Climate-enhanced assessment for GOA Pacific cod (Model 19.14.51)

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Introduction

Gulf of Alaska (GOA) Pacific cod showed a marked decline in abundance during and following the 2014-2016 marine heatwave (Barbeaux et al. 2018). Although temperatures returned to near normal in 2017 and the first half of 2018, starting in September of 2018 temperatures again exceed the 90th percentile of the long-term mean (1982-2012) and entered into another heatwave that has continued through to the current date (Fig. 1). Temperatures at depth were hotter in June of 2019 than during the 2014-2016 heatwave (Fig. 2) which is the most recent month available. With surface temperatures in the GOA at exceptionally high levels through the summer, the current heatwave will be expected continue through winter 2020 (Bond pers. comm.). In 2018 the stock was assessed using a stock synthesis (Methot and Wetzel 2013) age-structured model with CFSR bottom temperatures used to scale catchability for one of the two survey indices used in the model and natural mortality was modeled at a separate, much higher value, for the 2014-2016 heatwave years. Exploratory models described in Barbeaux et al. 2019 which used temperature and the marine heatwave index to explore changes in natural mortality during heatwave conditions showed promise and appeared to indicate a connection between natural mortality and extreme events.

The model approved by the North Pacific Fisheries Management Council (Council) used for management of the stock in 2019 has been updated to include aging error, aging bias, and include data from an additional survey (Barbeaux unpublished white paper 2019). Research models which include a marine heatwave index have been explored to explain variability in recruitment and natural mortality. These models show improved overall model performance as they help explain prior downturns in Pacific cod abundance during previous heatwaves in 1983, 1997-1998, and 2003-2005. All the model explored indicate a reduction in recruitment and increase in natural mortality during extreme high temperature events (>90th percentile increase over the 1982-2012 mean). The International Panel on Climate Change (IPCC) indicates that higher global temperatures will precipitate more marine heatwaves in the near future. It can therefore be hypothesized that the productivity of Gulf of Alaska cod will change from what has been experienced over the past 30 years. This paper introduces Model 19.14.51 which incorporates all of the climate enhanced features explored in the past assessments as well as temperature based growth. This model will be used to explore changes in the productivity of Gulf of Alaska Pacific cod with increases in water temperature in the GOA.

Methods

Survey indices

AFSC Bottom trawl survey

The Alaska Fisheries Science Center (AFSC) has been conducting standardized bottom trawl surveys for groundfish and crab in the Gulf of Alaska since 1984. From 1984-1997 these were conducted every third year, and every two years between 1999 and 2017. Two or three commercial fishing vessels are contracted to conduct the surveys with fishermen working alongside AFSC scientists. Survey design is stratified random with the strata based on depth and distance along the shelf, with some concentrated strata in troughs and canyons (Raring et al. 2016). There are generally between 500 and 825 stations completed during each survey conducted between June and August starting in the Southeast and ending in the Western Gulf of Alaska. Some changes in methods have occurred over the years with the addition of electronics to monitor how well the net is tending on-bottom, also to measure differences in net and trawl door dynamics and detect when general problems with the trawl gear occur. Surveys conducted prior to 1996 are considered to have more uncertainty given changes in gear mensuration. Also, the trawl duration changed in 1996 to be 15 minutes instead of 30. Since 1996, methods have been consistent but in some years the extent of the survey has varied. In 2001 the Southeastern portion of the survey was omitted and in 2011, 2013, and 2017 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints. Pacific cod length composition and age data have been collected from this survey for the entire time series.

AFSC bottom trawl survey abundance estimates are presented in Table 1.

<u>AFSC longline survey</u>

Japan and the United States conducted a cooperative longline survey for sablefish in the GOA annually from 1978 to 1994, adding the AI region in 1980 and the eastern BS in 1982 (Sasaki 1985, Sigler and Fujioka 1988). Since 1987, the Alaska Fisheries Science Center has conducted annual longline surveys of the upper continental slope, referred to as domestic longline surveys, designed to continue the time series of the Japan-U.S. cooperative survey (Sigler and Zenger 1989). The domestic longline survey began annual sampling of the GOA in 1987 (Rutecki et al. 1997). The domestic survey samples waters from 100m to 1000 m including major gullies of the GOA in addition to sampling the upper continental slope. A Relative Population Number (RPN) index of Pacific cod abundance and length compositions for 1990 through 2018. Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman et al. (2015) and Echave et al. (2012). Pacific cod length composition data have been collected from this survey since the start of the time series.

AFSC longline survey abundance estimates are presented in Table 2.

<u>IPHC longline survey</u>

The International Pacific halibut commission (IPHC) longline survey differs from the AFSC longline survey in gear configuration and sampling design, but catches substantial numbers of Pacific cod. More information on this survey can be found in Soderlund et al. (2009). A major difference between the two longline surveys is that the IPHC survey samples the shelf consistently from ~ 10-500 meters, whereas the AFSC longline survey samples the slope and select gullies from 100-1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey may catch smaller and younger Pacific cod than the AFSC longline survey. The IPHC longline survey relative population number's (RPN) were calculated using the same methods as the AFSC longline survey data (but using different depth strata). Stratum areas (km2) from the RACE trawl surveys were used for IPHC RPN calculations. Length data on Gulf of Alaska Pacific cod started being collected during this survey in 2018.

IPHC longline survey abundance estimates are presented in Table 3.

Fisheries

Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components. On board sampling for catch, length, and age composition is conducted by fisheries technicians (observers) based on a nested sampling frame (AFSC 2018). Total Pacific cod catch estimates are based on observer samples and Alaska Department of Fish and Game landings data (Cahalan *et al.* 2014) and for Pacific cod are thought to be comprehensive with little to no unreported catch.

Catch estimates by fleet are presented in Table 4 and overall catch estimates in comparison to ABC and OFL recommendations are presented in Table 5.

Environmental indices

CFSR bottom temperature indices

The Climate Forecast System Reanalysis (CFSR) is the latest version of the National Centers for Environmental Prediction (NCEP) climate reanalysis. The oceanic component of CFSR includes the Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 4 (MOM4) with an iterative sea-ice (Saha et al. 2010). It uses 40 levels in the vertical with a 10-meter resolution from surface down to about 262 meter. The zonal resolution is 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 1979-2019 (Table 1).

Sum of annual marine heatwave cumulative intensity index (MHCI)

The daily sea surface temperatures for January 1981 through August 2019 were retrieved from the NOAA High-resolution Blended Analysis Data database (NOAA 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300m 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 heat wave 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 MHWCI were then summed for each year to create an annual index of MHCI and summed for each year for the months of January through March, November, and December to create an annual winter index of MHCI (Table 2).

The Model

Model 19.14.51 is a climate-enhanced refinement of the model used for the management of Pacific cod in 2019 (Model 18.10.44; Barbeaux et al 2018) developed in SS v3.30. It is a single sex, age-based model with age-based selectivity. The model has data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and three survey indices (post-1990 GOA AFSC bottom trawl survey, AFSC longline survey, and IPHC longline survey indices). There are two data differences between this model and the one used for 2019. Age data prior to 2007 were included in this model and IPHC longline survey data are incorporated into the model. The pre-2007 age data were believed to be positively biased and therefore not used in the 2019 management model. Model 19.14.51 models aging bias within the model in two time blocks; pre-2007 and 2007-2019. Addition of this feature allows for the use of the pre-2007 age data. The IPHC longline survey data was not used in the 2019 management model as length data were not yet available at the time of its development. These data became available in October 2018 and were used in the development of this model.

As in the 2019 model, AFSC longline survey catchability is fit with a scaling parameter fit to the CFSR bottom temperature estimates for 0-20 cm fish. Barbeaux et al. (2017) show the center of abundance of Pacific cod in the GOA move deeper and better overlap the depth surveyed by the AFSC longline survey, a finding confirmed for the GOA by Yang et al. (2019). Length composition data were available for all three fisheries and all three indices. Age composition and conditional length-at-age were available for the three fisheries for 2010-2018 and AFSC bottom trawl survey for 1987-2017.

As in previous models growth was parameterized using the standard three parameter von Bertalanffy growth curve. However new to this model L_∞ and K were both modeled as linearly dependent on the CFSR bottom temperature estimates for 0-20 cm fish through a single scaling parameter for each parameter. Also new to this model recruitment was modeled as standard Beverton-Holt model with R_0

scaled to the winter marine heatwave index and both steepness and mean R_0 fit with uninformative priors. The standard deviation of the log recruitment deviations were fixed at sigma R = 0.44 (Barbeaux et al. 2016). Selectivities for all fisheries and indices besides the IPHC longline survey were fit using six parameter double-normal selectivity curves. The IPHC longline survey was fit using a two parameter logistic curve.

Variability in estimated age in SS is based on the standard deviation of estimated age. Weighted least squares regression has been used in the past several assessments to estimate a linear relationship between standard deviation and age. The regression was recomputed in 2011, yielding an estimated intercept of 0.023 and an estimated slope of 0.072 (i.e, the standard deviation of estimated age was modeled as 0.023 + 0.072 × age), which gives a weighted R2 of 0.88.

Parameters governing the weight-at-length were estimated outside the model using AFSC GOA bottom trawl survey data through 2015, giving the following values:

	Value
α:	5.631×10^{-6}
β:	3.1306
Samples:	7,366

The length at 50% maturity was calculated using the morp_mature function in the sizeMat R package (Torrejon-Magallanes 2017) using all of the length at maturity data available from the Stark (2007) study for the Gulf of Alaska. This included some maturity data that was not available to Stark (2007) at the time of publication and some maturities from March and April not used in the calculation of L50% published. This resulted in the following values: length at 50% maturity = 57.3 cm and slope of linearized logistic equation = -0.27365

New to this model natural mortality was parameterized by age with five nodes at ages 1, 3, 5, 7, and 9 with linear interpolation between nodes (Methot *et al.* 2018). Ages 1, 3, and 5 were scaled to the winter marine heatwave index. All nodes are fit with a lognormal priors (μ =-0.81, σ =0.41). Model sensitivity tests determined no significant improvement in model fit with annual varying natural mortality for ages 7 through 10. Age 0 natural mortality was fixed at 1.0 as there was no data to inform this value.

Results

Model fits

Model 19.14.51 provides a better overall fit (-62.18 AIC) than the newly proposed Model 19.14.48d (the best fit model presented in the September plan team (Barbeaux unpublished white paper) to the survey indices and length composition and a marginally worse fit to conditional age at length data (Table 8). The improved fit to the survey indices was driven by an improvement to the LL survey, while fits to the trawl and IPHC surveys were slightly worse (Figure 4). Selectivity for all fleets are shown in Figure 5 and Table 10. Length composition fits were better for all fleets while fits to the conditional age at length data were marginally worse for all fleets (Table 9 and Figures 6 - 17). In general, there was little practical difference in model fits to Model 19.14.48d. The retrospective is degraded in this model (Fig. 18) compared to Model 19.14.51, however the Mohn's ρ, Woods Hole ρ, and RMSE are all at acceptable levels.

Natural mortality

Natural mortality was fixed at 1.0 for age 0, scaled to the winter MHWI for ages 1-6 with nodes at 1, 3,and 5, and fit for all years for ages 7-10. Age 1 has the highest estimated natural mortality dropping to age 5 then increasing to age 7 and remaining stable such that there is a u-shaped natural mortality (Table

11 and Figures 19-20). The highest natural mortality for ages 1 - 6 was predicted during years with positive winter heatwave indices with the highest natural mortality during the 2014-2016 marine heatwave.

Growth and maturity

In Model 19.14.51 with L_∞ and K scaled freely to CFSR temperatures length increased with increasing temperature (Fig. 21). This resulted in heavier fish at age (Fig. 21 and Fig. 22) and because the model uses length at 50% mature to set maturity cod were also younger at $A_{50\%}$ in the warm years (Fig. 23).

Recruitment

In Model 19.14.51 R_0 in a Beverton-Holt stock-recruit curve was scaled to the winter MHCI. Steepness was also fit within the model with an uninformative prior. Steepness was estimated at 0.796, but with high uncertainty (σ= 0.219699). As the winter MHCI intensified the R_0 is projected to decrease (Fig. 24) reducing average recruitment at a given spawning biomass. In this model σ_R remained static at 0.44 and was not fit.

Time series

The overall trend in the time series match that estimated in last year's model (18.10.44) and Model 19.14.48d in that it shows a steep increase in biomass through the early 1990s followed by a long decline through the mid-2000s (Fig. 25). All three models have a very large 1977 and 2012 recruitments with high average recruitment through the 1980s and in the late 2000s and a sharp decline in recruitment for 2014-1016. The main difference is a much higher average number of recruits at age-0 to make up for the higher natural mortality at younger ages. Spawning biomass in the late 2000s does not increase as much as the previous models, with only a slight increase with the increased recruitment in 2006-2009. Therefore Model 19.14.51 does not show as steep a decline as observed in the models with a single block of high natural mortality (e.g. 18.10.44 and 19.14.48d). The trend in F is similar in all models with a smooth increasing trend up until 2016 with a sharp increase through 2017 and then a sharp decrease in 2018 when the drop in cod abundance triggered a sharp cut in the ABC (Fig. 26)

Projections

For future projections we do not have temperature projections for the Gulf of Alaska. Projections previously produced for the southeastern Bering Sea show a steady increase in sea surface temperatures (Fig. 27) exceeding 2 °C by 2040 under RCP85 (Hermann et al. 2019). The recent marine heatwaves in the GOA have already exceeded these temperatures (e.g. 2016 winter sea surface temperatures were on average 2.67 °C higher than the 1982-2012 daily means). For these projections we scaled the average winter temperatures at 0, 0.66, 1.02, 1.51, 1.93 and 2.67°C above the 1982-2012 average and fixed all years to 2043 at these values. These values were experienced during previous heatwaves and therefore future conditions could be specified to mimic conditions during these years in the forecast.ss files. For all future years therefore recruitment, natural mortality, and growth were set to be the same as those during the years experiencing those same conditions in the past. An unfished spawning biomass was calculated for each scenario and catch specified either at 0 or at $F_{40\%}$, none of the catch scenarios included the North Pacific groundfish control rules. We set catch at 0 (termed zero catch spawning biomass) to determine the spawning biomass in 2043 when left unfished and compared this to the model derived equilibrium "unfished spawning biomass."

For increasing temperatures we see an increase in the zero catch 2043 spawning biomass up to an increase of average sea surface temperature to 0.6 °C above the 1982-2012 mean (Fig. 28). This is the 90th percentile of the mean. After 0.6°C the model predicts an exponential decline in both the unfished and zero catch spawning biomass. This tracks with increasing growth and no impacts on recruitment or natural mortality until the heatwave are experienced. The impacts of growth are outweighed by the impacts of increased natural mortality and decreased recruitment. With a 1.5°C increase the unfished and zero catch spawning biomass is at 20% of the modeled virgin biomass under 1977-2015 average conditions.

Under the various temperature increase scenarios we project an exponential decrease in both spawning biomass and projected catch (Fig. 29 and 30). In the 2.67 °C scenario the equilibrium unfished spawning biomass drops to a low of 6833.28 t with an $F_{40\%}$ catch in 2043 at 1,823 t and catch at B_{MSY} of 1562.96 t.

