Exploration of Gulf of Alaska Pacific cod (*Gadus macrocephalus*) stock dynamics for September Plan Team

Steven Barbeaux

Introduction

This report presents alternative assessment models for the Gulf of Alaska (GOA) Pacific cod stock. The objective of this report was to provide the Plan Team and SSC with an overview of model and methods being developed for the Gulf of Alaska Pacific cod stock. This approach involves a number of simplifications compared to the relatively complex models presented in recent years for GOA Pacific cod. A goal was to disentangle interactions among modeled components, particularly the seasonal fishery selectivities, to ease interpretation. Growth and selectivity treatments were also simplified so that alternative hypotheses could be explored. Another benefit of model simplification was detailing data compilation issues and gaining familiarity with available data. New datasets (the AFSC sablefish longline survey index for Pacific cod along with length composition data from this survey) are also introduced. In the course of this study, over 150 models were developed and examined. This document represents a subset of models deemed to be most informative for discussion and stock management going forward.

There has been wide-array of models presented over the past 16 years (see Amar and Palsson 2015 for a summary). While model fits to data have been reasonable, historical retrospectives over different assessments suggest that the recent models had quite different pre-1980 biomass estimates compared to others (Fig.1). The female spawning biomass for 1977-1987 from the 2014 and 2015 models was also more than double previous model results (Fig. 1). The large 1977 year class (Fig. 2) was estimated to be 2.7 times larger than the next largest year class (2012), despite limited data suggesting such a large deviation. This large year class estimate in the selected 2015 stock assessment model configuration (hereafter referred to as the 2015 Model) apparently occurred by limiting the range of aging bias parameters. Data suggesting a high 1977 year class was limited to a pulse of fish observed in the longline fishery length composition data in during 1980 (consistent with the length of 3 year old Pacific cod). Data from the trawl fishery was sparse but failed to indicate a similar influx.

Models presented here are intended as examples to stimulate discussion and help provide guidance rather than candidate final model configurations for management recommendations.

General Approach

Stock Synthesis version 3.24U was applied. To the extent practical, among the models examined, 20 were selected to sets of hypotheses and/or model fits (Fig. 3). Overall results are summarized in Table 1 and Fig. 4. The main differences between all models below and the 2015 model are:

1) Seasons were aggregated (annual data),
2) All selectivities were modeled using the double normal option in SS,
3) Fishery selectivities were constant over time,
4) Ages were restricted to 12 ages with a 12+ group instead of extending 20 years
5) Age determination bias was dropped from model estimation,
6) Lengths were binned from 0.5 cm to 116.5 cm at 1 cm increments, instead of to 109.5cm,
7) Multinomial sample size for fishery composition data was set at the number of hauls or 200 (instead of 400 from the 2015 Model), whichever was smallest,
8) Age composition and size at age data were included,
9) Conditional age at length data were excluded,
10) Age of L_0 in the von Bertalanffy model set to 0.5,
11) The initial recruitment offset (R1 option in SS) was dropped.

Alternative models considered:

1) AFSC GOA sablefish longline survey (longline survey) index of Pacific cod abundance
2) Length composition from the longline survey
3) Model tuning using the Francis method
4) M estimation
5) Dome-shaped selectivity
6) Estimating Q
7) Time-varying fishery selectivity (different than "blocks")
8) Separate catchability and selectivity for pre-1993 bottom trawl survey data
9) Removing pre-1990 bottom trawl survey data
10) Excluding 27cm from survey data, and

The Base Model - Model 16.6

Model 16.6 is considered to be the most basic model presented in this here with subsequent model building from this initial framework (Fig. 3). The age-based model included ages 1 to 11 and an age 12+ group for all older fish. Note that the previous assessments had ages up to 20, but the oldest cod ever aged in the Gulf of Alaska was 14, and limited to a single individual. Of the 8,362 Pacific cod aged since 1987 from the bottom trawl survey there have only been nine cod aged 12 years old or older. For this model there was assumed to be no aging error or bias in the age data.

Natural mortality (M) was assumed M = 0.38 based on equation 7 of Jensen (1996) and ages at 50% maturity reported by Stark (2007). From Stark (2007) A_{50} = 8.539/1.963 = 4.35 and therefore M=1.65/A_{50} = 0.38 following Jensen (1996). Maturity was calculated as a function of age following Stark (2007) with A_{50} at 4.3499 and slope of -1.9632. Fishing mortality was estimated through a hybrid method in which the Pope's approximation provides initial values for an iterative adjustment of the continuous F values which then closely approximates the observed catch. These parameterizations were the same in the 2015 Model.

For this analysis weight was fit in a two parameter lognormal linear model with no priors and starting values based on a linear regression of length at age data from the 1990-2013 bottom trawl survey data.

