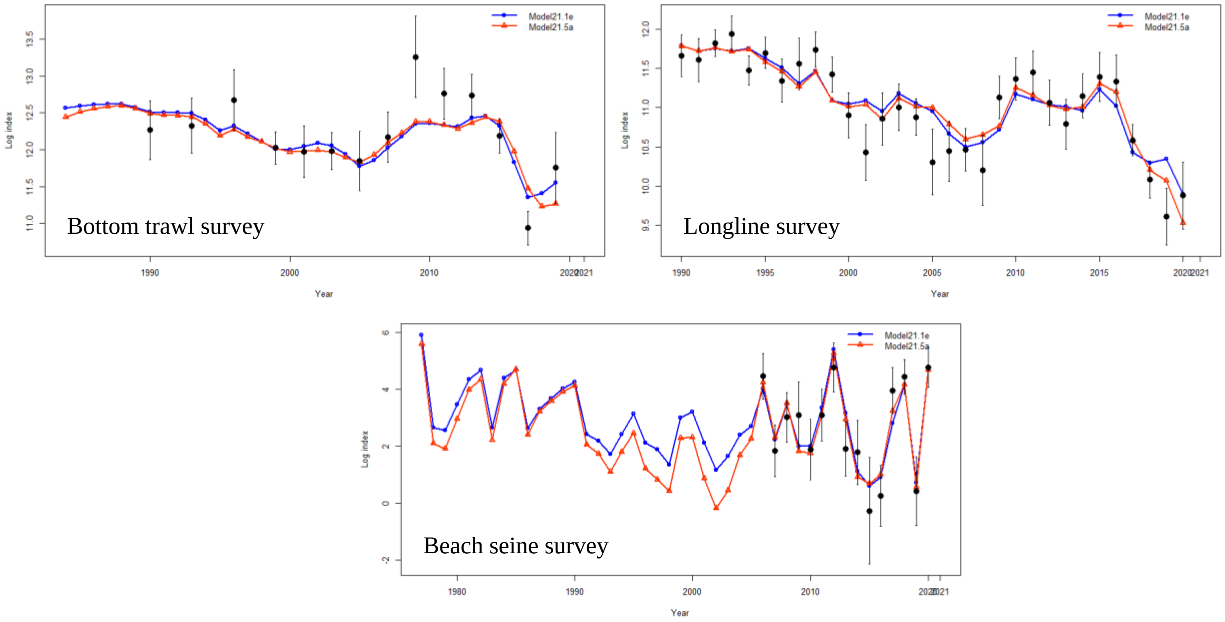

Figure 8 – Model fits to survey data for (Top left) Bottom trawl survey in tons, (Top left) Longline survey in relative population numbers, and Beach seine age-0 survey in fish per set for Model 21.1e (blue) and Model 21.5a (red).

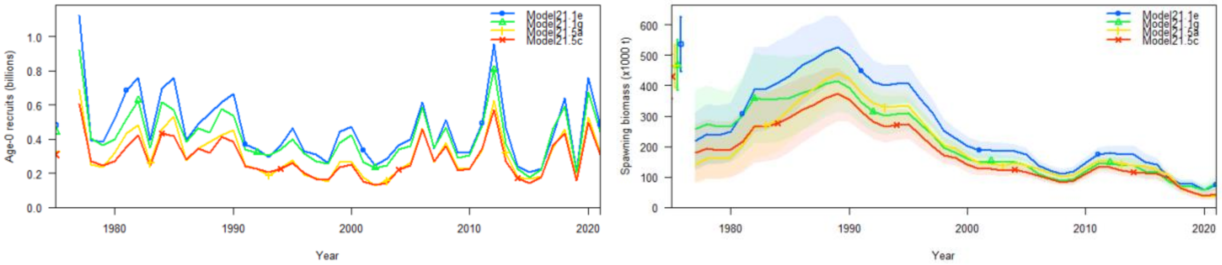

Figure 9 – (Left) Estimate of the number of age-0 recruits and (Right) estimate of the spawning biomass for 1978-2021for Model 21.1e, 21.1g. 21.5a, and 21.5c.