Conclusions

Under climate change and expected warming in the Gulf of Alaska the population dynamics of Pacific cod will change likely leading to a much lower carrying capacity in the GOA for this species. The current reference points set at equilibrium conditions from 1977-2015 are not likely to be relevant in the near future. If Pacific cod falls below $B_{17.5\%}$ using the 1977-2015 equilibrium conditions a rebuilding plan will be needed. Model 19.14.51 provides one method to calculate new biological reference points which includes climate impacts on the stocks growth, recruitment, and natural mortality could be derived for this species. However it should be noted that this method would not take into consideration the requirements under Steller Sea lion rules which require a closure of the directed fishery when the Pacific cod population reaches at or below $B_{20\%}$ of the virgin biomass (this needs to be checked, does the regulations state virgin or unfished spawning biomass or simply indicate the reference points?).

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Tables

Table 1. Pacific cod abundance measured in biomass (t) and numbers of fish (1000s), as assessed by the GOA bottom trawl survey. Point estimates are shown along with coefficients of variation.

Year	Biomass(t)	CV	Abundance	CV
1984	550,971	0.096	320,525	0.102
1987	394,987	0.085	247,020	0.121
1990	416,788	0.100	212,132	0.135
1993	409,848	0.117	231,963	0.124
1996	538,154	0.131	319,068	0.140
1999	306,413	0.083	166,584	0.074
2001	257,614	0.133	158,424	0.118
2003	297,402	0.098	159,749	0.085
2005	308,175	0.170	139,895	0.135
2007	232,035	0.091	192,306	0.114
2009	752,651	0.195	573,469	0.185
2011	500,975	0.089	348,060	0.116
2013	506,362	0.097	337,992	0.099
2015	253,694	0.069	196,334	0.079
2017	107,342	0.128	56,199	0.117

Table 2. ABL Longline Relative Population Numbers (RPNs) and CVs for Pacific cod.

Year	RPN	CV	Year	RPN	CV
1990	116,398	0.139	2007	34,992	0.140
1991	110,036	0.141	2008	26,881	0.228
1992	136,311	0.087	2009	68,391	0.138
1993	153,894	0.114	2010	86,722	0.138
1994	96,532	0.094	2011	93,732	0.141
1995	120,700	0.100	2012	63,749	0.148
1996	84,530	0.141	2013	48,534	0.162
1997	104,610	0.169	2014	69,653	0.143
1998	125,846	0.115	2015	88,410	0.160
1999	91,407	0.113	2016	83,887	0.172
2000	54,310	0.145	2017	39,523	0.101
2001	33,841	0.181	2018	23,853	0.121
2002	51,900	0.170			
2003	59,952	0.150			
2004	53,108	0.118			
2005	29,864	0.214			
2006	34,316	0.197			

Table 3. IPHC Longline Relative Population Numbers (RPNs) and CVs for Pacific cod.

Year	RPN	CV	Year	RPN	CV
1997	29,431.29	0.24	2008	22,201.86	0.17
1998	16,389.47	0.20	2009	30,228.94	0.16
1999	12,387.02	0.21	2010	27,836.75	0.16
2000	14,599.59	0.22	2011	31,728.38	0.15
2001	12,192.47	0.23	2012	23,604.72	0.17
2002	16,372.69	0.21	2013	26,333.14	0.18
2003	15,361.62	0.22	2014	27,789.64	0.16
2004	16,075.93	0.20	2015	16,853.72	0.20
2005	16,397.51	0.23	2016	11,888.02	0.23
2006	15,761.12	0.20	2017	10,241.65	0.23
2007	18,196.23	0.19	2018	13,198.32	0.16

Table 4. Catch (t) for 1991 through 2018 by jurisdiction and gear type (as of 2018-10-09)

	Federal					State				
Year	Trawl	Long-line	Pot	Other	Subtotal	Long-line	Pot	Other	Subtotal	Total
1991	58,093	7,656	10,464	115	76,328	0	0	0	0	76,328
1992	54,593	15,675	10,154	325	80,747	0	0	0	0	80,747
1993	37,806	8,963	9,708	11	56,488	0	0	0	0	56,488
1994	31,447	6,778	9,161	100	47,485	0	0	0	0	47,485
1995	41,875	10,978	16,055	77	68,985	0	0	0	0	68,985
1996	45,991	10,196	12,040	53	68,280	0	0	0	0	68,280
1997	48,406	10,978	9,065	26	68,476	0	7,224	1,319	8,542	77,018
1998	41,570	10,012	10,510	29	62,121	0	9,088	1,316	10,404	72,525
1999	37,167	12,363	19,015	70	68,614	0	12,075	1,096	13,171	81,785
2000	25,443	11,660	17,351	54	54,508	0	10,388	1,643	12,031	66,560
2001	24,383	9,910	7,171	155	41,619	0	7,836	2,084	9,920	51,542
2002	19,810	14,666	7,694	176	42,345	0	10,423	1,714	12,137	54,483
2003	18,884	9,525	12,765	161	41,335	62	7,943	3,242	11,247	52,582
2004	17,513	10,326	14,966	400	43,205	51	10,602	2,765	13,419	56,624
2005	14,549	5,732	14,749	203	35,233	26	9,653	2,673	12,351	47,584
2006	13,132	10,244	14,540	118	38,034	55	9,146	662	9,863	47,897
2007	14,775	11,539	13,573	44	39,932	270	11,378	682	12,329	52,261
2008	20,293	12,106	11,230	63	43,691	317	13,438	1,568	15,323	59,014
2009	13,976	13,968	11,951	206	40,101	676	9,919	2,500	13,096	53,196
2010	21,765	16,540	20,116	429	58,850	826	14,604	4,045	19,475	78,325,
2011	16,453	16,668	29,233	722	63,076	1,035	16,675	4,627	22,337	85,412
2012	20,072	14,467	21,238	722	56,499	866	15,940	4,613	21,419	77,918
2013	21,700	12,866	17,011	476	52,053	1,089	14,156	1,303	16,547	68,600
2014	26,798	14,749	19,957	1,046	62,550	1,007	18,445	2,838	22,290	84,841
2015	22,269	13,054	20,653	408	56,384	578	19,719	2,808	23,104	79,489
2016	15,217	8,153	19,248	346	42,964	806	18,609	1,708	21,123	64,087
2017	13,041	8,978	13,426	67	35,512	149	13,011	62	13,222	48,734
2018	2,882	2,537	2,393	95	7,907	205	3,659	195	4,058	11,965

Table 5. History of Pacific cod catch (t, includes catch from State waters), Federal TAC (does not include State guideline harvest level), ABC, and OFL. ABC was not used in management of GOA groundfish prior to 1986. Catch for 2018 is current through 2018-10-09. The values in the column labeled "TAC" correspond to "optimum yield" for the years 1980-1986, "target quota" for the year 1987, and true TAC for the years 1988-present. The ABC value listed for 1987 is the upper bound of the range. Source: NPFMC staff.

Year	Catch	TAC	ABC	OFL
1980	35,345	60,000	-	-
1981	36,131	70,000	-	-
1982	29,465	60,000	-	-
1983	36,540	60,000	-	-
1984	23,898	60,000	-	-
1985	14,428	60,000		-
1986	25,012	75,000	136,000	-
1987	32,939	50,000	125,000	-
1988	33,802	80,000	99,000	-
1989	43,293	71,200	71,200	-
1990	72,517	90,000	90,000	-
1991	76,328	77,900	77,900	-
1992	80,747	63,500	63,500	87,600
1993	56,488	56,700	56,700	78,100
1994	47,485	50,400	50,400	71,100
1995	68,985	69,200	69,200	126,000
1996	68,280	65,000	65,000	88,000
1997	68,476	69,115	81,500	180,000
1998	62,121	66,060	77,900	141,000
1999	68,614	67,835	84,400	134,000
2000	54,508	59,800	76,400	102,000
2001	41,619	52,110	67,800	91,200
2002	42,345	44,230	57,600	77,100
2003	52,582	40,540	52,800	70,100
2004	56,624	48,033	62,810	102,000
2005	47,584	44,433	58,100	86,200
2006	47,897	52,264	68,859	95,500
2007	52,261	52,264	68,859	97,600
2008	59,014	50,269	64,493	88,660
2009	53,196	41,807	55,300	66,000
2010	78,325	59,563	79,100	94,100
2011	85,412	65,100	86,800	102,600
2012	77,918	65,700	87,600	104,000
2013	68,600	60,600	80,800	97,200
2014	84,840	64.738	88,500	107,300
2015	79,489	75,202	102,850	140,300
2016	64,087	71,925	98,600	116,700
2017	48,734	64,442	88,342	105,378
2018	11,965	13,096	17,000	23,565

Table 6. CFSR June mean temperature at mean depth for Pacific cod at 20 cm length bins in the central Gulf of Alaska.

Year	0-20 CM	20-40 CM	40-60 CM	60-80 CM	80+ CM
1979	4.91	4.70	5.08	4.80	5.13
1980	5.03	4.74	4.92	4.78	4.94
1981	5.71	5.20	5.36	5.24	5.35
1982	4.00	4.08	4.52	4.19	4.57
1983	5.11	4.87	5.25	4.97	5.26
1984	4.73	4.75	5.23	4.87	5.24
1985	4.57	4.58	5.17	4.72	5.22
1986	4.73	4.53	5.00	4.65	5.03
1987	5.30	5.00	5.31	5.08	5.33
1988	4.70	4.60	4.95	4.69	4.98
1989	4.05	3.95	4.40	4.06	4.45
1990	4.12	4.11	4.53	4.21	4.58
1991	4.38	4.26	4.62	4.35	4.66
1992	4.89	4.60	4.89	4.68	4.90
1993	4.52	4.37	4.70	4.46	4.72
1994	4.47	4.46	4.82	4.55	4.85
1995	4.04	4.04	4.62	4.19	4.69
1996	4.50	4.40	4.77	4.50	4.80
1997	4.56	4.46	4.85	4.56	4.88
1998	5.73	5.20	5.52	5.29	5.52
1999	4.43	4.38	4.86	4.50	4.92
2000	4.51	4.43	4.79	4.52	4.82
2001	4.98	4.80	5.02	4.85	5.04
2002	4.20	4.10	4.36	4.16	4.40
2003	5.30	5.15	5.39	5.22	5.39
2004	4.60	4.58	4.98	4.68	5.01
2005	4.91	4.89	5.27	4.98	5.30
2006	4.63	4.57	4.97	4.67	5.01
2007	4.13	3.85	4.29	3.96	4.34
2008	4.33	4.17	4.56	4.26	4.59
2009	3.66	3.81	4.31	3.93	4.38
2010	5.21	4.78	5.08	4.86	5.08
2011	4.55	4.27	4.66	4.37	4.69
2012	4.00	3.64	4.08	3.75	4.11
2013	4.18	4.14	4.64	4.26	4.69
2014	4.73	4.62	4.96	4.71	4.98
2015	5.88	5.42	5.59	5.47	5.55
2016	5.71	4.99	5.10	5.02	5.08
2017	4.75	4.42	4.58	4.46	4.58
2018	5.10	4.79	5.02	4.85	5.03
2019	5.94	5.46	5.63	5.51	5.61

Table 7. Data used in the development of Model 19.14.51

Data	Source	Type	Years included
Federal and state fishery catch, by gear type	AKFIN	metric tons	1977 – 2018
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2018
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2018
GOA NMFS bottom trawl survey biomass and abundance estimates	AFSC	metric tons, numbers	1984 – 2017
AFSC Sablefish Longline survey Pacific cod RPN	AFSC	RPN	1990 – 2018
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1984 – 2017
GOA NMFS bottom trawl survey age composition	AFSC	number, by age	1990 – 2017
GOA NMFS bottom trawl survey mean length-at-age and conditional age-at-length	AFSC	mean value and number	1990 – 2017
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	Number, by cm bin	1990 – 2018
CFSR bottom temperature indices	National Center for Atmospheric Research	Temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2019
Winter marine heatwave cumulative index	NOAA	Annual cummulative index of °C days above the daily 90th percentile (1982-2012) for Jan-Mar and Nov-Dec	1981-2019

Table 8. Model 19.14.48d and 19.14.51 likelihoods, parameters, and key results for model evaluation.

		M19.14.48d	**Model19.14.51**
	AIC	5715.44	5653.26
	# Parameters	184	212
Likelihoods			
	Total	2673.72	2614.63
	Surveys	-17.1732	-20.20
	Length Composition	1408.78	1347.70
	Cond. Age at length	1289.51	1297.76
	Parameter Priors	0.57643	2.52
Results			
	Rvirgin	385.423	2766.04
	LN(R0)	12.8621	14.83
	LN(R0)_ENV parameter	NA	-4.03E-04
	BH steepness	1.000	0.796
	M or Mat age 0	0.432	1.000
	M 2014-2016	0.690	NA
	M age 1	NA	1.08
	M age 3	NA	0.52
	M age 5	NA	0.39
	M age 7	NA	0.51
	M age 9	NA	0.45
	M age 1 env. parameter	NA	2.72E-04
	M age 3 env. Parameter	NA	3.31E-03
	M age 5 env. Parameter	NA	2.71E-04
	L_∞	107.639	111.608
	L∞ env. Parameter	NA	2.43E-02
	VonBert K	0.157	0.147
	VonBert K env. Parameter	NA	-8.01E-03
	SSB_Virgin_thousand_mt	259.000	335.428
Retrospectives			
	Mohn’s ρ	-0.007	0.127
	Woods Hole ρ	0.088	0.078
	RMSE	0.153	0.132

Table. 9 Likelihoods by fleet for Model 19.14.48d and 19.14.51,

Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv	IPHCLL	Model
Age_like	1289.510	224.061	273.193	209.221	583.034			Model19.14.48d
Age_like	1297.760	225.518	271.446	207.706	593.088			Model19.14.51
Length_like	1408.780	402.526	273.000	294.993	220.797	209.102	8.367	Model19.14.48d
Length_like	1347.700	381.637	261.466	286.513	214.660	199.892	3.527	Model19.14.51
Surv_like	-17.173				-8.631	-2.709	-5.833	Model19.14.48d
Surv_like	-20.199				-4.996	-12.622	-2.582	Model19.14.51

Table 10. Selectivity at age by year for each fishery and survey for Model 19.14.51. Only years where values change are presented.