Unlike the 2015 Model there were no seasonal differences in weight at length included in the model, however final model results (Fig. 5) closely matched the average weight at length model used in the 2015 Model. Growth was modeled using the original three parameter von Bertalanffy growth curve as in the 2015 Model. All parameters were fit within the model with no priors and starting values based on fits to all available length at age data from the bottom trawl survey (Fig. 5 and Fig. 6). Age at L_0 was set at 0.5 cm. Using different ages at L_0, between 0.5 and 1.5, were also explored but showed little influence on model results. Models using a four parameter Richards formulation were explored, but made little difference within the model and were not presented here.

Recruitment was modeled as a standard Beverton-Holt recruitment curve with steepness assumed to be 1.0 assuming no relationship between stock size and recruitment, Sigma-R was assumed to be 0.44, (based on a series of sensitivity runs with an earlier model, not shown), and a uniform prior on $\mathrm{Ln}(R_0)$ with no R_1 offset. Recruitment deviations were fit in two phases with main recruitment deviations 1977-2015 fit in phase 1 and early recruitment deviations 1965-1976 fit in phase 2. Model 16.6 results are provided in Table 1.

The AFSC summer bottom trawl survey number of fish was the single index of abundance used in this model. The survey was conducted tri-annually from 1984-1999 and biannually 1999-2015 (Fig. 7). Catchability (Q) was assumed to be 1.0 in this model. Model 16.6 had a poor fit to the bottom trawl survey index, particularly for years with large increases in abundance as in 1984, 1996, 2009, 2011, and 2013 (Fig. 7). The estimates for these years were well below the observed values.

Size composition data were collected for all survey years, the survey length composition data were binned from 0.5 cm to 116.5 cm at 1 cm increments. Initial models had a maximum size at 109.5 cm, but test runs showed this impacted results under differing assumptions on M, Q, and selectivity. We iteratively increased the size by 1 cm until the maximum size category no longer impacted model results. Length selectivity was fit as a single double normal curve (Fig. 8). This functional form is constructed from two underlying and rescaled normal distributions, with a horizontal line segment joining the two peaks. This form uses the following six parameters:

1. Beginning of peak region (where the curve first reaches a value of 1.0),
2. Width of peak region (where the curve first departs from a value of 1.0),
3. Ascending “width” (equal to twice the variance of the underlying normal distribution),
4. Descending width,
5. Initial selectivity (at minimum length/age), and
6. Final selectivity (at maximum length/age).

All but parameter 1 (beginning of peak region) are transformed: The widths are log-transformed and the other parameters are logit-transformed. For this model the survey selectivity was restricted to be asymptotic with the two parameters controlling the downward limb of the curve (parameters 4 descending width and 6 final selectivity) fixed to force the curve asymptotic. The remaining four parameters were fit with bounded uniform priors. The multinomial sample sizes for the survey length composition data were set at 100 for all years. This was a strong assumption on the consistency of the surveys over the years to properly measure species composition of the surveyed population, even when sample sizes changed among years. Although survey timing was variable, particularly in the 1980s, we assumed a survey date of 0.583 (July 1), the same as the fisheries. SS3 did not allow for annually varying timing for the survey.

The choice of asymptotic selectivity for the bottom trawl survey has substantial impacts on the results of the stock assessment model. It assumes (with a fixed catchability of Q = 1.0 and fixed mortality at M=0.38) that all fish above a certain size are fully available to the survey and with fixed catchability and natural mortality will produce conservative estimates of recruitment and abundance. Different assumptions are explored in models presented below.

Aged based and length based selectivities using non-parametric selectivity patterns were initially investigated for the bottom trawl survey composition data in models not presented here. In order to conduct “Jitter” and retrospective analyses the waypoints needed substantial bounding to function or created many local likelihood minima that made model fitting problematic. Results from the double-normal were more easily interpretable and functioned better during “jitter” exercises in finding a consistent “true” minima. The logistic model was also explored for asymptotic selectivities, however the restricted double normal provided better fits in all cases and allowed for easy conversion to dome-shaped when needed.

Age composition data for 1990-2013 were available and although they were included in the model likelihood (Fig. 5), they were not fit independently from the length composition data with selectivity being modeled as a function of length. Weight and length at age data were available for 1990-2013 and inform the growth model (Fig 10).

Fishery dependent data were aggregated into three gear types: trawl, longline, and pot (Fig. 11). Unlike the 2015 Model, seasons were not implemented in this model. Catch estimates were available for 1977-2015 for all three fisheries and match those used in the 2015 Model in aggregate. Equilibrium catch for the trawl and longline fisheries were set at 1,000 t and 2,000 t based on historic fish records (Major 1985). The pot fishery had 0 catch until 1987 and therefore equilibrium set at 0. In comparison the 2015 Model had equilibrium catch set at 5,600 t for the January-April trawl fishery and 0 for all others. This makes little difference in model results since catch was relatively low. Standard errors in all catch estimates were assumed to be 0.05 and fishery timing was set at 0.583 (the end of June) for all fisheries.

