2. Assessment of the Pacific cod stock in the Gulf of Alaska

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Executive Summary

Summary of Changes in Assessment Inputs

Relative to last year's assessment, the following changes have been made:

Changes in the input data

1. Federal and state catch data for 2016 were updated and preliminary federal and state catch data for 2017 were included;
2. Commercial federal and state fishery size composition data for 2016 were updated, and preliminary commercial federal and state fishery size composition data for 2017 were included;
3. AFSC bottom trawl survey abundance index and length composition data for 2017 were included;
4. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2017 were included;
5. An alternative method for estimating fishery catch-at-length data was explored for data post-1990;
6. Length composition data from ADF&G port sampling program were used to augment pot fishery catch composition data where observer data were missing.

Changes in the methodology

Last year Model 17.08.25 was accepted for management advice and here is presented with new 2017 survey and fishery data. Four additional models are presented based on presentations made in September 2017 (see appendix). Details of differences are shown in the section "Analytic approach." These models vary in the specification of the prior distribution for natural mortality and survey catchability, and slight modifications how periods for constant selectivity were specified.

All proposed models presented were single sex age-based models with length-based selectivity. The models have data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the Auke Bay Longline survey indices). Length composition data were available for all three fisheries and both indices. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was parameterized as a standard Beverton-holt with steepness fixed at 1.0 and sigma R at 0.44. All selectivities were fit using six parameter double-normal selectivity curves.

Model 17.08.25 continued to perform well and is most consistent with last year's model.

Summary of Results

The addition of the new method for estimating the fishery catch-at-lengths and applying ADF&G port sampling data in the pot fishery made only a small difference in model results and was an improvement of how estimates were derived. Model 17.09.35 provided the best fit to the data represents a balance between acknowledging a mortality event (with *M* changing in 2015-2016) and overfitting survey data. Also, this model performed well in retrospective analyses. This recommended model configuration differs from the 2016 Model in allowing natural mortality to change for 2015 and 2016. It also adds a feature that allows the catchability in the AFSC longline RPN index to be conditioned on water temperature.

Based on projections with this model, a reduction of the ABC below maximum permissible ABC to 18,000 t in 2018 and 17,000 t in 2019 is proposed because doing so increases the estimated probability (to roughly 50%) that the stock will be above the 20% of unfished for 2019 and 2020. Results are summarized below:

Quantity	As estimated or *specified last* year for:		As estimated or *specified this* year for:	
	2017	2018	2018	*2019
M (natural mortality rate)	0.47	0.47	0.49	0.49
Tier	3a	3a	3b	3b
Projected total (age 0+) biomass (t)	426,384	428,885	170,565	198,942
Female spawning biomass (t)				
Projected	91,198	98,479	36,209	34,424
$B_{100\%}$	196,776	196,776	168,583	168,583
$B_{40\%}$	78,711	78,711	67,433	67,433
$B_{35\%}$	68,872	68,872	59,004	59,004
F_{OFL}	0.652	0.652	0.42	0.40
$maxF_{ABC}$	0.530	0.530	0.34	0.32
F_{ABC}	0.530	0.530	0.31	0.31
OFL (t)	105,378	94,188	23,565	21,412
maxABC (t)	88,342	79,272	19,401	17,634
ABC (t)	88,342	79,272	**18,000	**17,000
Status	As determined *this* year for: 2015	2016	2016	2017
Overfishing	no	n/a	No	n/a
Overfished	n/a	no	n/a	No
Approaching overfished	n/a	no	n/a	No

* All 2019 values based on 2018 catch of 18,000 t.
** Reduction from max to 18,000 t and 17,000 t to maintain stock above $B_{20\%}$ in 2019 and 2020 based on estimated end of year catch in 2017 of 48,940 t.