Fleet	Yr	0	1	2	3	4	5	6	7	8	9	10
Trawl	1977	0.000	0.001	0.081	0.784	1.000	0.563	0.558	0.558	0.558	0.558	0.558
Trawl	1978	0.000	0.001	0.073	0.757	1.000	0.564	0.558	0.558	0.558	0.558	0.558
Trawl	1979	0.000	0.000	0.043	0.626	0.999	0.596	0.558	0.558	0.558	0.558	0.558
Trawl	1980	0.000	0.000	0.004	0.208	0.976	0.998	0.559	0.558	0.558	0.558	0.558
Trawl	1981	0.000	0.000	0.023	0.485	0.999	0.816	0.558	0.558	0.558	0.558	0.558
Trawl	1982	0.000	0.001	0.113	0.862	1.000	0.560	0.558	0.558	0.558	0.558	0.558
Trawl	1983	0.000	0.000	0.022	0.481	0.998	0.812	0.558	0.558	0.558	0.558	0.558
Trawl	1984	0.000	0.001	0.070	0.752	1.000	0.565	0.558	0.558	0.558	0.558	0.558
Trawl	1985	0.000	0.000	0.025	0.498	0.999	1.000	0.558	0.558	0.558	0.558	0.558
Trawl	1986	0.000	0.005	0.232	0.988	0.998	0.559	0.558	0.558	0.558	0.558	0.558
Trawl	1987	0.000	0.000	0.033	0.568	0.999	0.646	0.558	0.558	0.558	0.558	0.558
Trawl	1988	0.000	0.000	0.024	0.500	0.999	0.897	0.558	0.558	0.558	0.558	0.558
Trawl	1989	0.000	0.000	0.024	0.497	0.999	1.000	0.558	0.558	0.558	0.558	0.558
Trawl	1990	0.000	0.001	0.011	0.081	0.336	0.776	1.000	1.000	1.000	1.000	0.558
Trawl	2004	0.000	0.001	0.011	0.081	0.336	0.776	1.000	1.000	1.000	1.000	0.558
Trawl	2005	0.000	0.000	0.002	0.016	0.087	0.308	0.690	0.983	1.000	1.000	0.620
Trawl	2006	0.000	0.000	0.002	0.016	0.087	0.308	0.690	0.983	1.000	1.000	0.620
Trawl	2007	0.000	0.002	0.024	0.137	0.455	0.876	1.000	1.000	0.675	0.558	0.558
Trawl	2016	0.000	0.002	0.024	0.137	0.455	0.876	1.000	1.000	0.675	0.558	0.558
Trawl	2017	0.000	0.001	0.012	0.098	0.405	0.867	1.000	1.000	1.000	0.812	0.558
Trawl	2018	0.000	0.001	0.012	0.098	0.405	0.867	1.000	1.000	1.000	0.812	0.558
Longline	1977	0.000	0.000	0.003	0.280	0.997	1.000	1.000	1.000	1.000	0.798	0.520
Longline	1978	0.000	0.000	0.003	0.288	0.997	1.000	1.000	1.000	1.000	0.806	0.520
Longline	1979	0.000	0.000	0.006	0.393	0.998	1.000	1.000	1.000	1.000	0.757	0.520
Longline	1980	0.000	0.000	0.003	0.288	0.997	1.000	1.000	1.000	1.000	0.811	0.520
Longline	1981	0.000	0.000	0.002	0.262	0.998	1.000	1.000	1.000	1.000	0.797	0.520
Longline	1982	0.000	0.000	0.007	0.410	0.998	1.000	1.000	1.000	1.000	0.733	0.520
Longline	1983	0.000	0.000	0.003	0.301	0.997	1.000	1.000	1.000	1.000	0.849	0.520
Longline	1984	0.000	0.000	0.004	0.333	0.998	1.000	1.000	1.000	1.000	0.999	0.520
Longline	1985	0.000	0.000	0.004	0.336	0.998	1.000	1.000	1.000	1.000	1.000	0.520
Longline	1986	0.000	0.000	0.000	0.093	0.937	1.000	1.000	1.000	1.000	0.898	0.520
Longline	1987	0.000	0.000	0.004	0.327	0.998	1.000	1.000	1.000	1.000	0.981	0.520
Longline	1988	0.000	0.000	0.001	0.170	0.999	1.000	1.000	1.000	1.000	0.847	0.520
Longline	1989	0.000	0.000	0.003	0.274	0.998	1.000	1.000	1.000	1.000	0.796	0.520
Longline	1990	0.000	0.000	0.002	0.045	0.335	0.899	1.000	1.000	1.000	1.000	0.520
Longline	2004	0.000	0.000	0.002	0.045	0.335	0.899	1.000	1.000	1.000	1.000	0.520
Longline	2005	0.000	0.000	0.001	0.041	0.376	0.964	0.991	0.520	0.520	0.520	0.520
Longline	2006	0.000	0.000	0.001	0.041	0.376	0.964	0.991	0.520	0.520	0.520	0.520
Longline	2007	0.000	0.000	0.001	0.037	0.325	0.911	1.000	0.589	0.520	0.520	0.520
Longline	2016	0.000	0.000	0.001	0.037	0.325	0.911	1.000	0.589	0.520	0.520	0.520
Longline	2017	0.000	0.000	0.000	0.117	0.997	1.000	1.000	1.000	1.000	0.521	0.520
Longline	2018	0.000	0.000	0.000	0.117	0.997	1.000	1.000	1.000	1.000	0.521	0.520
Pot	1977	0.000	0.000	0.000	0.010	0.173	0.783	1.000	0.743	0.288	0.288	0.288
Pot	2012	0.000	0.000	0.000	0.010	0.173	0.783	1.000	0.743	0.288	0.288	0.288
Pot	2013	0.000	0.000	0.000	0.050	0.704	1.000	1.000	0.673	0.288	0.288	0.288
Pot	2018	0.000	0.000	0.000	0.050	0.704	1.000	1.000	0.673	0.288	0.288	0.288
AFSC BT Survey	1977	0.001	0.010	0.075	0.317	0.754	1.000	0.523	0.174	0.174	0.174	0.174
AFSC BT Survey	1995	0.001	0.010	0.075	0.317	0.754	1.000	0.523	0.174	0.174	0.174	0.174
AFSC BT Survey	1996	0.000	0.018	0.100	0.331	0.708	0.985	1.000	1.000	1.000	1.000	1.000
AFSC BT Survey	2005	0.000	0.018	0.100	0.331	0.708	0.985	1.000	1.000	1.000	1.000	1.000
AFSC BT Survey	2006	0.000	0.032	0.141	0.390	0.741	0.984	1.000	1.000	1.000	1.000	1.000
AFSC BT Survey	2018	0.000	0.032	0.141	0.390	0.741	0.984	1.000	1.000	1.000	1.000	1.000
AFSC LL Survey	1977	0.000	0.000	0.000	0.000	0.140	0.996	0.986	0.636	0.271	0.145	0.127
AFSC LL Survey	2018	0.000	0.000	0.000	0.000	0.140	0.996	0.986	0.636	0.271	0.145	0.127
AFSC LL Survey	2019	0.000	0.000	0.000	0.000	0.140	0.996	0.986	0.636	0.271	0.145	0.127
IPHC LL Survey	1977	0.000	0.000	0.000	0.003	0.058	0.586	0.970	0.999	1.000	1.000	1.000
IPHC LL Survey	2018	0.000	0.000	0.000	0.003	0.058	0.586	0.970	0.999	1.000	1.000	1.000

Table 11. Natural mortality by age and year for Model 19.14.51.

Yr	0	1	2	3	4	5	6	7	8	9	10
1977	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1978	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1979	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1980	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1981	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1982	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1983	1	1.090	0.827	0.564	0.479	0.395	0.451	0.507	0.479	0.451	0.451
1984	1	1.095	0.846	0.596	0.496	0.397	0.452	0.507	0.479	0.451	0.451
1985	1	1.089	0.824	0.559	0.477	0.395	0.451	0.507	0.479	0.451	0.451
1986	1	1.088	0.817	0.547	0.471	0.394	0.450	0.507	0.479	0.451	0.451
1987	1	1.085	0.807	0.529	0.461	0.393	0.450	0.507	0.479	0.451	0.451
1988	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1989	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1990	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1991	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1992	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1993	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1994	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1995	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1996	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
1997	1	1.090	0.826	0.563	0.479	0.395	0.451	0.507	0.479	0.451	0.451
1998	1	1.129	0.995	0.860	0.635	0.409	0.458	0.507	0.479	0.451	0.451
1999	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2000	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2001	1	1.088	0.821	0.553	0.473	0.394	0.450	0.507	0.479	0.451	0.451
2002	1	1.098	0.856	0.614	0.506	0.398	0.452	0.507	0.479	0.451	0.451
2003	1	1.131	1.005	0.879	0.644	0.409	0.458	0.507	0.479	0.451	0.451
2004	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2005	1	1.086	0.811	0.537	0.465	0.393	0.450	0.507	0.479	0.451	0.451
2006	1	1.085	0.807	0.530	0.461	0.393	0.450	0.507	0.479	0.451	0.451
2007	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2008	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2009	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2010	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2011	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2012	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2013	1	1.083	0.801	0.520	0.456	0.392	0.449	0.507	0.479	0.451	0.451
2014	1	1.114	0.924	0.733	0.568	0.403	0.455	0.507	0.479	0.451	0.451
2015	1	1.154	1.142	1.129	0.773	0.418	0.462	0.507	0.479	0.451	0.451
2016	1	1.197	1.477	1.758	1.095	0.433	0.470	0.507	0.479	0.451	0.451
2017	1	1.091	0.830	0.569	0.482	0.395	0.451	0.507	0.479	0.451	0.451
2018	1	1.104	0.879	0.654	0.527	0.400	0.453	0.507	0.479	0.451	0.451

Table 12. Weight at age by year for Model 19.14.51.

Yr	0	1	2	3	4	5	6	7	8	9	10
1977	3.07E-04	0.069	0.308	0.754	1.389	2.170	3.048	3.978	4.923	5.853	8.794
1978	3.07E-04	0.069	0.308	0.754	1.389	2.170	3.048	3.978	4.923	5.853	8.794
1979	3.07E-04	0.069	0.308	0.754	1.389	2.170	3.048	3.978	4.923	5.853	8.794
1980	3.07E-04	0.069	0.311	0.758	1.395	2.178	3.059	3.992	4.939	5.871	8.280
1981	3.07E-04	0.070	0.309	0.760	1.396	2.180	3.061	3.995	4.943	5.875	8.023
1982	3.07E-04	0.068	0.314	0.764	1.410	2.196	3.082	4.021	4.974	5.911	7.965
1983	3.07E-04	0.070	0.305	0.759	1.394	2.183	3.063	3.997	4.946	5.879	7.672
1984	3.07E-04	0.069	0.313	0.755	1.406	2.190	3.082	4.017	4.969	5.906	7.856
1985	3.07E-04	0.069	0.313	0.769	1.400	2.203	3.088	4.035	4.988	5.928	8.172
1986	3.07E-04	0.069	0.312	0.767	1.416	2.194	3.100	4.039	5.002	5.941	8.203
1987	3.07E-04	0.070	0.310	0.763	1.410	2.207	3.082	4.041	4.994	5.942	7.467
1988	3.07E-04	0.069	0.314	0.765	1.413	2.211	3.110	4.040	5.017	5.958	7.720
1989	3.07E-04	0.068	0.310	0.765	1.406	2.201	3.098	4.049	4.993	5.953	7.897
1990	3.07E-04	0.068	0.303	0.750	1.393	2.174	3.063	4.006	4.966	5.889	7.900
1991	3.07E-04	0.069	0.305	0.742	1.376	2.163	3.040	3.978	4.932	5.872	8.016
1992	3.07E-04	0.069	0.306	0.746	1.367	2.147	3.032	3.958	4.909	5.846	8.170
1993	3.07E-04	0.069	0.309	0.751	1.379	2.146	3.026	3.965	4.907	5.843	8.088
1994	3.07E-04	0.069	0.307	0.753	1.382	2.153	3.017	3.948	4.901	5.828	7.996
1995	3.07E-04	0.069	0.308	0.752	1.388	2.161	3.030	3.946	4.893	5.831	7.941
1996	3.07E-04	0.069	0.306	0.751	1.380	2.161	3.029	3.948	4.877	5.808	7.959
1997	3.07E-04	0.069	0.308	0.750	1.383	2.158	3.035	3.956	4.889	5.804	7.863
1998	3.07E-04	0.070	0.308	0.754	1.383	2.163	3.036	3.967	4.902	5.821	7.825
1999	3.07E-04	0.069	0.316	0.766	1.405	2.187	3.072	4.004	4.956	5.883	7.838
2000	3.07E-04	0.069	0.309	0.768	1.404	2.189	3.068	4.005	4.950	5.887	7.770
2001	3.07E-04	0.069	0.308	0.754	1.405	2.186	3.068	3.997	4.947	5.876	7.901
2002	3.07E-04	0.068	0.310	0.757	1.394	2.195	3.075	4.009	4.954	5.890	8.008
2003	3.07E-04	0.070	0.303	0.751	1.380	2.159	3.055	3.980	4.924	5.848	8.109
2004	3.07E-04	0.069	0.315	0.755	1.398	2.179	3.061	4.017	4.962	5.895	7.950
2005	3.07E-04	0.070	0.310	0.767	1.393	2.185	3.065	4.000	4.971	5.901	7.829
2006	3.07E-04	0.069	0.313	0.764	1.417	2.189	3.085	4.020	4.974	5.932	7.756
2007	3.07E-04	0.068	0.310	0.765	1.405	2.207	3.076	4.024	4.974	5.913	7.820
2008	3.07E-04	0.069	0.302	0.749	1.389	2.170	3.064	3.978	4.934	5.862	7.727
2009	3.07E-04	0.068	0.305	0.740	1.375	2.161	3.036	3.980	4.905	5.843	7.549
2010	3.07E-04	0.069	0.302	0.741	1.358	2.135	3.015	3.938	4.892	5.797	7.417
2011	3.07E-04	0.069	0.311	0.749	1.378	2.142	3.021	3.958	4.899	5.841	7.633
2012	3.07E-04	0.068	0.306	0.756	1.377	2.151	3.010	3.942	4.892	5.817	7.693
2013	3.07E-04	0.069	0.300	0.740	1.373	2.130	2.994	3.898	4.839	5.768	7.653
2014	3.07E-04	0.069	0.306	0.738	1.365	2.145	2.997	3.913	4.831	5.757	7.456
2015	3.07E-04	0.070	0.310	0.753	1.370	2.146	3.026	3.932	4.866	5.773	7.345
2016	3.07E-04	0.069	0.317	0.769	1.406	2.174	3.056	3.998	4.927	5.853	7.295
2017	3.07E-04	0.069	0.311	0.773	1.415	2.199	3.065	4.002	4.960	5.876	7.405
2018	3.07E-04	0.069	0.305	0.756	1.407	2.191	3.068	3.982	4.930	5.870	7.419