Fishery catch length composition data were treated the same as the data used in the 2015 Model except once calculated, seasonally separated data were then collapsed into a single value per year and gear with proportions weighted by gear and seasonal catch biomass estimates (Fig. 12, Fig. 13, and Fig. 14). This method assumes that observer coverage is proportional to seasonal catch. The sample size was set at the number of hauls up to a maximum of 200 for each gear type and year, no tuning of the model was performed.

Fishery length composition selectivity was fit for each gear as single double normal curves and for all but the pot fishery, restricted to be asymptotic with the two parameters controlling the downward limb of the curve (parameters 4 descending width and 6 final selectivity) fixed to force the curve asymptotic. For the pot fishery parameters 4 and 6 were fit within the model allowing for a dome-shaped selectivity. For all fisheries parameter 5, which controls the selectivity at the first length bin, was fixed at -999. This setting ignores the initial selectivity algorithm and simply decays the small fish selectivity according to parameter 3 (Fig 8).

Length composition predictions fit the overall shape of the distribution across all years, however annual variability in the distributions and lack of flexibility in the chosen selectivity curves show some trends in the residuals. In general mean predicted lengths were reproduced (Fig.15), however the predicted length distributions were broader and missed the highest peaks of the distributions (Fig 16) as shown in the Pearson’s residual plots (Fig. 16). In addition the model does not fit the bottom trawl survey data well in years where a large number of small fish were observed such as 2009. The large number of small fish causes survey availability to fit above zero ($S_{0.5cm}$*Q = 0.118) for the smallest fish (Fig. 8).

Addition of Sablefish longline data - Model16.6.0

Model 16.6.0 had the same configuration as Model 16.6 except Gulf of Alaska AFSC Sablefish longline survey data were added (Fig. 18). These data included the Relative Population numbers (RPN) of Pacific cod as an index of abundance and Pacific cod length composition data for 1990 through 2015 (Fig 18). These data were provided by Dr. Dana Hanselman of the Auke Bay Laboratory and a description of the methods for the AFSC sablefish longline survey and how the datasets were developed can be found in Hanselman et al. (2015) and Echave et al. (2013).

This index mirrors the trend observed in the bottom trawl survey for 1990 through 2015 with a decline in abundance from 1990 through 2008 and a sharp increase in 2009. Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 19 and Fig. 20). The data reveal consistent and steep unimodal distributions with a decreasing trend in mean size since the mid-1990s, matching the trend observed in all three fisheries, but not in the bottom trawl survey (Fig. 21 and Fig. 16). Catchability (Q) for this index was set as a floating estimate with no bias adjustment. The multinomial sample sizes for the length composition data were set at 100 for all years.

Selectivity for the longline survey length composition data was modeled using a single double normal selectivity curve with parameters 4 and 6 (see above) fixed such that selectivity was constrained to be asymptotic (Fig. 22). It was the opinion of the survey managers that the survey was well distributed throughout the Gulf of Alaska sampling across depths from 50 m to 1000 m and was therefore thought to be a thorough survey of adult Pacific cod in the region. Parameter 5 was set to -999 which ignores the initial selectivity algorithm and simply decays the small fish selectivity to near 0 as per parameter 3.

Model 16.6.0 predictions of the longline survey index follows the 1990-2008 decline in abundance and although it does increase in 2009, the model fails to match the sharp increase in the data for 2009-2011 (Fig. 18). Fits to the length composition data consistently underestimate the high peak of the mode and overestimates the abundance of fish larger than 75 cm (Fig. 23 and Fig. 24). For the other data components model fits were similar to that of Model 16.6 (Fig. 21 and Table 1). There was some degradation of the fit to the bottom trawl survey index, but the fit to the bottom trawl survey length and age data was improved (Table 2). Further the addition of the longline survey data improved the fit to the trawl length composition data, but degraded the fit to the pot and longline length composition data.

Ten-year retrospective analyses (Hanselman et al. 2013) show a marked improvement in the Mohn's rho and RMSE when the longline survey data were added with little impact on the Wood's Hole rho (Table 3 and Fig. 25), suggesting an improvement in stability in the most recent estimates with little effect on predictions of earlier data. The effects of the large and uncertain recent year classes were still apparent with large deviations from the most terminal estimate in the first 6 years of the retrospective.

Length and age composition sample size explorations - Model 16.6.1.2

We implemented the Francis method (reference) for tuning the model and explore the model sensitivity to the length composition sample size as implemented in the R4SS package (Hicks et al. 2016). Model 16.6.1.2 was a Francis method tuned Model 16.6.0. The model was tuned over three iterations, until the Francis weights diagnostics neared 1.0 for the length and age composition data.