Area apportionment

In 2012 the ABC for GOA Pacific cod was apportioned among regulatory areas using a Kalman filter approach based on trawl survey biomass estimates. In the 2013 assessment, the random effects model (which is similar to the Kalman filter approach, and was recommended in the Survey Average working group report which was presented to the Plan Team in September 2013) was used; this method was used for the ABC apportionment for 2014. The SSC concurred with this method in December 2013. Using this method with the trawl survey biomass estimates through 2017, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	44.9%	45.1%	10.0%	100%
2018 ABC	8,082	8118	1,800	18,000
2019 ABC	7,633	7,667	1,700	17,000

Responses to SSC and Plan Team Comments Specific to this Assessment

November 2016 Plan Team

The Team recommends that the author examine and incorporate where possible relevant data from the IPHC and ADFG surveys. Specific to the ADFG survey, the Team recommended coordinating with planned studies for alternative evaluation of these data to develop a refined index for pollock.

> *ADFG were revamping their database and survey data were not available until mid-October 2017. This was too late to formally incorporate these data into this year's assessment. Similarly, the IPHC survey time series was not obtained until mid-October, again too late to formally add the data to the assessment model and have it vetted properly. Both these surveys were examined and will be described in this assessment. The IPHC survey matches the bottom trawl survey index and is particularly close for 2006-2016.*

The Team recommends that fishery otoliths be aged to support this stock assessment and this should include resolving past data which may have been subjected to biased age-determination methods. In particular, the Team recommends that the otoliths used in the Stark 2007 maturity-at-age study be re-evaluated for potential bias in the age-determination method used.

> *The Stark (2007) otoliths were marked as "critical" in the prioritization process, but were not read due to the volume of requested otoliths. The fishery otoliths were marker as "High" priority this year and also were not read. Both these collections have now been upgraded to "Critical." The 2015 and 2016 fishery otoliths have been read, but were not completed until the second week of October, too late to be incorporated into this assessment. However, they will be described.*

December 2017 SSC

The SSC noted that the estimated value for M in the author's preferred model was 0.47, using a prior with a mean of 0.38 and a CV of 0.1. A number of studies were referenced suggesting a range of M that is potentially broader than implied by the current prior. All three Pacific cod assessments could benefit from a consistent formal prior on M based on the variety of studies referenced in each. The SSC recommends that a prior for use in all Pacific cod assessments be developed for 2017 and explored for use in the GOA Pacific model.

> *Models were explored this year using a prior for M developed by Grant Thompson for the EBS cod stock (see Thompson et al. 2017), lognormal with a mean of -0.81 and cv of 0.42.*

The SSC recommends that ageing additional fishery otoliths for this assessment be a priority, noting that the AFSC has an ongoing ageing-prioritization analysis which may guide their future efforts, and the author has recommended working with the age and growth lab on this project. Along these lines, ages underlying the study defining current maturity schedules (Stark, 2007) should be re-aged, and the data re-analyzed in light of recent information regarding ageing bias (i.e., Kastelle et al., 2017).

> *The Stark (2007) otoliths were marked as "critical" in the prioritization process, but were not read due to the volume of requested otoliths. The fishery otoliths were marker as "High" priority this year and also were not read. Both these collections have now been upgraded to "Critical."*

The 2015 and 2016 fishery otoliths have been read, but were not completed until the second week of October, too late to be incorporated into this assessment. However, they will be described.

Aging bias should be explicitly included in the next assessment.

Aging error was explored in several model configurations. There appears to be performance issues when implemented that needs additional work before a model with aging error should be accepted for management. Aging error was not included in the suite of models presented this year, but is marked as a high priority next year. The authors are currently working with the Age and Growth program at the AFSC to develop aging error and aging bias alternatives for the stock synthesis model.

Introduction

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, occurring at depths from shoreline to 500 m. The southern limit of the species' distribution is about 34° N latitude, with a northern limit of about 63° N latitude. Pacific cod is distributed widely over Gulf of Alaska (GOA), as well as the eastern Bering Sea (EBS) and the Aleutian Islands (AI) area. Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the EBS, AI, and GOA. Recent research indicates the existence of discrete stocks in the EBS and AI (Canino et al. 2005, Cunningham et al. 2009, Canino et al. 2010, Spies 2012). Pacific cod is not known to exhibit any special life history characteristics that would require it to be assessed or managed differently from other groundfish stocks in the GOA and the Pacific cod stock in the GOA is managed as a single stock.