Figures

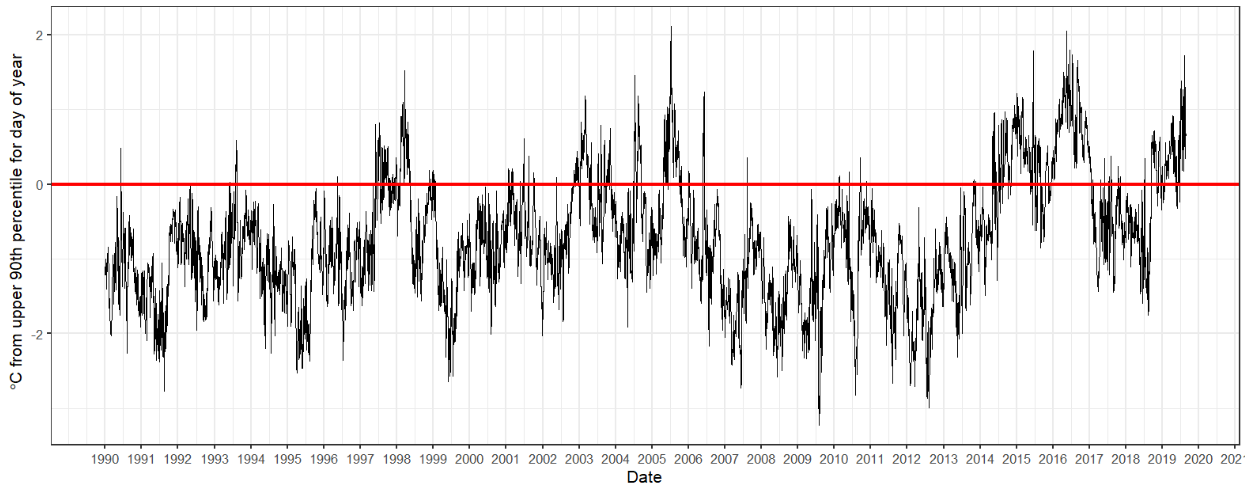

Figure 1. Sea surface temperature from the NOAA high-resolution blended analysis data for the central Gulf of Alaska (ESRL 2019)

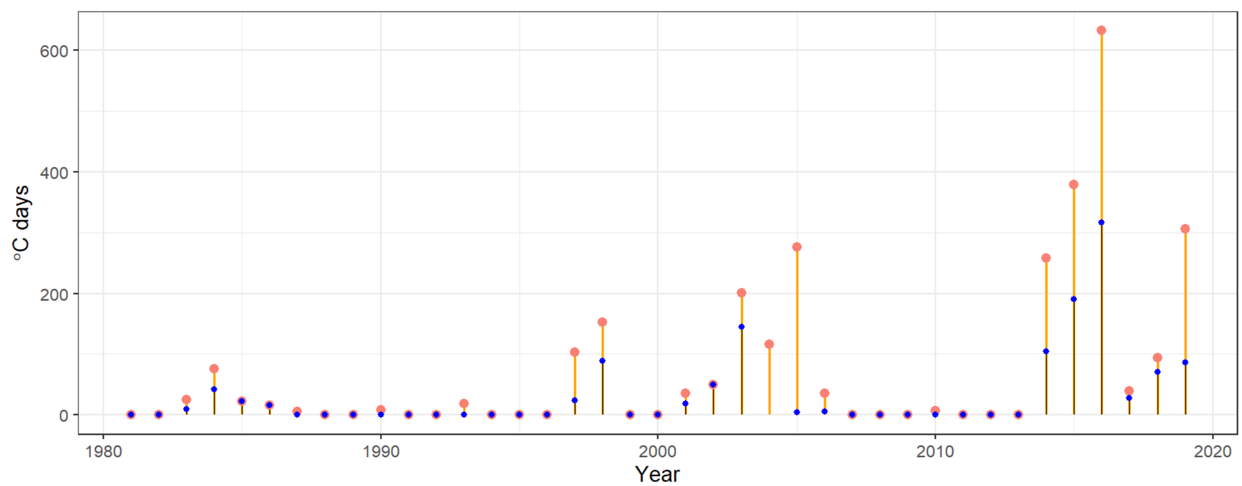

Figure 2. Marine heatwave cumulative index (orange) and winter marine heatwave cumulative index (blue) for central GOA in waters less than 300m.

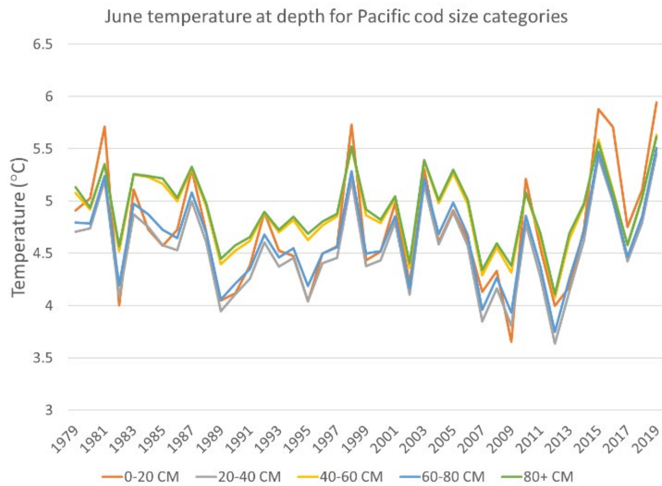

Figure 3. Climate Forecast System Reanalysis (CFSR) average temperatures at depth for the mean depths of Pacific cod at different length categories.

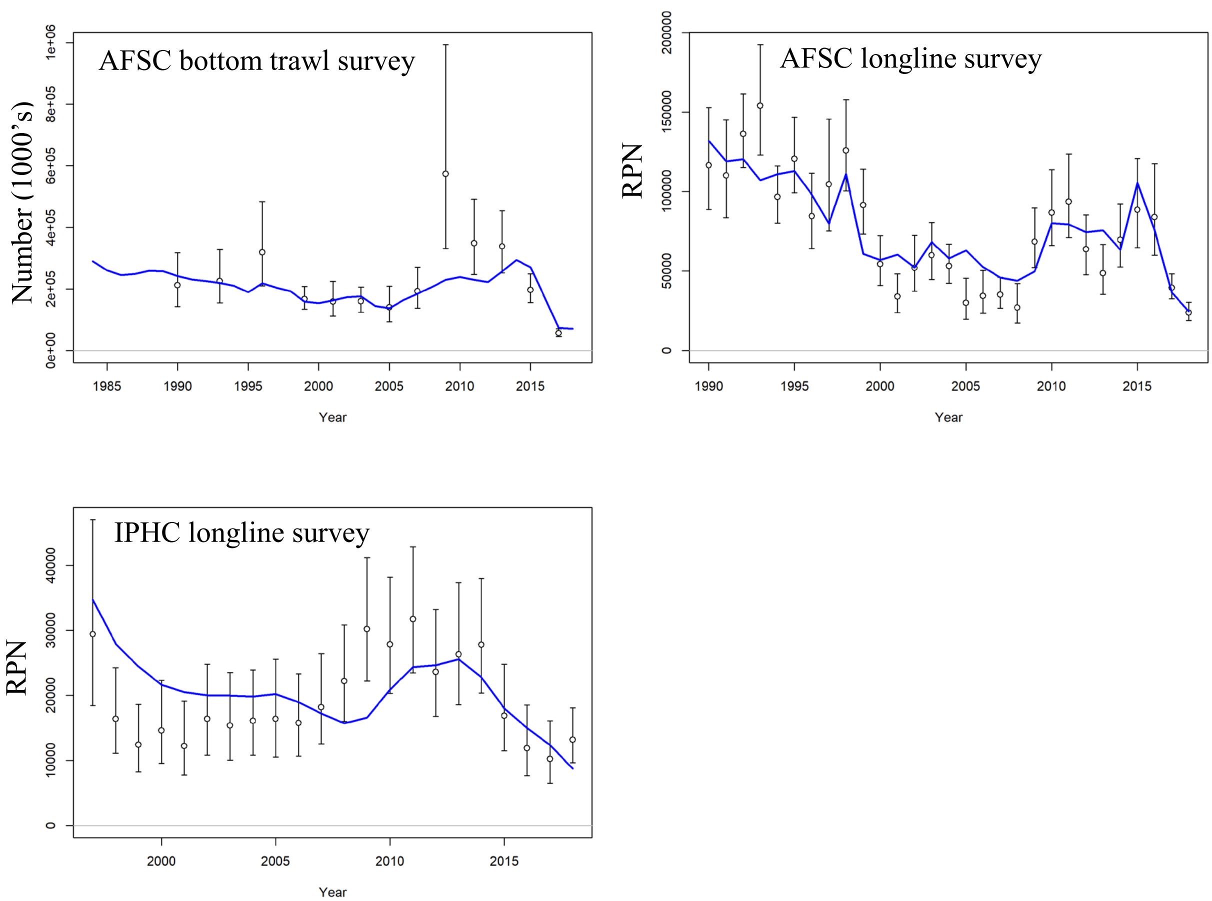

Figure 4. Survey indices and Model 19.14.51 fits (blue line)

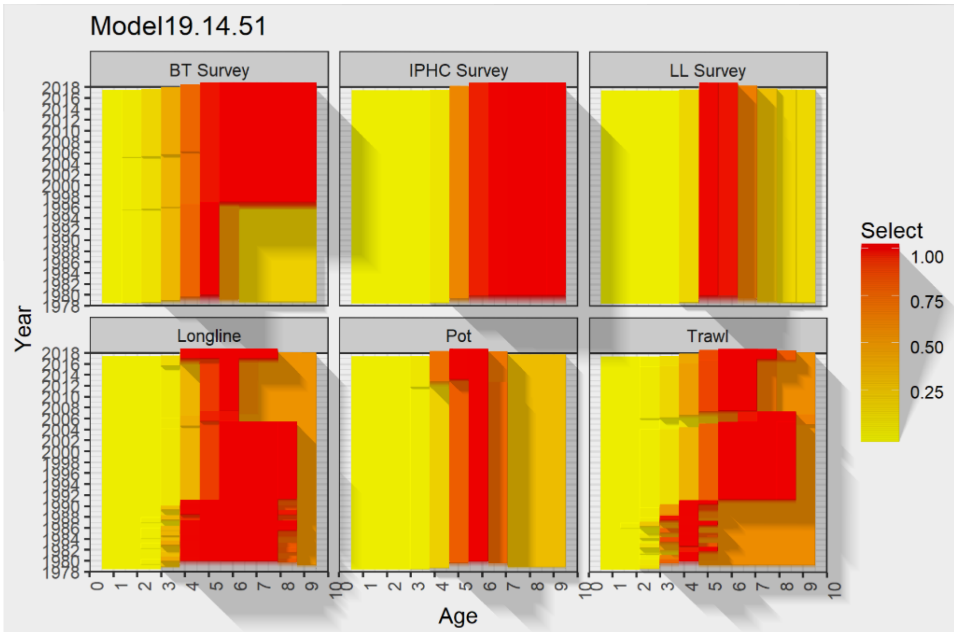

Figure 5. Selectivity at age for fisheries and surveys.

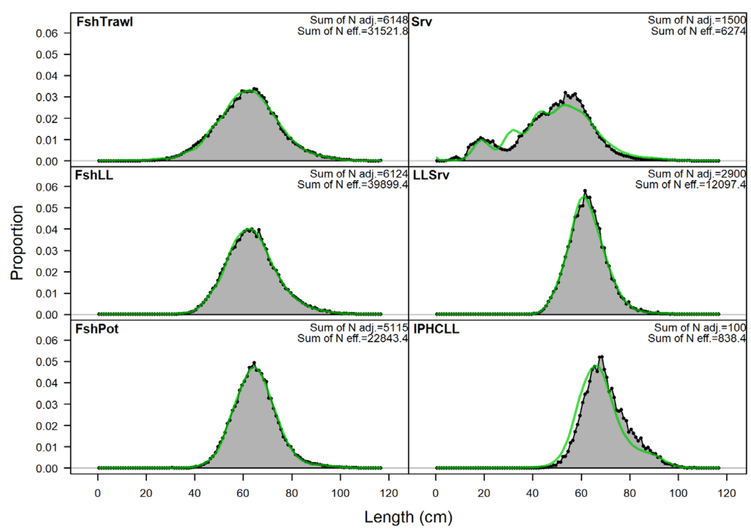

Figure 6. Overall fits to length composition by index and fishery.

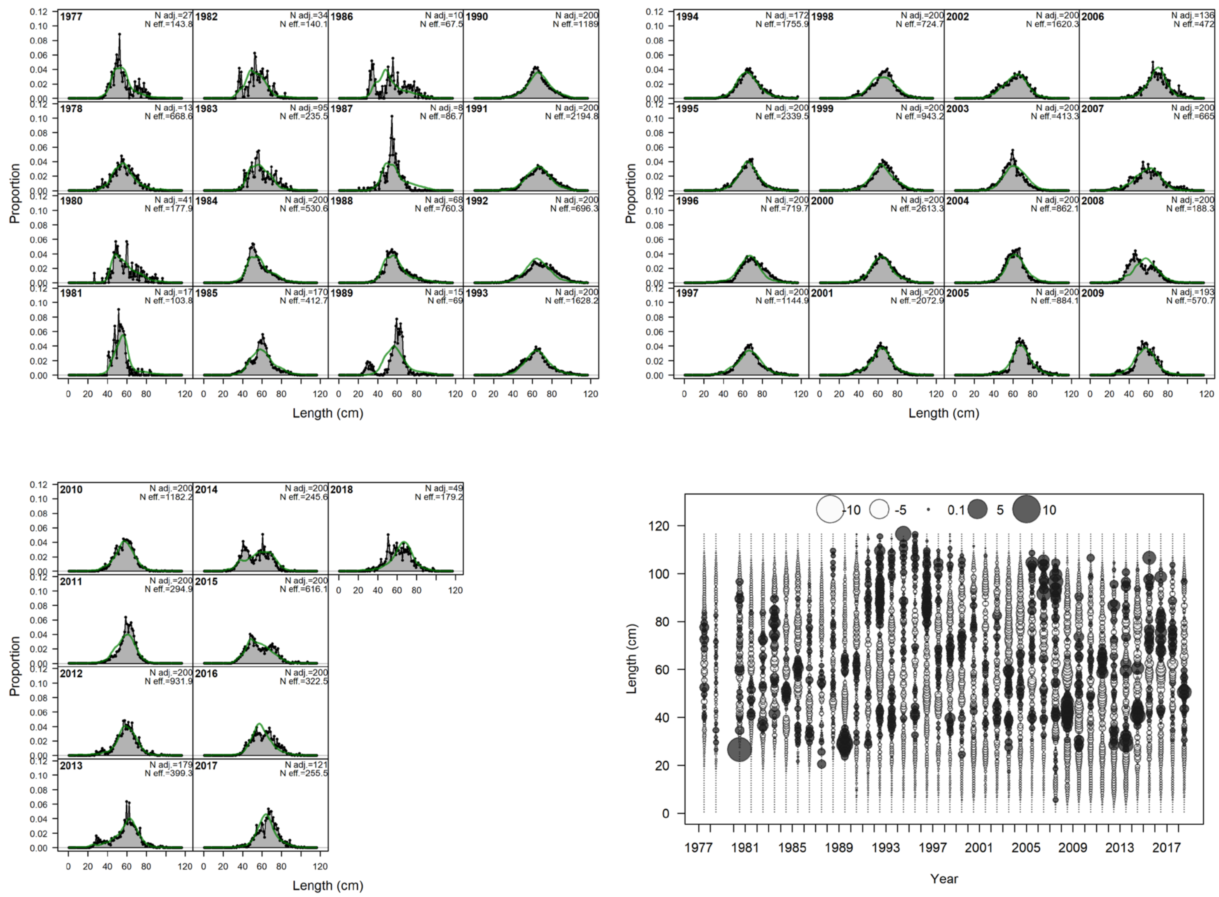

Figure 7. Trawl fishery length composition and fits (green line) and standardized residuals.