The Francis method resulted in adjustment factors between 0.07 and 0.74 (Table 4) and impacted the model with lower weighting of the length and age composition data. Fits to both survey indices were improved (Fig.26 and Fig. 27) with a decrease in the RMSE of bottom trawl survey by 14% and longline survey by 8% (Table 4). Fits to the trawl and longline fishery length composition were degraded (Fig.28) with 30% and 27% decreases in harmonic mean effective Ns. The bottom trawl survey length and age composition had a 21% and 25% decrease in the harmonic mean effective Ns. Fit to the pot fishery length composition data did not change as much as the other fisheries, with an 8% decrease in the effective sample size. The harmonic mean effective N for the longline survey length composition increased by 16% indicating an overall improvement to the longline survey data.

The largest impact to the model was the reduction in the magnitude of the 1973 and 1977 year classes (Fig 25). This was a direct result of down-weighting the longline fishery composition data where fish of sizes consistent with these year classes were most strongly observed. The bottom trawl survey index did not see an increase in abundance consistent with such large year classes and therefore the re-weighting of the model components settled on lower recruitments for these years. The 2011 and 2012 year classes were similarly diminished as they had most strongly been observed in the trawl and longline fishery and bottom trawl survey length composition data, but less strong in the pot fishery and longline survey length composition data. The change in the model estimates of early cod abundance was counter to the prevailing view that there was a large increase in cod starting in the 1980's. This is likely the result of reduced weight of the early fishery length composition data weighting causing the model to over fit the early trawl survey index data, which shows a stable to declining trend for this time period. It should be noted that the bottom trawl survey index data prior to 1990 are considered problematic because methods differed from the methods employed since 1990. This issue will be addressed below.

Exploring catchability, natural mortality, and dome-shaped selectivity

Five models were developed that have different assumptions on catchability, natural mortality, and selectivity. In the models presented above we assumed asymptotic selectivity for all survey selectivities, M = 0.38, and bottom trawl survey Q = 1.00. This is a compromise which provides conservative model results in comparison with if these were allowed to be fit freely in the model without strong constraints. For the models presented in this section we build on Model 16.6.1.2 using the same tuned settings so that model likelihoods and fits could be readily compared.

Model	**Model parameterization**
16.6.2.1 Q	Fit bottom trawl survey Catchability (Q) with an uniform prior
16.6.2.2 M	Fit natural mortality with a normal prior mean = 0.38,stedev =0.1
16.6.2.3 S	Allow dome-shaped selectivity
16.6.2.4 QM	Fit bottom trawl survey catchability with a uniform prior and natural mortality with a lognormal prior M=0.38, CV=0.1
16.6.2.5 QMS	Fit catchability, natural mortality as above, and allow dome-shaped selectivity

In Model 16.6.2.1Q the bottom trawl survey catchability (Q) was fit in the model with an uninformative prior. Catchability above 1.0 assumes an abundance (conditioned on selectivity) lower than survey estimates resulting in lower recruitment and higher estimated fishing mortality. Allowing Q to be fit in the model improved fits to all of the bottom trawl survey data components and the longline survey size composition, but degraded the fit to all other components (Table 5). The overall likelihood improved by -79.28 with the inclusion of this single parameter, however log catchability was estimated at 1.047 (Q=2.85; Fig. 30) reducing the biomass on average 24% from Model 16.6.1 and 9% lower on average than the raw survey estimate (without considering selectivity). The better fits to the bottom trawl survey index and length composition data were achieved by reducing overall biomass and increasing estimated fishing mortality (Fig. 30). The effect of allowing Q to increase was not only a reduction in overall abundance across all ages, but also a reduced proportion of fish at older ages (Fig. 31).

In Model 16.6.2.2M natural mortality (M) was fit in the model with an informative normal prior having a mean of 0.38 and standard deviation of 0.1. This model fits M at 0.81 (Fig. 30), well above most reasonable estimates of M in the literature for this species (Table 6; A'mar and Palsson 2015). All data components, except the pot fishery length composition data were fit better than in Model 16.6.1.2 for an overall improvement on the objective function of -108.59. The majority of this improvement was in a better fit to the length and age composition data from the two surveys. Both the longline and survey index fits were also improved (Table 5). This assumes higher R_0 and B_0 (Fig. 32) allowing higher recruitment and higher overall abundance in the model estimates. This model assumes a much higher proportion of young fish in the population (Fig. 31) in aggregate across years, the sum of the apical F was slightly lower that Model 16.6.1.