Review of Life History

The Aleut word for Pacific cod, *atxidax*, literally translates to "the fish that stops" (Betts *et al.* 2011). Recoveries from archeological middens on Sanak Island in the Western GOA show a long history (at least 4500 years) of exploitation. Over this period, the archeological record reveals fluctuations in Pacific cod size distribution which Betts *et al.* (2011) tie to changes in abundance due to climate variability (Fig. 2.1). Over this long period colder climate conditions appear to have consistently led to higher abundance with more small/young cod in the population and warmer conditions to lower abundance with fewer small/young cod in the population.

In the Gulf of Alaska, adult Pacific cod exhibited an annual cycle of condition, gonad index and liver index in which maximum values occur in ripe fish in March and minima in July. About 30–31 % of pre-spawning stored energy is expended during spawning. The energy associated with spawning derived from liver (24% and 18%), somatic tissue (22% and 33%) and gonad (53% and 48%) for females and males, respectively (Smith *et al.* 1990). The Pacific cod is similar to the Atlantic cod (*Gadus morhua*) in terms of energy cycling, maximum gonad sizes, energy expended during spawning and gonadal contribution to energy expenditure. However, in Pacific cod, somatic tissue contributes markedly to energy expended during reproduction. The Pacific cod differs from the walleye pollock (*Gadus chalcogrammus*) in that Pacific cod have a lower gonad index for females, but far higher for males, lose less weight than pollock during spawning, but spend more energy spawning than pollock with a loss of liver energy. This is evident in differences in gonad index (13% and 20% vs. 20% and 8% for females and males, respectively), spawning weight loss (25% vs. 38%), liver energy loss during spawning (71% vs. 55%) and energy cost of spawning (Smith *et al.* 1990). Total fecundity for Pacific cod is extremely high (Doyle and Mier, 2016) and spawning takes place in the sublittoral-bathyal zone (40 to 290 m) near bottom in late winter to early spring (Stark, 2007).

Pacific cod eggs are deposited in one batch and sink to the bottom after fertilization where they are adhesive and remain negatively buoyant (Matarese et al., 1989, Hurst et al., 2009). Eggs hatch in about 15 to 20 days. Temperature is suggested to be of major importance to successful egg development in the natural environment (Alderdice and Forrester 1971). Optimal temperature for incubation is 3° to 6°C, optimal salinity is 13 to 23 parts per thousand (ppt), and optimal oxygen concentration is from 2 to 3 ppm to saturation. Little is known about the optimal substrate type for egg incubation.

Pacific cod hatch at about 3-4 mm and immediately orient toward the surface (Laurel et al., 2008). Larvae are pelagic, occurring primarily in the upper 45 m of the water column shortly after hatching, moving downward in the water column as they grow. Larvae being diel migration after flexion at about 10 to 17 mm and undergo metamorphosis at about 25 to 35 mm (Hurst et al, 2009; Ichthyoplankton Information System, 2016). There appears to be a connection between water temperature and larval production where cold sea surface temperatures are more likely to have high larval abundance while warm sea surface temperatures more often result in low larval abundance (Doyle and Mier 2016, Table 2; Fig. 2.2 and Fig. 2.3). In Pacific cod, it appeared that temperature plays an important role in growth potential during the pre-feeding larval stage. Pacific cod larvae do not achieve the same amount of growth at warm temperatures (i.e. 6–8°C) compared to cooler temperatures (i.e. 0–4°C), even though growth rates are higher at warmer temperatures. There also appears to be a strong positive connection between mean larval length and sea surface temperature, particularly in April through May when larvae are at their peak abundance (Doyle and Mier, 2016). However, mortality of larvae is higher at warmer temperatures (Laurel *et al.* 2008). It should, therefore, be noted that high larval abundance may not equate to high recruitment at older ages, conditions between the larval stage and recruitment must also be favorable. For example, because temperatures were lower, production of larval and juvenile cod was high in 2013. However, mean standard length of larvae in 2013 was smaller than 2011 even though production of larval and juvenile cod was much lower than 2013 (Siddon et. al, 2016). Strong westward advection and a low zooplankton prey base may have made ecosystem conditions unfavorable and may not have supported overwinter survival and ultimately recruitment at older ages was poor for the 2013 year class. While faster growth and shorter duration in the water column for Pacific cod in 2011 and access to an earlier spring bloom, may have allowed some resilience to the overall poor 2011 conditions, resulting in an average 2011 year class (Doyle and Mier, 2016; Strom et. al., 2016). In 2015 with the highest sea surface temperatures recorded during a larval survey occurred and very few larvae or juvenile cod were encountered. These findings suggest a dome shaped relationship between larval survival in the spring, and subsequent sustained access to prey resources needed for growth and overwintering.