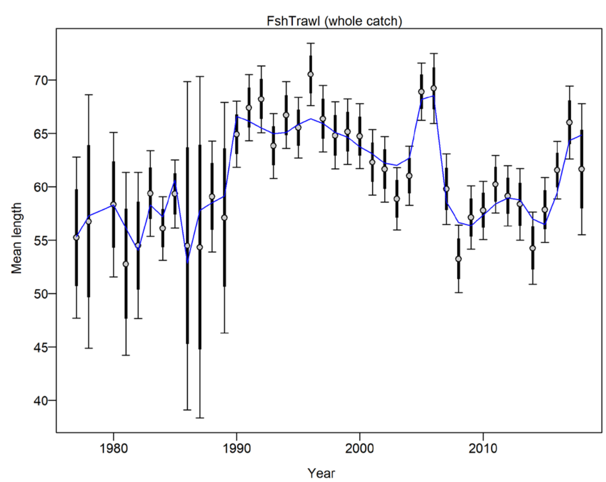

Figure 8. Trawl fishery mean length and model fit (blue line).

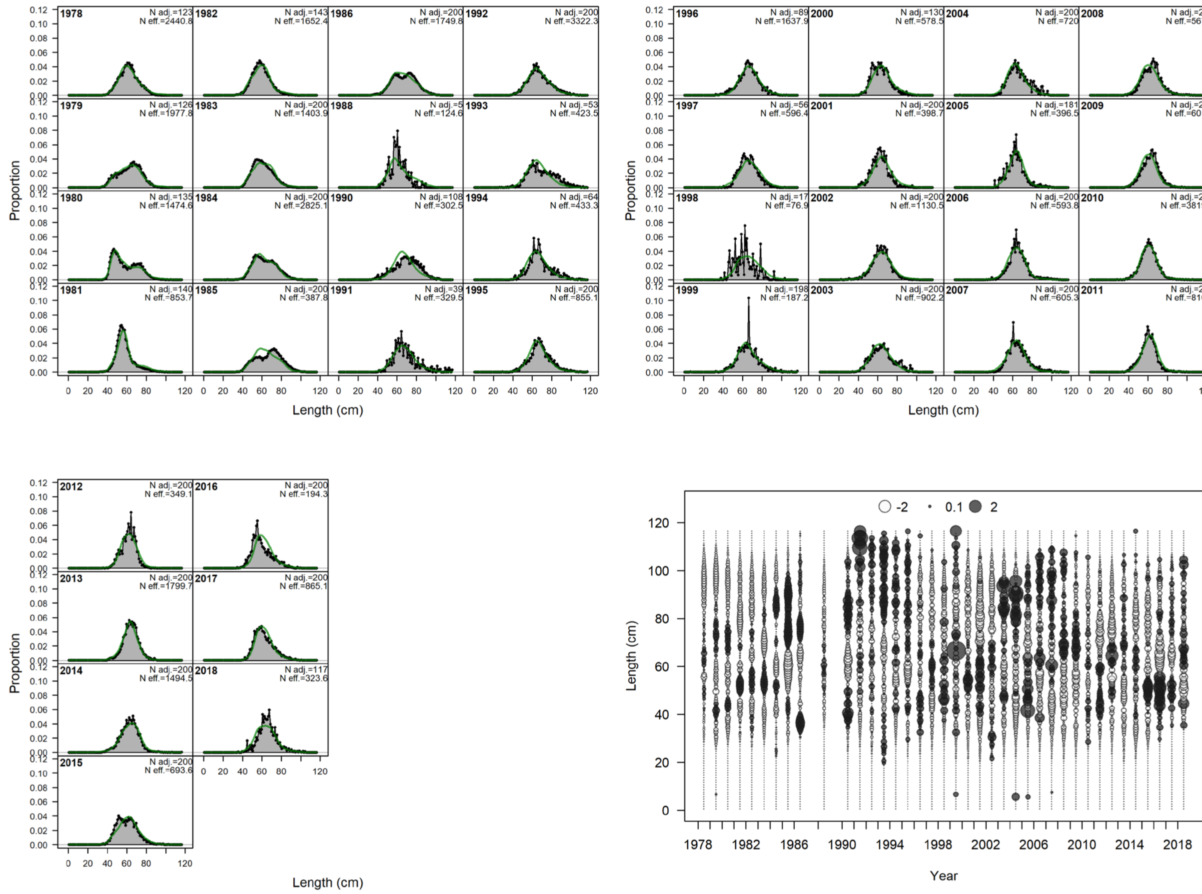

Figure 9. Longline fishery length composition and fits (green line) and standardized residuals.

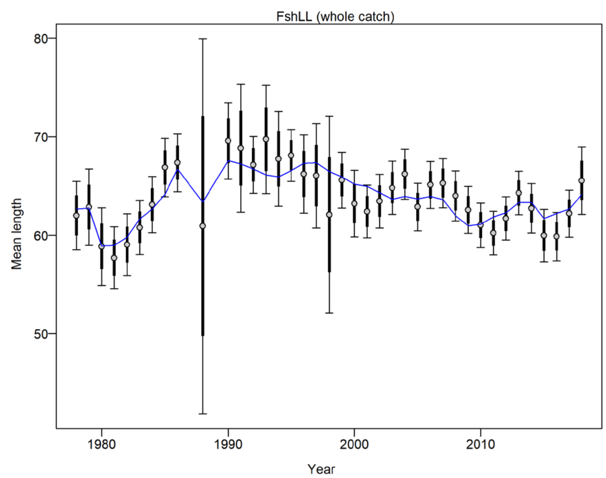

Figure 10. Longline fishery mean length and model fit (blue line).

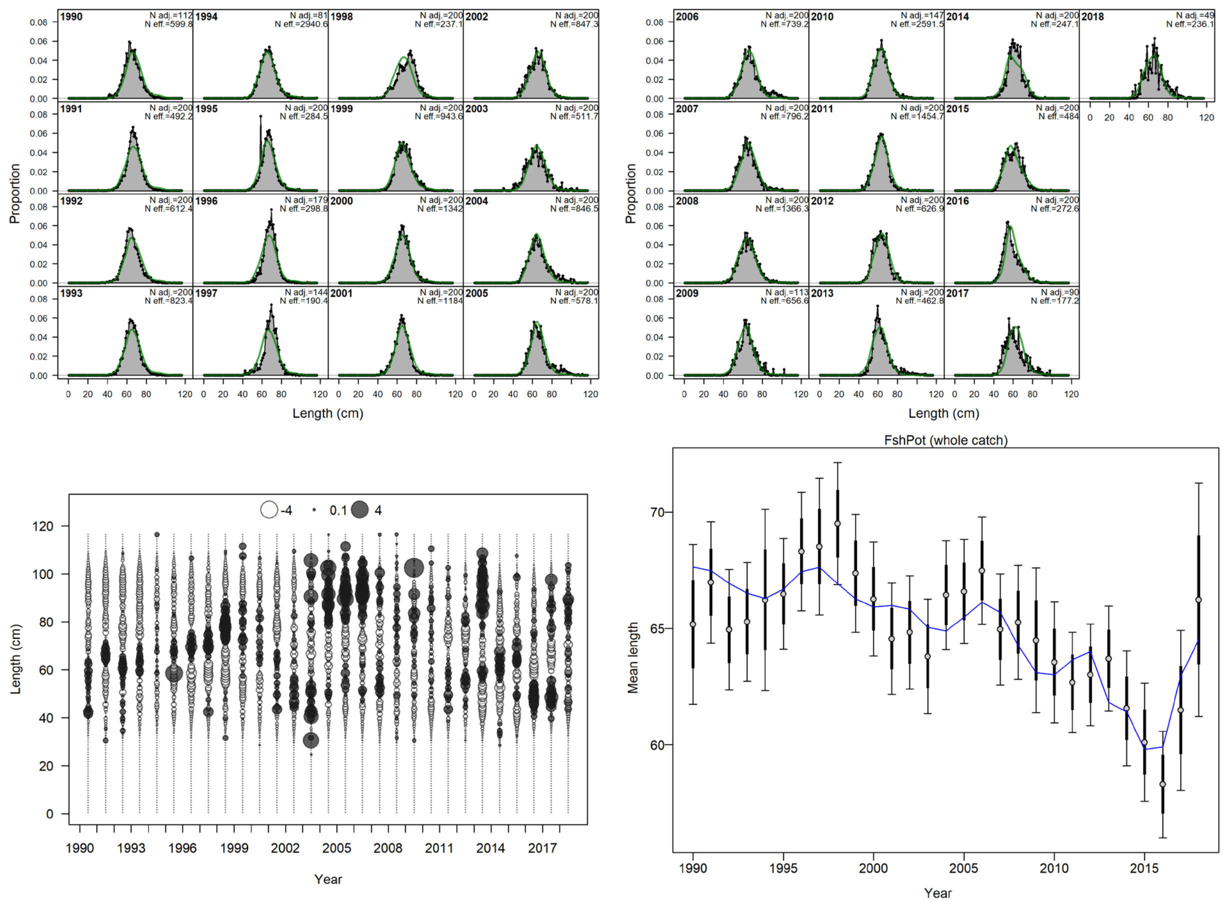

Figure 11. Pot fishery length composition and fits (green line)), standardized residuals, and mean length with model fit (blue line).

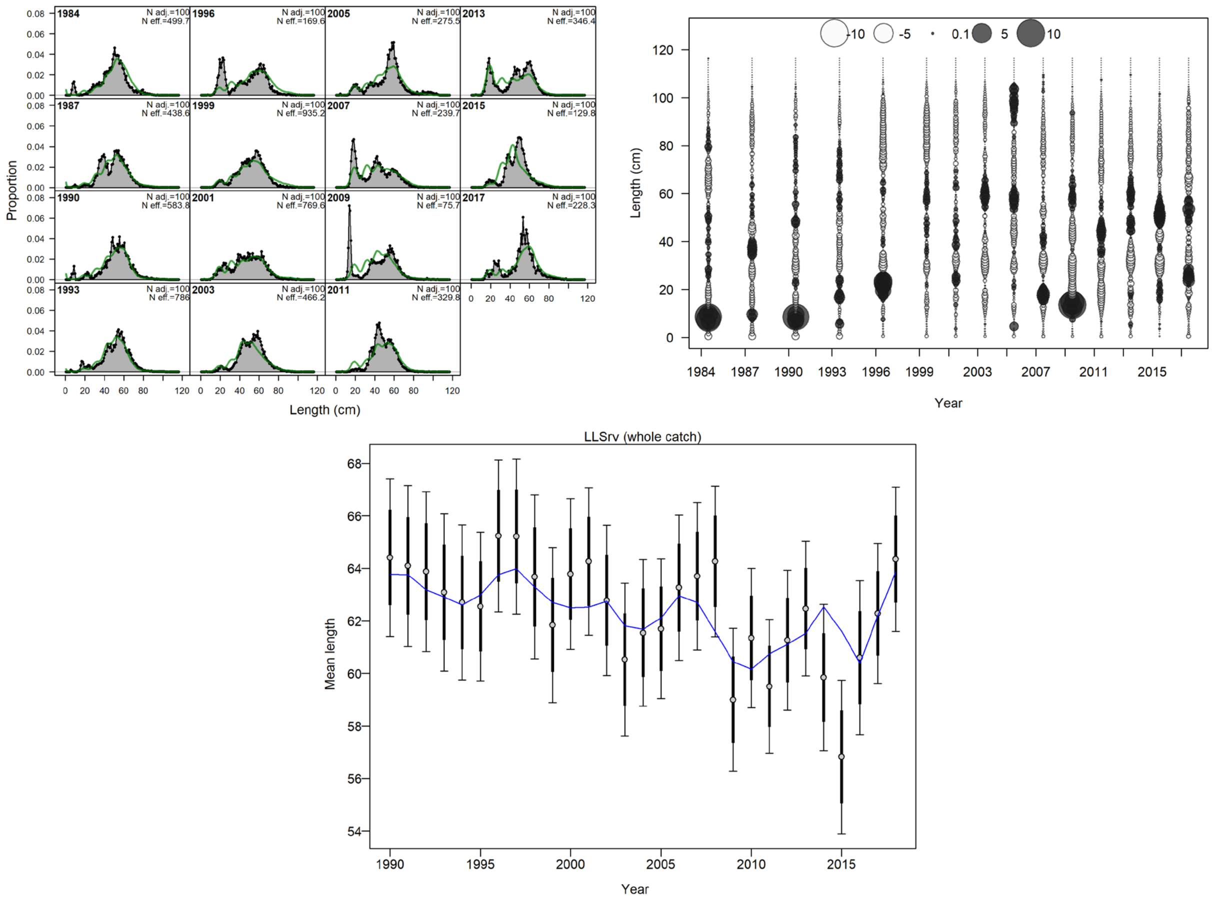

Figure 12. AFSC bottom trawl length composition and fits (green line), standardized residuals, and mean length with model fit (blue line).

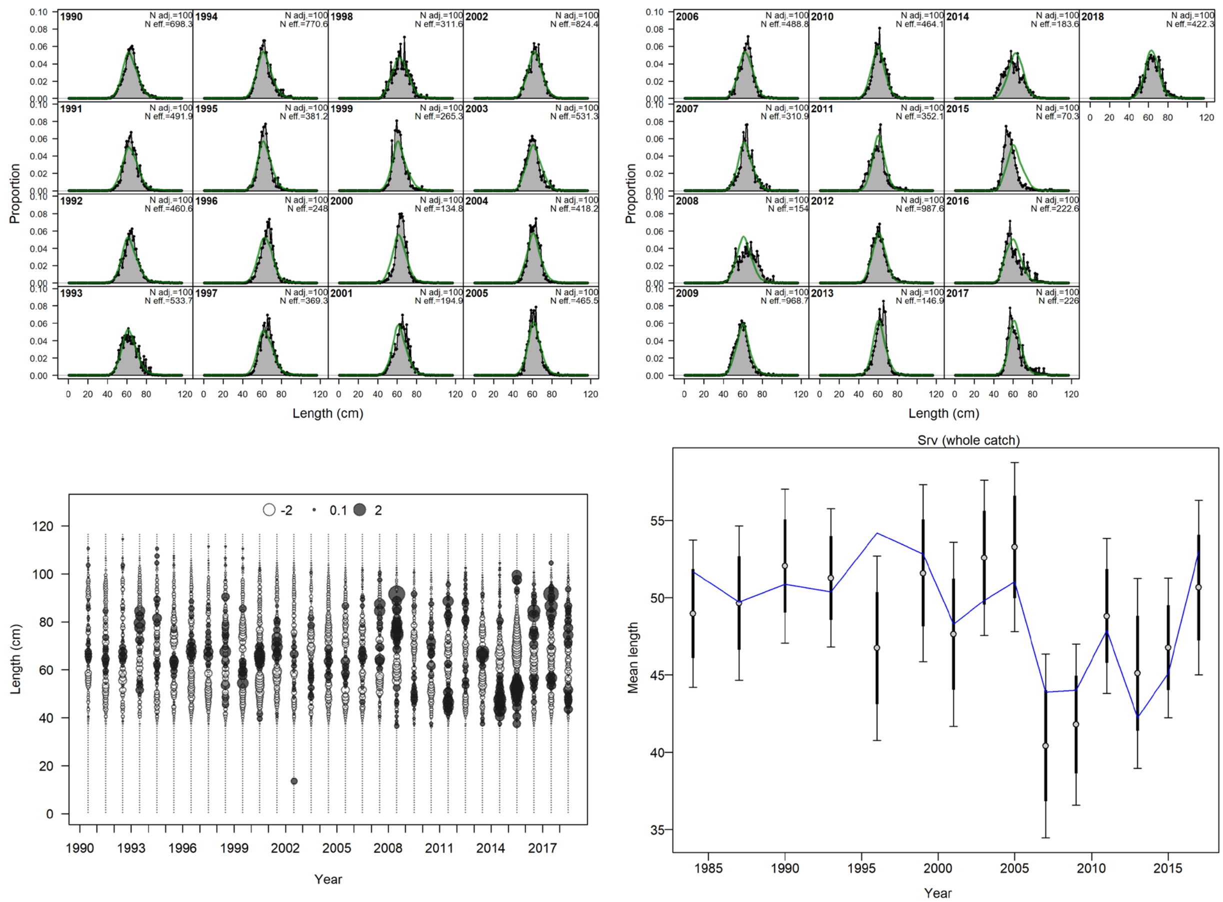

Figure 13. AFSC longline length composition and fits (green line), standardized residuals, and mean length with model fit.