In Model 16.6.2.3S we allow all selectivities, except for the longline fishery to be dome-shaped fitting parameters 4 and 6 in the double normal selectivity curves with uninformative priors (Fig. 33). The longline fishery remained asymptotic to provide stability to the model. Reviewing the distribution of the longline fishery (Fig.34 and Fig. 35) shows it has the widest spatial extent and is deeper on average than either trawl or pot where larger cod should be encountered. The raw length frequency data (Fig. 20) shows a larger proportion of fish > 80 cm in the longline fishery. The addition of the 6 selectivity parameters improved the fit to the model by -127.1. Allowing for dome-shaped selectivity showed a greater improvement to both surveys than either fitting M or Q. Improvement was also attained in the fits to the composition data for all but the pot and longline fishery length composition data. The dome-shaped selectivity in the longline survey removed the pattern of higher positive residuals in the larger fish (Fig. 33). Allowing for dome-shaped selectivity in the surveys and fisheries allows a higher biomass at the fixed natural mortality by assuming a larger portion of the population are not observed. This model places greater than 5% of the pacific cod population biomass in the 12+ age group and assumes there is a cryptic elder component of the stock resulting in a much higher historic biomass estimates and much lower fishing mortality estimates than Model 16.6.1. The sum of the Apical Fs in this model closely follow those produced in the 2015 Model (Fig 31). Estimates of both R_0 and B_0 were also similar (Fig. 35). Although initial abundance estimates are much lower (Fig. 32), the proportion of biomass by age in aggregate across all years considered also closely matches the 2015 Model (Fig. 31). This model produces the highest historical biomass estimates of all models evaluated.

Model 16.6.2.3QM fits both catchability and natural mortality within the model. Catchability was parameterized with a uniform prior and natural mortality as a normal prior with a mean of 0.38 and standard deviation of 0.1. The model fit M at 0.69 (Fig 35), substantially higher than independent estimates of M for pacific cod. Log catchability was estimated at 0.634 (Q=1.89). The improvement in fit from Model 16.6.2.2 M with the addition of 1 parameter (Q) was less than 0.4 overall (Table 1 and Table 5), yet the model results were substantially different. The model fit the bottom trawl survey index better (-5.26 to -3.35) than Model 16.6.2.2M, as expected, however it fit worse to the longline survey index data (-4.71 to -2.76). In addition improvements to the longline survey, trawl, and pot fishery length composition and bottom trawl age composition fits were counteracted by worse fits to the trawl survey and longline length composition data. Although the positive residuals on older fish in the longline survey persisted in this model, they were less pronounced than in models in which M was not fit (Fig. 33). As one would expect, the model predictions were intermediate of Models 16.6.2.1Q and 16.6.2.3M (Fig. 31 and Fig. 32) as the model was balancing the effects of Q and M to achieve the best fit (Fig. 30)

Model 16.6.2.3QMS fits both catchability and natural mortality within the model and allows selectivity for the trawl and pot fisheries and bottom trawl and longline surveys to be dome-shaped. As in the previous model, catchability was parameterized with a uniform prior and natural mortality as a normal prior with a mean of 0.38 and standard deviation of 0.1. In this model, the same as Model 16.6.2.3S, the six parameters controlling the downward arm of the double normal for the trawl fishery and bottom trawl and longline surveys were fit allowing the shapes to become dome-shaped (Fig. 33). This model produced the best fit of all the models evaluated. The addition of the 6 parameters improved the model by -41 likelihood points above Model 16.6.2.4QM (Table 1). The model fit M at 0.5 (Fig 30). A natural mortality of 0.5 was higher than that produced by the Jenson (1996) method (M=0.38), but the same as estimated by Thompson and Zenger (1995), and lower than 5 of the 12 estimates retrieved from the literature (Table 6). Log of catchability was estimated at 0.49 (Q=1.64; Fig. 30). Selectivity at larger sizes (>70 cm) was higher in this model than in Model 16.6.2.3S showing the influence of both M and Q on model fitting. All data components, except Longline survey length composition and bottom trawl survey index, were fit better than any other 16.6.2 models. The fit to the longline survey length composition was surpassed by Model 16.6.2.3S and the fit to the bottom trawl survey was only surpassed by the two other models that fit catchability (Models16.6.2.1Q and 16.6.2.4QM). Although Q was greater than 1.0 due to selectivity estimates the total biomass was on average 182% higher than raw bottom trawl survey estimates across all surveyed years (Fig. 36) and 151% higher than estimates from Model 16.6.1 with Q=1.0. Unlike Models 16.6.2.3S and the 2015 Model which had a significant proportion (~6%) of population biomass in the 12+ age group, the higher M in Model 16.6.2.5QMS had on average less than 2% of the population biomass in the 12+ age group. Virgin female spawning biomass (B_0) was estimated at near 200 kt, below the 300 kt estimate from the 2015 Model, but above the 184 kt from Model 16.6.1. R_0 was estimated at the third highest value after the two other models (16.6.2.2M and 16.6.2.4QM) that estimated higher natural mortality.