The settlement transition for Pacific cod is poorly understood but generally thought to be relatively early due to the general lack of individuals larger than 15 mm in the ichthyoplankton surveys and presence of 35 to 50 mm sizes individuals in nearshore trawl surveys during mid-July (Doyle and Mier 2016, Laurel et al., 2016). Older juveniles occur mostly over the inner continental shelf at depths of 60 to 150 m. Adults occur in depths from the shoreline to 500 m, although occurrence in depths greater than 300 m is fairly rare. Preferred substrate is soft sediment, from mud and clay to sand. Average depth of occurrence tends to vary directly with age for at least the first few years of life, going deeper with age. In the GOA trawl survey, the percentage of fish residing in waters less than 100 m tends to decrease with length. The GOA trawl survey also indicates that fish occupying depths greater than 200 m are typically in the 40-90 cm range. Temperature also plays a role in adult distribution where the center of abundance shift to deeper water in years with warmer than average bottom temperatures (Fig. 2.4) and could result in a change of catchability and/or selectivity to bottom trawl or longline sampling gear.

Metabolic demands for ectothermic fish like Pacific cod, are largely a function of thermal experience and tend to increase exponentially with increasing temperatures. Fish can minimize metabolic costs through behaviors such as movement to thermally optimal temperatures, or can increase consumption of food energy to meet increasing metabolic demands. The latter requires sufficient access to abundant or high energy prey resources. However, in a laboratory study on age 1+ Pacific cod, juveniles exhibited a predisposition for heightened lipid synthesis at colder temperatures and higher growth rates at lower rations. This energy allocation strategy is thought to facilitate specific physiological needs such as oxygen transport, digestive ability, assimilation efficiency, and nutrient utilization (Sreenivasan and Heintz, 2016). Food habits data show a transition for Pacific cod from pelagic zooplankton and epifauna between 0 to10 cm, to an increasing proportion of shrimp, forage fish, and commercial crab between 15 and 60 cm, then an increasing reliance on pollock and other fish at greater than 60 cm (Fig. 2.5; Livingston *et al.* 2017; data available at https://access.afsc.noaa.gov/REEM/WebDietData/DietDataIntro.php). How these factors impact Pacific cod due to changes in the ecosystem, particularly the impacts of the anomalous warm years of 2014-2016, are better described in the Ecosystem Section below.

Studies on natural mortality in Pacific cod have found a wide range of values (Table 2.1). It is conceivable that mortality rates, both fishing and natural, may vary with age in Pacific cod. In particular, very young fish likely have higher natural mortality rates than older fish (note that this may not be particularly important from the perspective of single-species stock assessment, so long as these higher natural mortality rates do not occur at ages or sizes that are present in substantial numbers in the data).

For example, a Leslie matrix analysis of a Pacific cod stock occurring off Korea estimated the instantaneous natural mortality rate of 0-year-olds at 9.10 yr^{-1} (Jung et al. 2009). This may be compared to a mean estimate for age-0 Atlantic cod (*Gadus morhua*) in Newfoundland of 4.17% per day, with a 95% confidence interval ranging from about 3.31% to 5.03% (Gregory et al. in prep.); and age-0 Greenland cod (*Gadus ogac*) of 2.12% per day, with a 95% confidence interval ranging from about 1.56% to 2.68% (Robert Gregory and Corey Morris, *pers. commun.*). Although little is known about the likelihood of age-dependent natural mortality in adult Pacific cod, Atlantic cod may exhibit increasing natural mortality with age (Greer-Walker 1970). Natural mortality has also been linked to condition in gadids, where low condition at the population level predicts increased natural mortality in mature fish (Dutil and Lambert 1999).