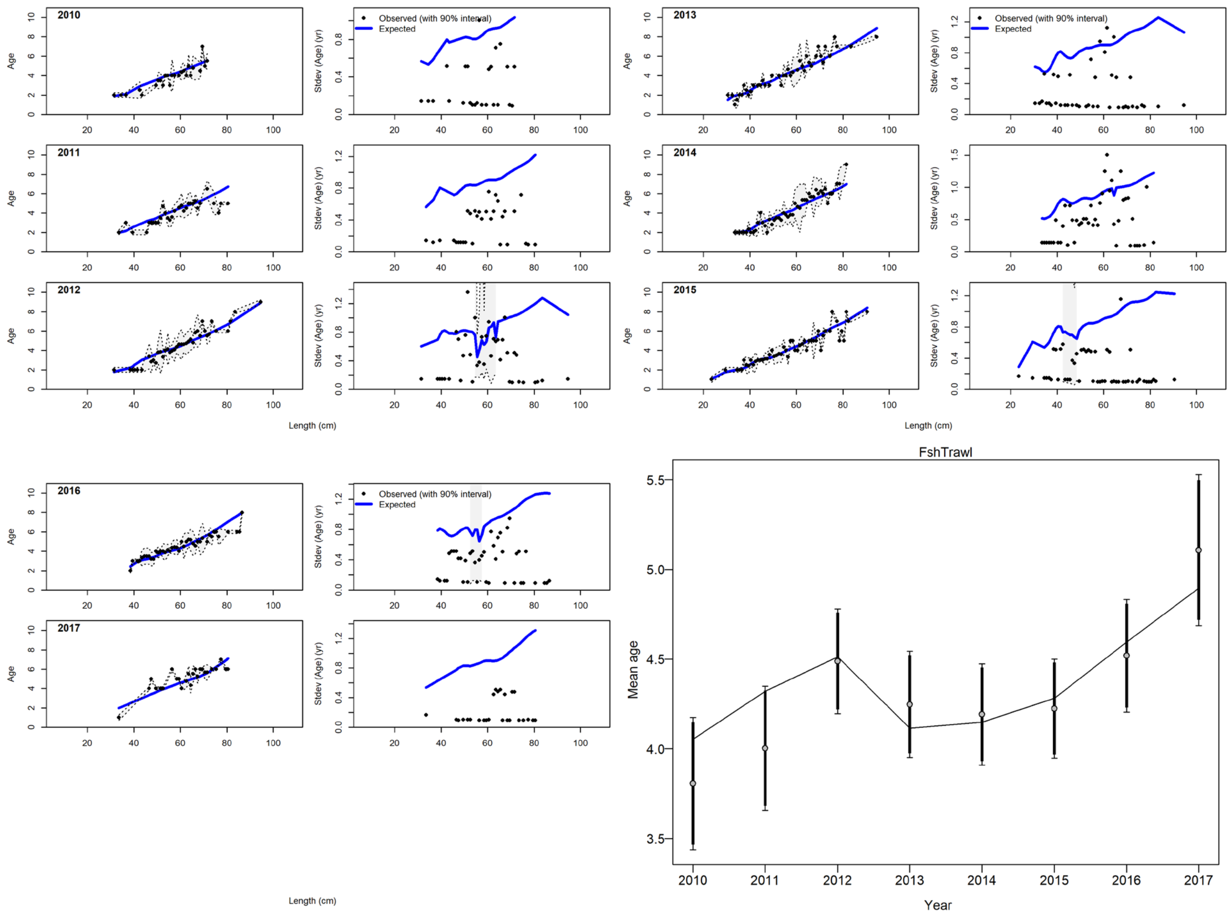

Figure 14. Trawl fishery conditional age-at-length with model fits and mean age.

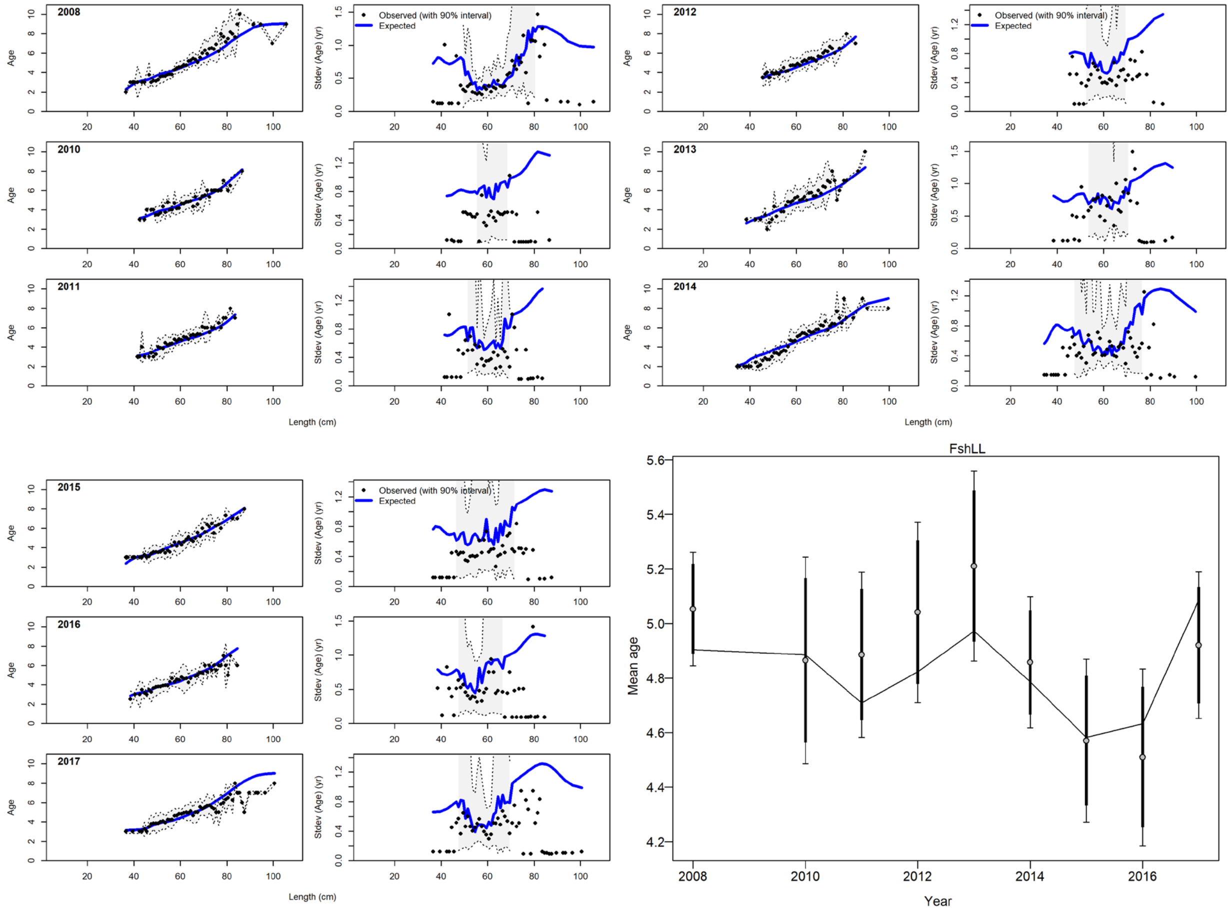

Figure 15. Longline fishery conditional age-at-length with model fits and mean age.

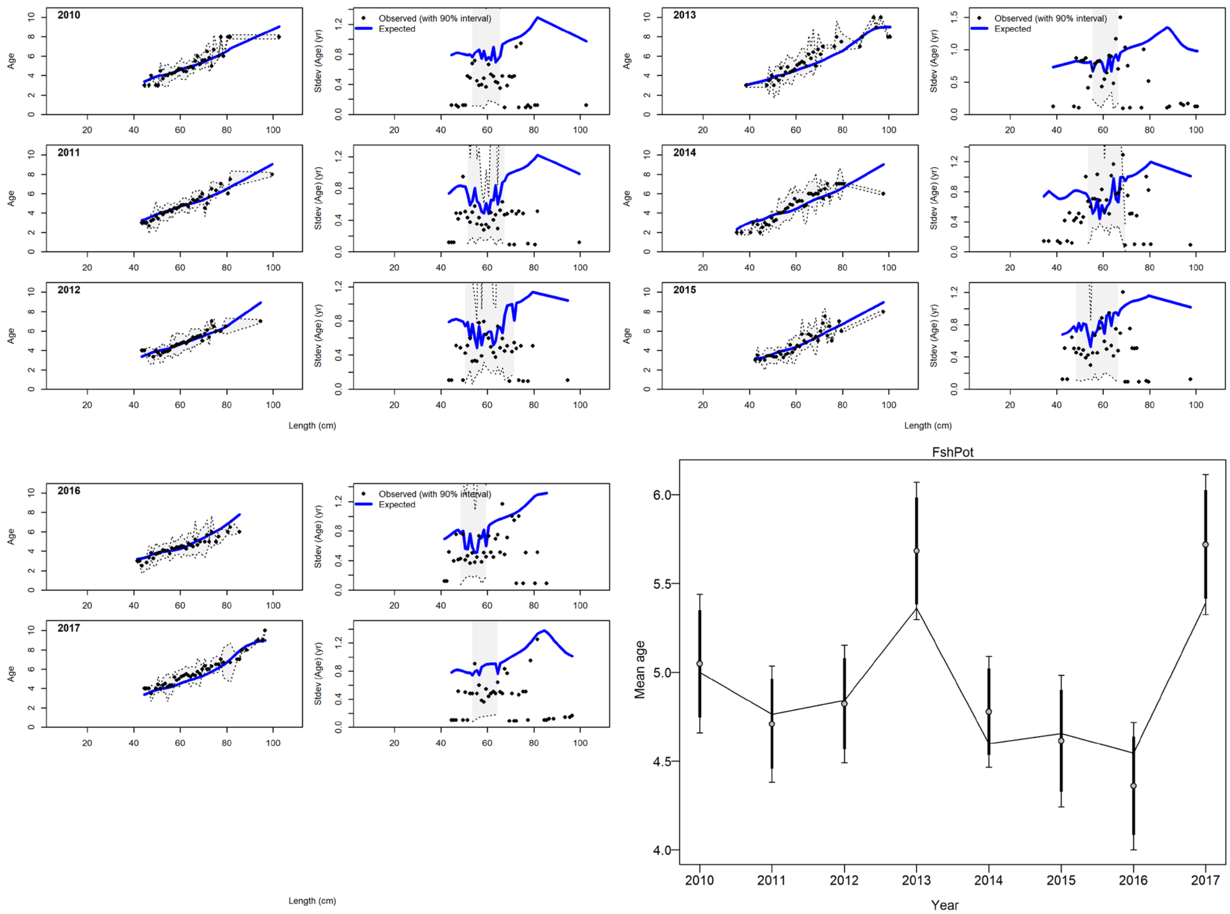

Figure 16. Pot fishery conditional age-at-length with model fits and mean age.

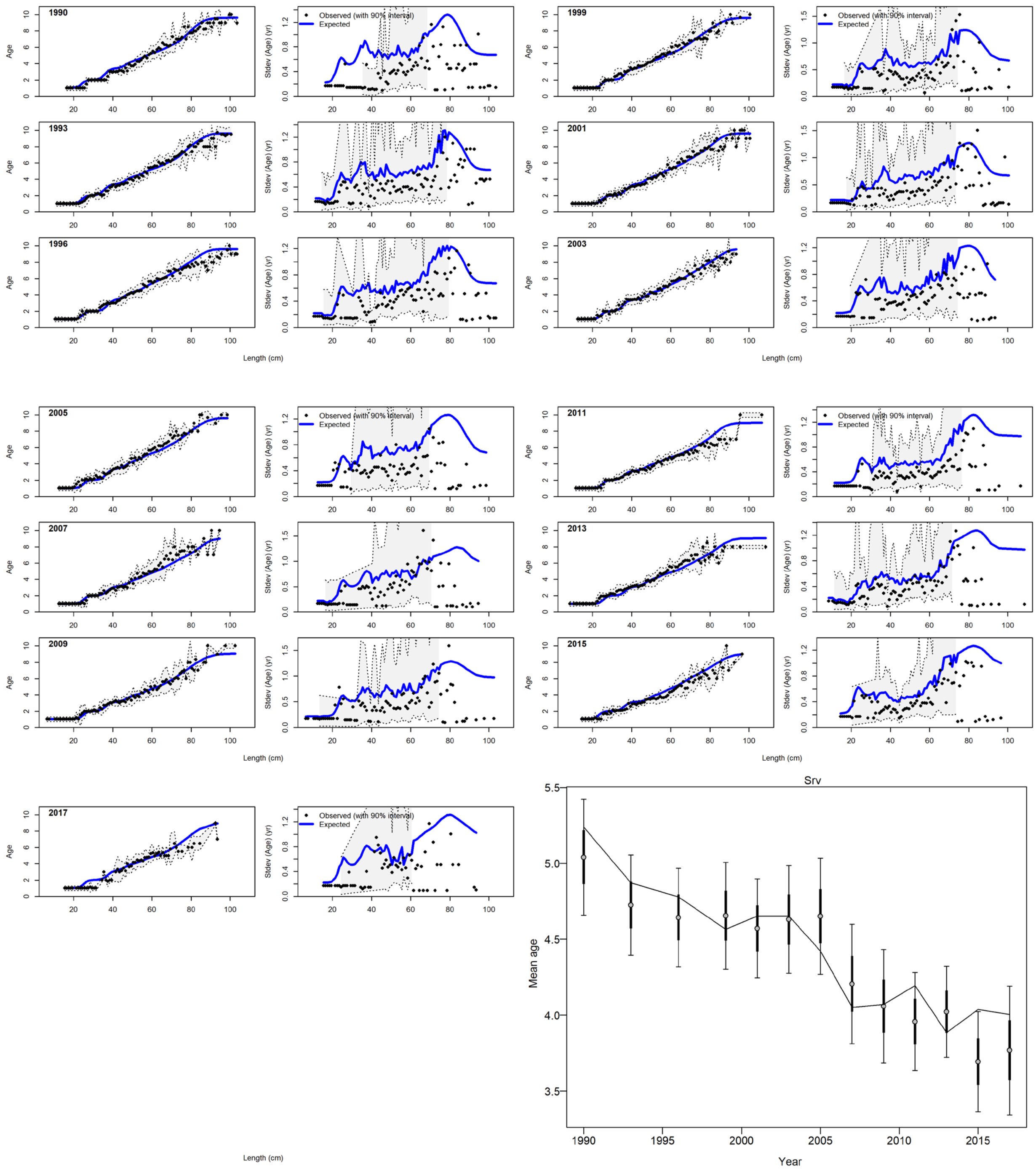

Figure 17. AFSC bottom trawl survey conditional age-at-length with model fits and mean age.