Model 16.6.3

Model 16.6.3 follows the same configuration as Model 16.6.1.2 using the same Francis method adjustment factors, but differs in having annually varying selectivity parameters for the trawl and longline fisheries and time blocks for the bottom trawl survey (Fig. 37). The Francis method adjustment factors were retained from Model 16.6.1 so that model likelihoods could be readily compared. For trawl and longline fisheries parameters 1, 2, and 3 were allowed to vary annually using multiplicative deviations between 1977 and 2015 and 1978 and 2015 with a standard deviation of 0.2. Parameters 1, 2, and 3 of the bottom trawl survey length composition selectivity were allowed to differ between time blocks 1977-1993 and 1994-2015. Survey selectivity was allowed to change after 1993 when the survey changed from 30 minute to 15 minute tow durations. Although models with annually varying pot fishery selectivity parameters were evaluated they showed no appreciable improvement in fit and therefore not presented here.

The addition of time varying selectivity added 234 "parameters" to the model, but only decreased the objective function by -58.57 points. However, 231 of these parameters were penalized random deviations on the main selectivity parameters for the fishery selectivities and should not be considered true parameters for comparisons of log likelihoods and AIC analyses of model fit. As would be expected the longline and trawl fishery length composition fits improved as well as the fit to the bottom trawl survey age composition and longline survey length composition. Fits to both survey indices and all other length composition data were slightly degraded (Table 7).

The predicted results from Model 16.6.3 were similar between Model 16.6.1 and Model 16.6.3 (Fig. 37), particularly for the more recent portion of the time series. The main difference in predictions were in higher initial (1977-1985) spawning biomass levels (Fig. 38) and fishing mortality in the Mid-1990s (Fig. 39 and Fig. 40). Neither R_0 nor virgin spawning biomass for Model 16.3.1 and Model 16.6.2 were substantially different at R_0 = 0.22 log (billions) and 0.23 log (billions) and B_0 = 184.63 kt and 197.8 Kt.

Similar results would likely be achieved by fixing selectivity in both the longline and trawl fisheries after 1990 when the domestic fisheries started while greatly reducing the number of parameters in the model, similarly there was little difference in the bottom trawl survey selectivity for the two time blocks and these could be discarded with little to no impact on model results.

The retrospective analysis of female spawning biomass resulted in a slight increase in the Mohn's rho from 0.07 for Model 16.6.1 to 0.08 in Model 16.6.3, Woods Hole rho from 0.001 to -0.003, and similarly negligible improvement in retrospective RMSE from 0.041 to 0.040. The divergence from the final results back to 2008 were still apparent and due to the exceptionally large recruitments observed in this time period.

Alternatives for the pre-1993 bottom trawl survey data - Model 16.6.4.1 and Model 16.6.4.2

Differences in survey methods support treating earlier surveys differently than later surveys. The 1984 and 1987 bottom trawl surveys were conducted by Japanese researchers using different trawl gear than used in later surveys. Prior to 1996 survey haul duration was 30 minutes, while the 1996 and later surveys had a 15 minute duration. The 2015 Gulf of Alaska walleye pollock stock assessment (Dorn et al. 2015) excludes the pre-1990 trawl survey data from the stock assessment model. Model 16.6.4.1 mirrors this approach with the 1984 and 1987 trawl survey data not included in the model and the block selectivity for the bottom trawl survey was also removed.

In the 2015 Model trawl survey catchability was set at 1.0 for the 1996-2015 surveys and a linear adjustment was fit with a uniform prior for earlier surveys. In addition separate catchability curves for the length composition data were fit in time blocks: 1977-1989, 1990-1995, 1996-2006, and 2007-2015. Model 16.6.4.2 mirrors this approach with adding a single parameter linear adjustment to catchability for pre-1996 surveys with a uniform prior and two blocks for survey selectivity: 1977-1995 and 1996-2006. For this model catchability for 1977-1993 was fit at 1.75, higher than 1.25 fit in the 2015 Model.

For the likelihoods of the non-bottom trawl components, the two models end up being less than 1 point different from each other and six likelihood points different from Model 16.6.3. Fits to the survey data between model 16.6.4.2 and 16.6.3 differed by -8 likelihood points. Across all data components Model 16.6.4.2 differed from Model 16.6.3 by -12 points for 1 additional parameters. Taking out or fitting the early trawl survey data reduced the fit to the longline survey index between -1 and -1.5 points. The fits in effect did not change between the two alternative configurations, and showed a minor improvement to Model 16.6.3.