Pacific cod are known to form dense spawning aggregations and to undertake seasonal migrations, the timing and duration of which may be variable (Shimada and Kimura 1994, Savin 2008). At least one study (Ueda et al. 2006) indicates that age-2 Pacific cod may congregate more, relative to age-1 Pacific cod, in areas where trawling efficiency is reduced (e.g., areas of rough substrate), causing their selectivity to decrease. Also, Atlantic cod have been shown to dive in response to a passing vessel (Ona and Godø 1990), which may complicate attempts to estimate catchability or selectivity. It is not known whether Pacific cod undertake a similar response.

Fishery

General description

During the two decades prior to passage of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1976, the fishery for Pacific cod in the GOA was small, averaging around 3,000 t per year. Most of the catch during this period was taken by the foreign fleet, whose catches of Pacific cod were usually incidental to directed fisheries for other species. By 1976, catches had increased to 6,800 t. Catches of Pacific cod since 1991 are shown in Table 2.2; catches prior to that are listed in Thompson et al. (2011). Presently, the Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components. Trawl gear took the largest share of the catch in every year but one from 1991-2002, although pot gear has taken the largest single-gear share of the catch in each year since 2003 (not counting 2017, for which data are not yet complete). Figure 2.6 shows landings by gear since 1977. Table 2.2 shows the catch by jurisdiction and gear type.

The history of acceptable biological catch (ABC) and total allowable catch (TAC) levels is summarized and compared with the time series of aggregate commercial catches in Table 2.3. For the first year of management under the MFCMA (1977), the catch limit for GOA Pacific cod was established at slightly less than the 1976 total reported landings. During the period 1978-1981, catch limits varied between 34,800 and 70,000 t, settling at 60,000 t in 1982. Prior to 1981 these limits were assigned for "fishing years" rather than calendar years. In 1981 the catch limit was raised temporarily to 70,000 t and the fishing year was extended until December 31 to allow for a smooth transition to management based on calendar years, after which the catch limit returned to 60,000 t until 1986, when ABC began to be set on an annual basis. From 1986 (the first year in which an ABC was set) through 1996, TAC averaged about 83% of ABC and catch averaged about 81% of TAC. In 8 of those 11 years, TAC equaled ABC exactly. In 2 of those 11 years (1992 and 1996), catch exceeded TAC.

To understand the relationships between ABC, TAC, and catch for the period since 1997, it is important to understand that a substantial fishery for Pacific cod has been conducted during these years inside State of Alaska waters, mostly in the Western and Central Regulatory Areas. To accommodate the State-managed fishery, the Federal TAC was set well below ABC (15-25% lower) in each of those years. Thus, although total (Federal plus State) catch has exceeded the Federal TAC in all but three years since 1997, this is basically an artifact of the bi-jurisdictional nature of the fishery and is not evidence of overfishing as this would require exceeding OFL. At no time since the separate State waters fishery began in 1997 has total catch exceeded ABC, and total catch has never exceeded OFL.

Changes in ABC over time are typically attributable to three factors: 1) changes in resource abundance, 2) changes in management strategy, and 3) changes in the stock assessment model. Assessments conducted prior to 1988 were based on survey biomass alone. From 1988-1993, the assessment was based on stock reduction analysis (Kimura et al. 1984). From 1994-2004, the assessment was conducted using the Stock Synthesis 1 modeling software (Methot 1986, 1990) with length-based data. The assessment was migrated to Stock Synthesis 2 (SS2) in 2005 (Methot 2005b), at which time age-based data began to enter the assessment. Several changes have been made to the model within the SS2 framework (renamed "Stock Synthesis," or SS3, in 2008) each year since then.