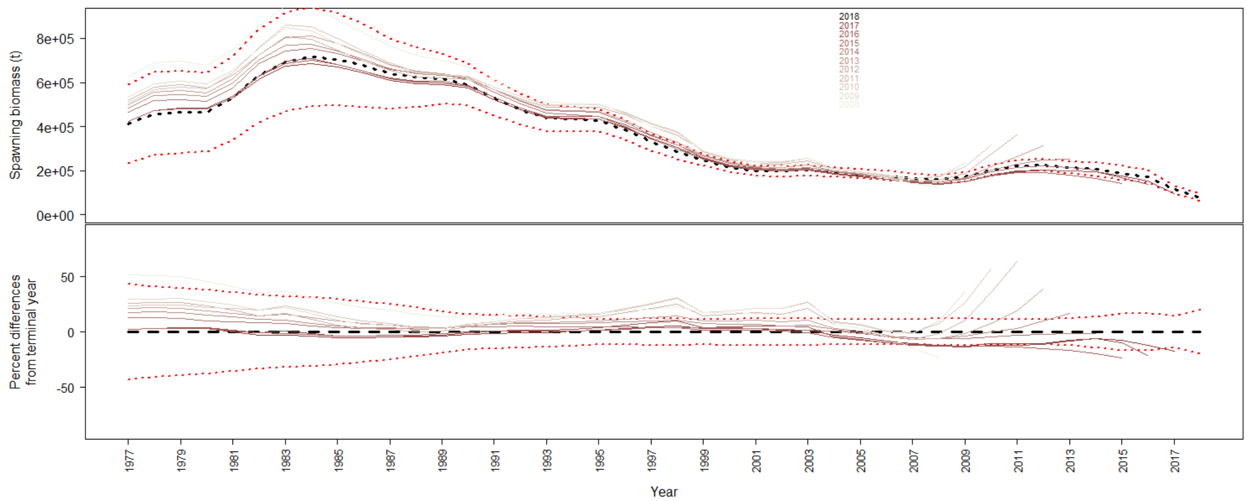

Figure 18. Spawning biomass (upper) and percent difference from terminal year (lower) from retrospective analysis.

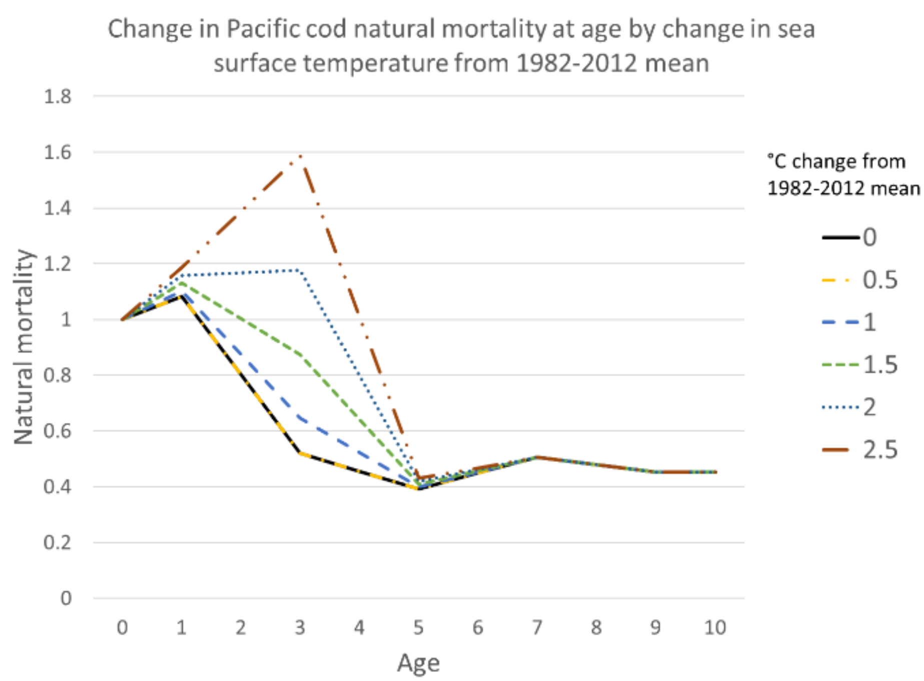

Figure 19. Natural mortality by age by change in temperature from the 1982-2012 mean.

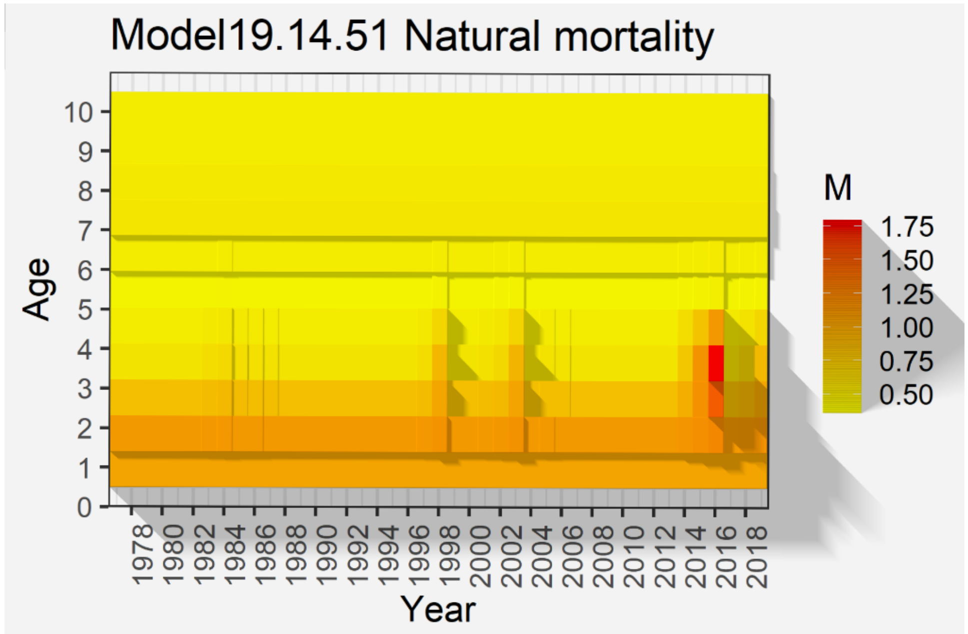

Figure 20. Natural mortality at age by year.

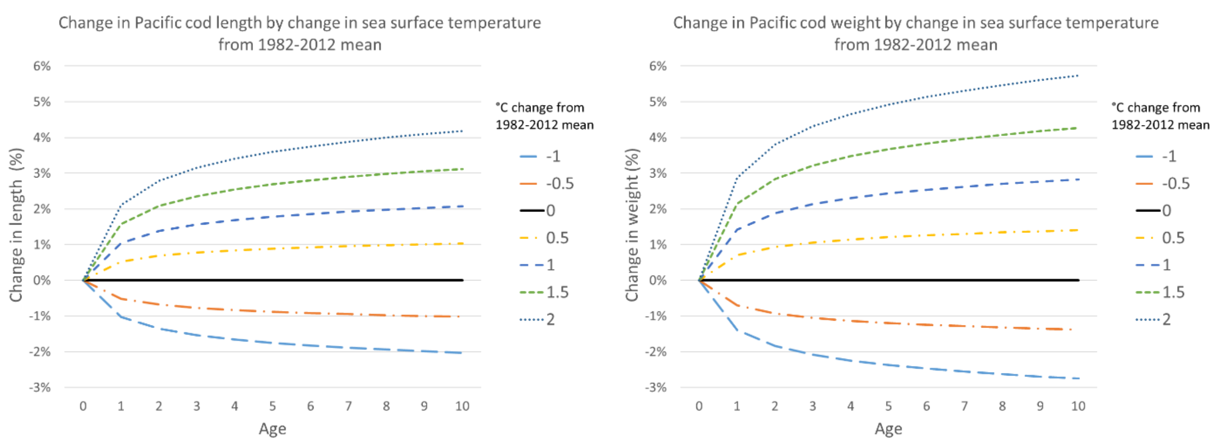

Figure 21. Change in length (left) and weight (right) by change in sea surface temperature from the 1982-2012 mean as a percentage of 0 °C change.

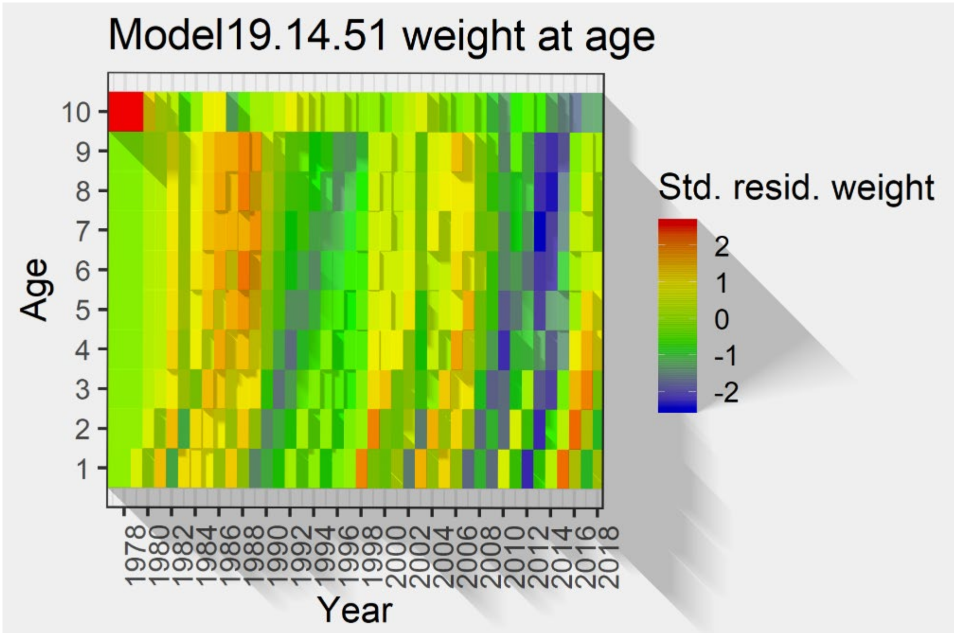

Figure 22. Standardized residuals of weight at length by year.

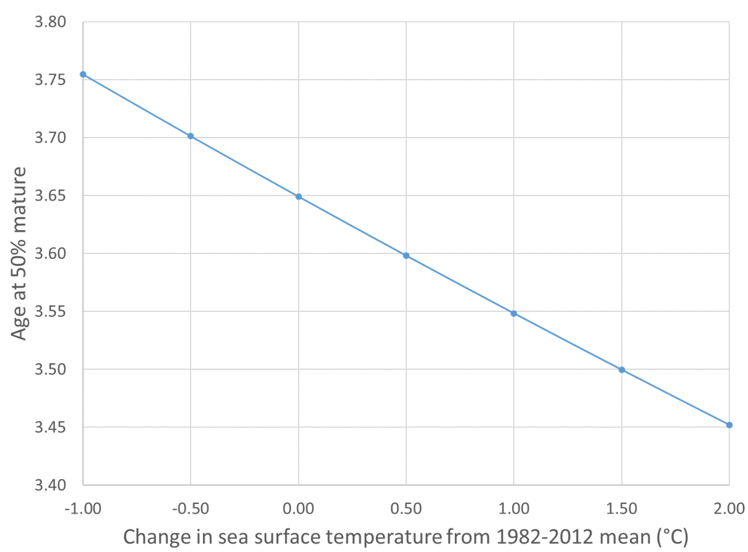

Figure 23. Age at 50% mature by change in sea surface temperature from the 1982-2012 mean in Model 19.14.51

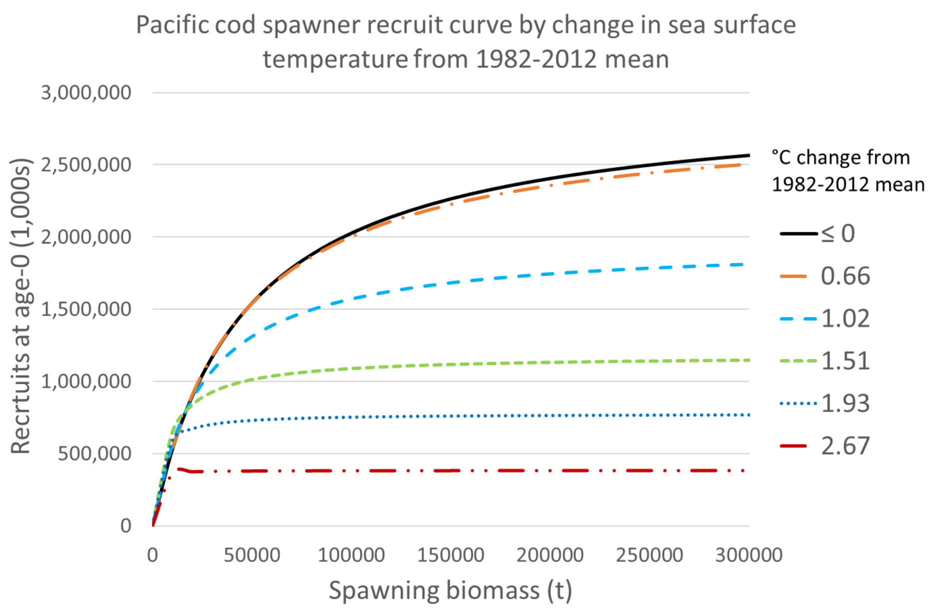

Figure 24. Beverton-Holt stock-recruit curves as a function of change in sea surface temperature for Model 19.14.51.