Model 16.6.4.1 with the bottom trawl survey data removed demonstrated a difference in early recruitment from Model 16.6.3 and 16.6.4.2. Model 16.6.3 and Model 16.6.4.2 had well above average 1980 year class and stronger 1981-1983 year classes than Model 16.6.4.1 (Fig. 41). In addition predictions for R_0 and B_0 were higher in Model 16.6.3 while in Model 16.6.4.1 and Model 16.6.4.2 there was little difference between these values (Fig. 41). Higher recruitment in Models 16.6.4.2 resulted in higher abundance and biomass in the mid-1980s in the models retaining the early survey data. In effect there were only minor differences in the results from these two alternative models.

Model 16.6.11S Model 16.6.15QM, Model 16.6.20, and Model 16.6.22QMS

These set of models were conducted to evaluate how the removal of the 1984 and 1987 survey data have on the fitting parameters in Models 16.6.1, 16.6.2.3S, 16.6.2.4QM, and 16.6.2.5QMS. Model 16.6.20 was parameterized the same as Model 16.6.1 and Model 16.6.22 was parameterized the same as Model 16.6.2.5QMS without the 1984 and 1987 bottom trawl survey data. Model 16.6.11S was parameterized the same as model 16.6.2.3S and Model 16.6.15 was parameterized the same as Model 16.6.2.4QM, except with annually varying selectivity as parameterized in Model 16.6.3 and without the 1984 and 1987 bottom trawl survey data.

Differences in parameter fits are shown in Figure 42. For the models where M and Q were not fit the impact of removing these data were consistent. For all but one modeling pair the differences between parameters were minor. In each pair the results were similar in that recruitment in the early 1980s was reduced when the 1984 and 1987 trawl data were removed (Fig. 43) resulting in lower abundance in the mid-1980s. There was also a consistent decrease in B_0 between the models with and without the 1984 and 1987 trawl survey data. The largest changes were observed in the parameters between Model 16.6.2.4QM and Model 16.6.15QM (Q and M fit and asymptotic selectivity) with shifts in both natural mortality and catchability. This in turn resulted in a substantial increase in R0, a decrease in initial Fishing mortalities for the longline and trawl fisheries, and decline in the B0. In addition overall recruitment and abundance was reduced throughout the time series in response to these changes. Where selectivity was allowed to become dome-shaped but Q and M were fit (Models 16.6.2.5QMS and Model 16.6.22QMS) no similar changes in Q and M were encountered and the only change of substance between these modeled pair was the CV of young fish parameter. Retrospectives for all models with Q or M fit were abysmal (Table 3).

Removing age 1 (<27cm) fish from bottom trawl survey – Series 16.7

The bottom trawl survey data on occasion encountered extremely high numbers of age 1 fish, the magnitude of which is not always observed in following years. In previous stock assessments the approach to dealing with these problem fish was to remove them from the data. This series of models looks at the effects of removing these fish from some of the models explored above.

In every case the removal of the small fish caused the fit to the trawl survey selectivity curve to go to 0 for the young fish where it had previously been above 0 even for the smallest fish (Fig. 44). The fit all the other length composition data remained nearly the same and the fit to the > 27cm survey length composition data remained rather poor. Although a numerical comparison of fit was not done between the two sets of models for the bottom trawl survey abundance index, a visual inspection of the fits (Fig. 45) appears to show a more reasonable fit was achieved to this index when the age 1 fish were removed. In every example for the growth parameters L0.5 was increased, Linf was decreased, K increased, CV of young fish decreased, and CV of old fish increased (Table1 and Fig. 46). In every case R0 decreased and B0 increased (Fig. 47) while initial Fs decreased with the removal of the Age 1 fish from the bottom trawl survey data. In all cased recruitment and abundance increased with slight decreases in F in response (Fig. 47 and Fig. 48).

The retrospective analyses for these models shows an increase in all of the metrics, a visual inspection of the predictions show a more consistent positive bias in the models without the small fish for the end years (Fig. 49). Model 16.7 was particularly poor with a Mohn's rho at 0.49.

Summary and conclusions

The decreasing trend in mean size of Pacific cod in the catch since the 1990s is a concern for this stock as it has been observed in every fishery. While possible, a simple trend in selectivity across all of the fleets seems unlikely. A look at length at age over time (Fig. 50) shows that growth has apparently been stable. Consequently, it seems that the trend may reflect a reduction in the number of older fish in the stock. The models examined to date suggest fishing mortality has increased and abundance declined over this period. The longline survey size composition data suggest increased recruitment in the near term. However, these signs have yet to appear in the fisheries data and the apparently strong 2012 year class remains highly uncertain.

Our results show that sampling effort matters. Fits to the historical data are affected by changing the sample size of the length composition data. The Francis method likely undervalues the fishery length composition data and relies too heavily on the bottom trawl survey abundance index when we know that there are issues with the reliability of this dataset in the early years.