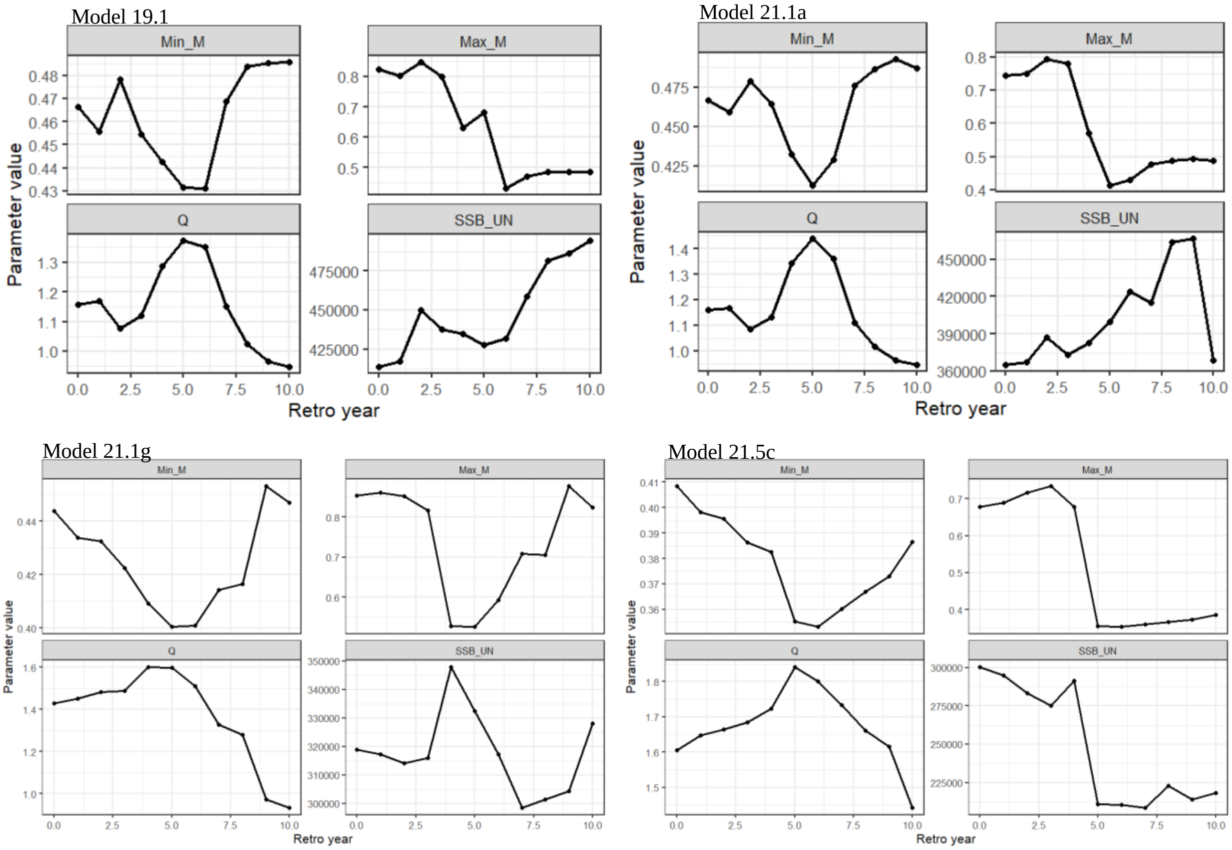

Figure 10 – Parameter values from retrospective analyses (Min_M=minumum natural mortality, Max_M=maximum natural mortality, Q = catchability, and SSB = unfished spawning biomass) for 10-year peals.

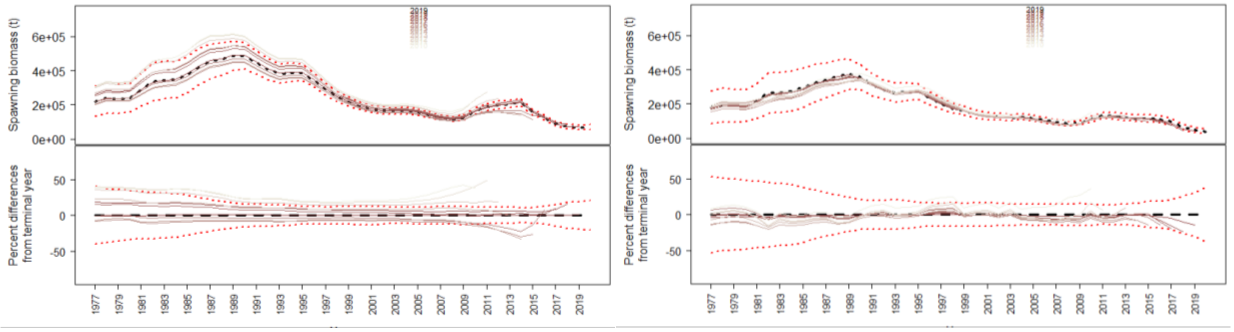

Figure 11 – Spawning stock biomass estimates from retrospective analyses for 10-year peals showing (top) spawning biomass and (bottom) percent different from terminal year for (left) Model 19.1 and (right) Model 21.5c.