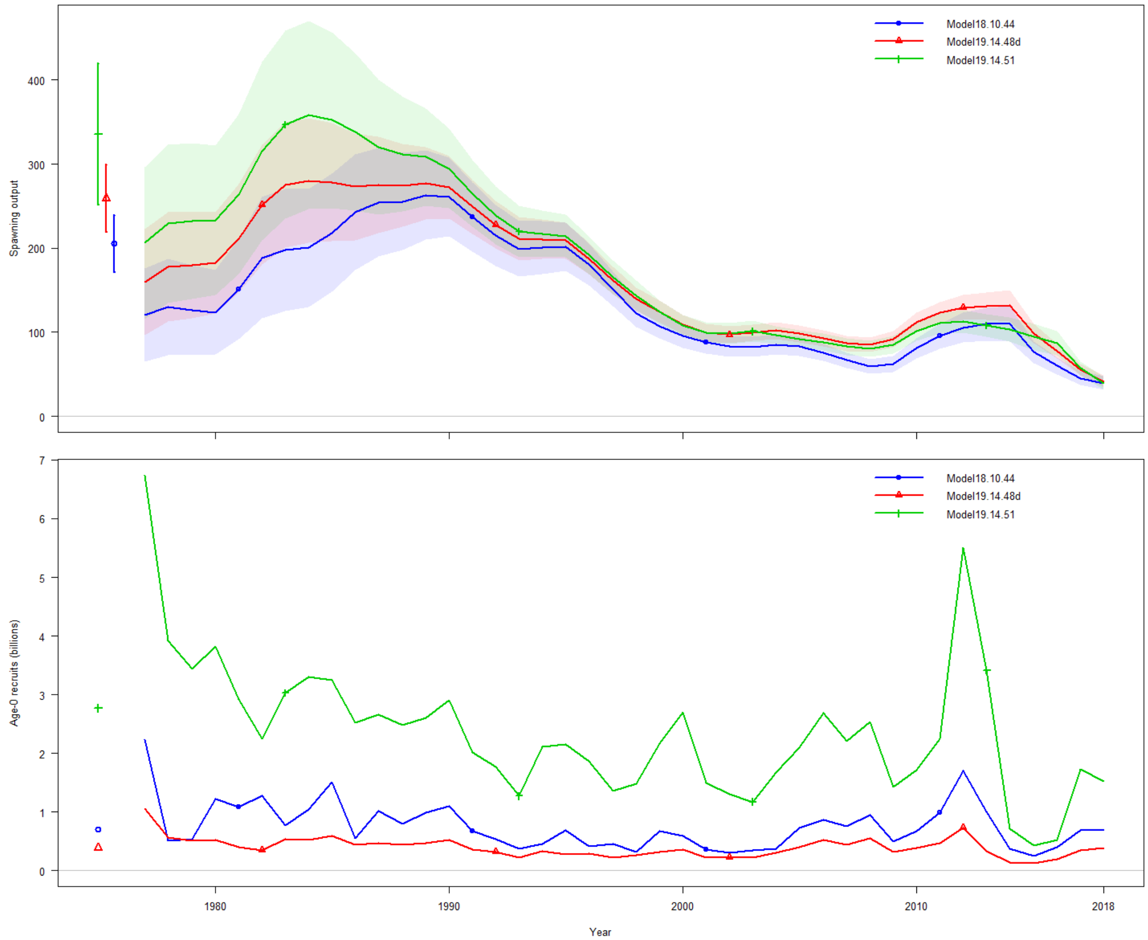

Figure 25. Female spawning biomass (1000's tons; upper) and age-0 recruitment (lower) for models 18.10.44, 19.14.48d, and 19.14.51.

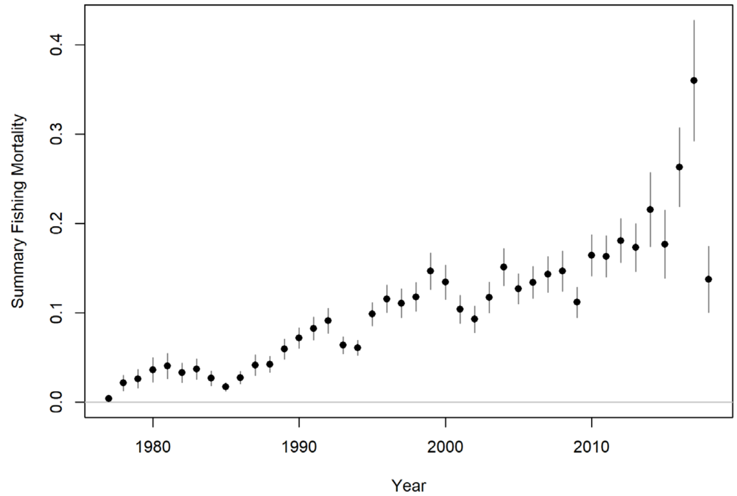

Figure 26. Fishing mortality at ages 3-8 under model 19.14.51.

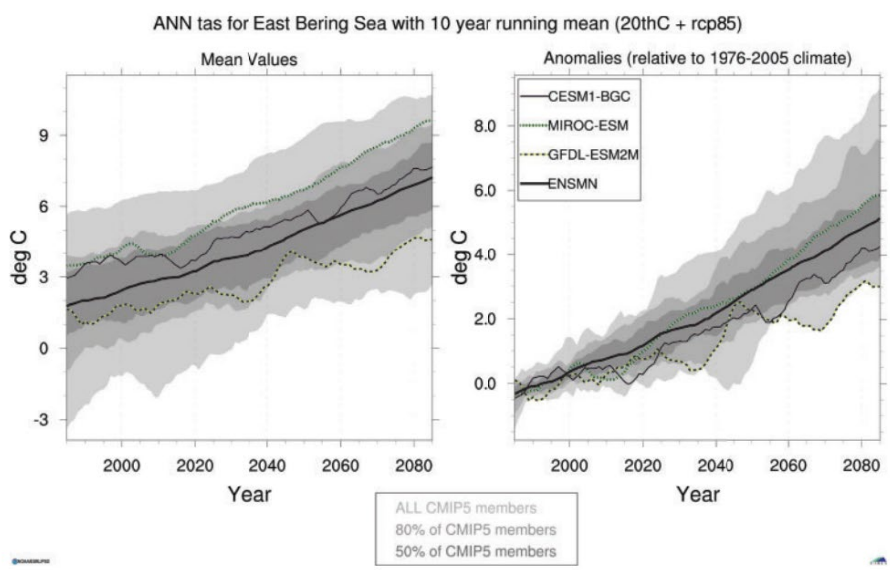

Figure 27. Characterization of the chosen ensemble members for the Bering Sea, relative to other CMIP5 models. Left panel: low-passed (10-year running mean), spatially averaged air temperature for the eastern Bering Sea from CMIP5 members under RCP8.5, from 1976 through 2080, obtained from the NOAA climate change web portal (https://www.esrl.noaa.gov/psd/ipcc/cmip5/). Ensemble mean of all CMIP5 models (ENSMN) is shown along with individual trajectories of CESM, MIROC, and GFDL models. Light grey, medium grey, and dark grey illustrate the range of: 100% of CMIP5 members, 80% of CMIP5 members nearest to ensemble mean, and 50% of CMIP5 members nearest to ensemble mean, respectively. Right panel illustrates temperature change relative to individual model climatologies during 1976–2005 from Hermann et al. 2019 Figure 2.

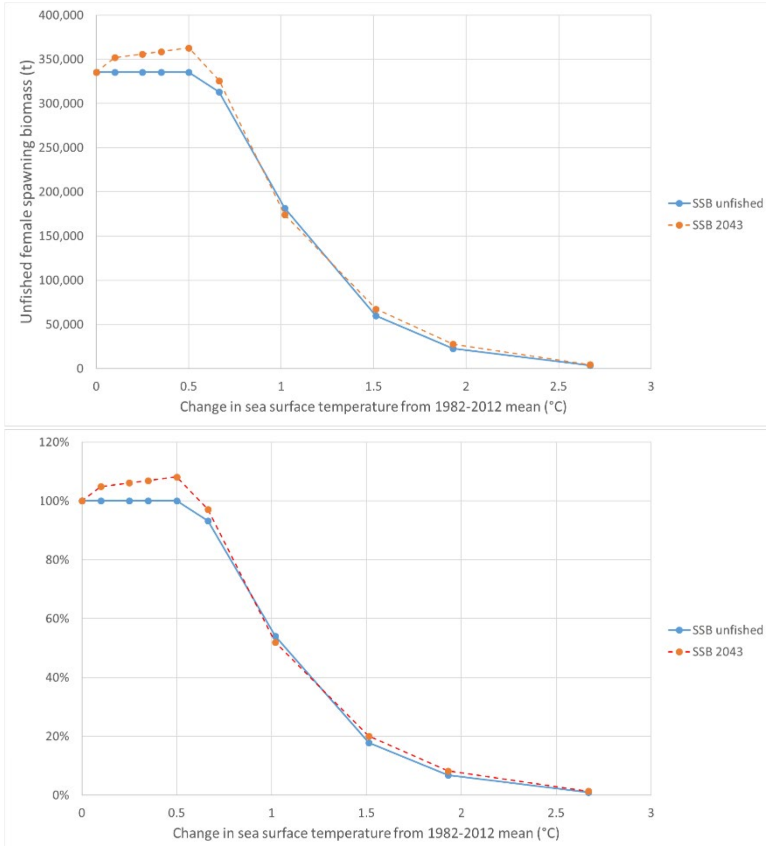

Figure 28. Unfished female spawning biomass and forecast female spawning biomass in 2043 with no catch from 2019-2043 (upper) and percent change from 1977-2015 unfished biomass (lower) with projected changes in sea surface temperature above the 1982-2012 mean. This was produced with a given static temperatures from 2019-2043.

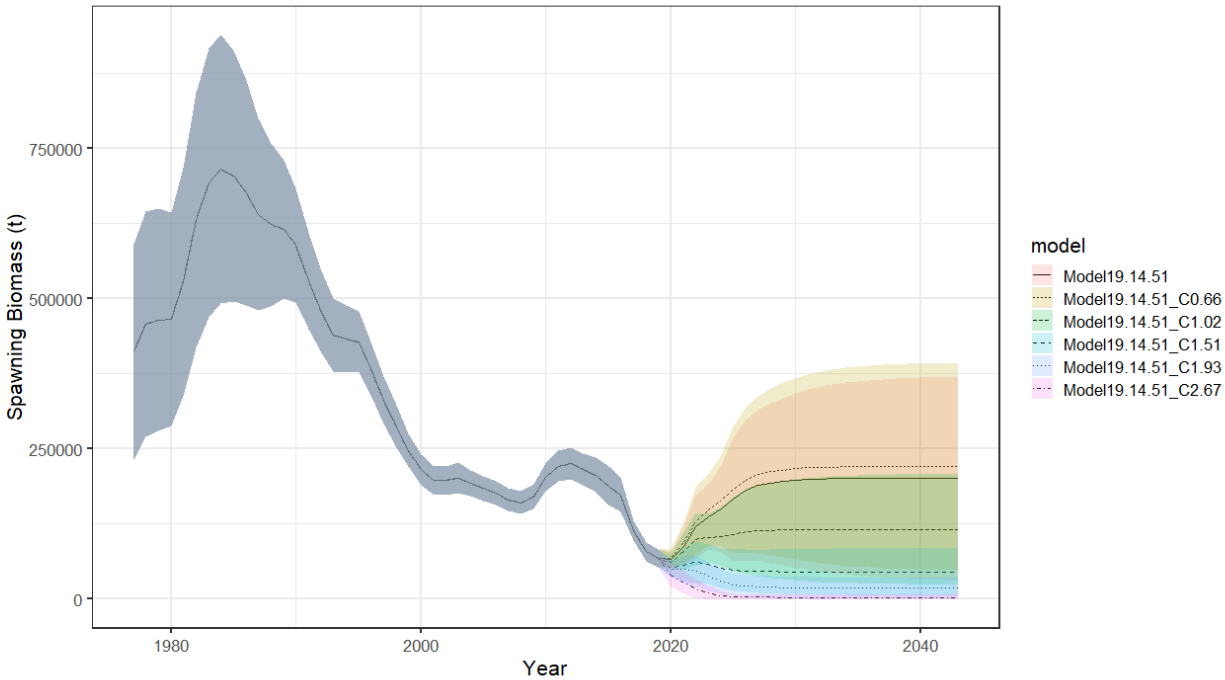

Figure 29. Projection of spawning biomass over different static increases in sea surface temperature (0, 0.66. 1.02, 1.51, 1.93, and 2.67 °C) using dynamic unfished spawning biomass for determining reference points and fishing at F35% and assuming average recruitment under the different static temperature scenarios.

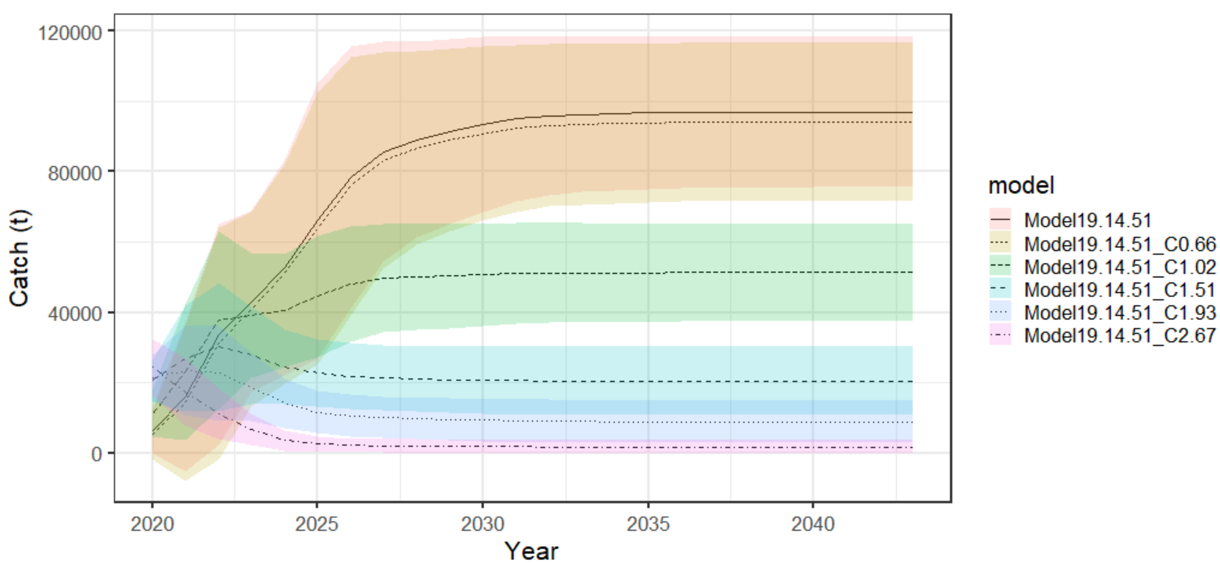

Figure 30. Projection of total catch over different static increases in sea surface temperature (0, 0.66. 1.02, 1.51, 1.93, and 2.67 °C) using dynamic unfished spawning biomass for determining reference points and fishing at F35% and assuming average recruitment under the different static temperature scenarios.