Second, a choice needs to be made on how to treat selectivity, dome-shaped assumes a portion of the older fish are cryptic and never observed, however using asymptotic selectivity without fitting Q and M likely results in an underestimate of abundance as the model reduces recruitment to fit the lack of older /larger fish in the data. Fitting either Q or M by itself results in estimates that appear outside the bounds of what is reasonable, this also greatly inflates the abundance of cod, in addition retrospective patterns become very poor/biased as the influx of new recruits in recent years reduces the estimates of each. Although not presented models fitting Q and M where the young fish are removed results in more stable retrospectives, although still rather poor. Inflated Q assumes lower abundance, inflated M shifts the population to younger fish and inflates the abundance. The worst retrospective bias was observed where M and Q were fit and selectivities were allowed dome-shaped curves. Again the model was sensitive to the influx of new recruits in recent times.

Future work will evaluate more fully models with aging error and conditional age at length data. Preliminary indications suggest that these model additions have much effect on model outcomes. Some models not presented here were fit with aging bias free in the model and tended result in quite a substantial negative bias in the older fish at -2 to -4 years. Such results were not substantiated by the age and growth lab, so this was left out of all models presented. The 2015 model had had this parameter (older age bias) constrained to positive values.

Expanding on Models 16.6.11, 16.6.20, 16.6.22, and Model 16.7.3 and examining conditional age at length data seems to hold the most promise for this year's SAFE report. Model 16.3.20, with time varying selectivity restricted to the older fishery data, may also be worth considering.

References

A'mar, T., and W. Palsson. 2015. 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. 173- 296. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Bakkala, R. G., and V. G. Wespestad. 1985. Pacific cod. In R. G. Bakkala and L. L. Low (editors), Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1984, p. 37-49. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-83.

Echave, K., C. Rodgveller, and S.K. Shotwell. 2013. Calculation of the geographic area sizes used to create population indices for the Alaska Fisheries Science Center longline survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-253, 93 p.

Fournier, D. 1983. An analysis of the Hecate Strait Pacific cod fishery using an age-structured model incorporating density-dependent effects. Can. J. Fish. Aquat. Sci. 40:1233-1243.

Hanelsman, D. H., B.Clark, and M. Sigler. 2013. Report of the groundfish plan team retrospective investigations group, Part II: the compilation. Report to the North Pacific Fisheries Management Council Plan Team September 2013. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501. Available: http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/2013/Sept/Retrospectives_2013_final3.pdf

Hanselman, D. H., C. Lunsford, and C. Rodgveller. 2015. Assessment of the sablefish stock in Alaska. In Stock assessment and fishery evaluation report for the groundfish resources of the GOA and BS/AI. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.

Hicks, A. Garrison, T.M., Punt, A.E., and others. 2016. r4ss: R Code for Stock Synthesis. R package version 1.24.4. https://github.com/r4ss

Jung, S., I. Choi, H. Jin, D.-w. Lee, H.-k. Cha, Y. Kim, and J.-y. Lee. 2009. Size-dependent mortality formulation for isochronal fish species based on their fecundity: an example of Pacific cod (Gadus macrocephalus) in the eastern coastal areas of Korea. Fisheries Research 97:77-85.

Ketchen, K.S. 1964. Preliminary results of studies on a growth and mortality of Pacific cod (Gadus macrocephalus) in Hecate Strait, British Columbia. J. Fish. Res. Bd. Canada 21:1051-1067.

Low, L. L. 1974. A study of four major groundfish fisheries of the Bering Sea. Ph.D. Thesis, Univ. Washington, Seattle, WA. 240 p.

Major, R. 1985. Condition of groundfish resources of the Gulf of Alaska region as assessed in 1984. NOAA Technical Memorandum NMFS F/NWC-80. U.S. Dept. Comm. National Oceanic and Atmospheric Administration National Marine Fisheries Service P. 211

Shimada, A. M., and D. K. Kimura. 1994. Seasonal movements of Pacific cod (Gadus macrocephalus) in the eastern Bering Sea and adjacent waters based on tag-recapture data. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 92:800-816

Thompson, G. G., and A. M. Shimada. 1990. Pacific cod. In L. L. Low and R. E. Narita (editors), Condition of groundfish resources of the eastern Bering Sea-Aleutian Islands region as assessed in 1988, p. 44-66. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-178.

Thompson, G. G, and H. H. Zenger. 1993. Pacific cod. In Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and H. H. Zenger. 1995. Pacific cod. In Plan Team for the Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1996, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Ueda, Y., Y. Kanno, and T. Matsuishi, T. 2004. Weight- based virtual population analysis of Pacific cod Gadus macrocephalus off the Pacific coast of southern Hokkaido, Japan. *Fisheries science*, *70*(5), pp.829-838.

Wespestad, V., R. Bakkala, and J. June. 1982. Current abundance of Pacific cod (Gadus macrocephalus) in the eastern Bering Sea and expected abundance in 1982-1986. NOAA Tech. Memo. NMFS F/NWC-25, 26 p.