Historically, the majority of the GOA catch has come from the Central regulatory area. To some extent the distribution of effort within the GOA is driven by regulation, as catch limits within this region have been apportioned by area throughout the history of management under the MFCMA. Changes in area-specific allocation between years have usually been traceable to changes in biomass distributions estimated by Alaska Fisheries Science Center trawl surveys or management responses to local concerns. Currently the area-specific ABC allocation is derived from the random effects model (which is similar to the Kalman filter approach). The complete history of allocation (in percentage terms) by regulatory area within the GOA is shown in Table 2.4. Table 2.2 and 2.3 include discarded Pacific cod, estimated retained and discarded amounts are shown in Table 2.5.

In addition to area allocations, GOA Pacific cod is also allocated on the basis of processor component (inshore/offshore) and season. The inshore component is allocated 90% of the TAC and the remainder is allocated to the offshore component. Within the Central and Western Regulatory Areas, 60% of each component's portion of the TAC is allocated to the A season (January 1 through June 10) and the remainder is allocated to the B season (June 11 through December 31, although the B season directed fishery does not open until September 1).

NMFS has also published the following rule to implement Amendment 83 to the GOA Groundfish FMP:

> "Amendment 83 allocates the Pacific cod TAC in the Western and Central regulatory areas of the GOA among various gear and operational sectors, and eliminates inshore and offshore allocations in these two regulatory areas. These allocations apply to both annual and seasonal limits of Pacific cod for the applicable sectors. These apportionments are discussed in detail in a subsequent section of this rule. Amendment 83 is intended to reduce competition among sectors and to support stability in the Pacific cod fishery. The final rule implementing Amendment 83 limits access to the Federal Pacific cod TAC fisheries prosecuted in State of Alaska (State) waters adjacent to the Western and Central regulatory areas in the GOA, otherwise known as parallel fisheries. Amendment 83 does not change the existing annual Pacific cod TAC allocation between the inshore and offshore processing components in the Eastern regulatory area of the GOA.
>
> "In the Central GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, catcher vessels (CVs) less than 50 feet (15.24 meters) length overall using hook-and-line gear, CVs equal to or greater than 50 feet (15.24 meters) length overall using hook-and-line gear, catcher/processors (C/Ps) using hook-and-line gear, CVs using trawl gear, C/Ps using trawl gear, and vessels using pot gear. In the Western GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, CVs using hook-and-line gear, C/Ps using hook-and-line gear, CVs using trawl gear, and vessels using pot gear. Table 3 lists the proposed amounts of these seasonal allowances. For the Pacific cod sector splits and associated management measures to become effective in the GOA at the beginning of the 2012 fishing year, NMFS published a final

> rule (76 FR 74670, December 1, 2011) and will revise the final 2012 harvest specifications (76 FR 11111, March 1, 2011)."
>
> "NMFS proposes to calculate of the 2012 and 2013 Pacific cod TAC allocations in the following manner. First, the jig sector would receive 1.5 percent of the annual Pacific cod TAC in the Western GOA and 1.0 percent of the annual Pacific cod TAC in the Central GOA, as required by proposed § 679.20(c)(7). The jig sector annual allocation would further be apportioned between the A (60 percent) and B (40 percent) seasons as required by § 679.20(a)(12)(i). Should the jig sector harvest 90 percent or more of its allocation in a given area during the fishing year, then this allocation would increase by one percent in the subsequent fishing year, up to six percent of the annual TAC. NMFS proposes to allocate the remainder of the annual Pacific cod TAC based on gear type, operation type, and vessel length overall in the Western and Central GOA seasonally as required by proposed § 679.20(a)(12)(A) and (B)."

The longline and trawl fisheries are also associated with a Pacific halibut mortality limit which sometimes constrains the magnitude and timing of harvests taken by these two gear types.

Recent fishery performance

Data for managing the Gulf of Alaska groundfish fisheries are collected in a myriad of ways. The primary source of catch composition data in the federally managed fisheries for Pacific cod are collected by on-board observers (Faunce *et al.* 2017). The Alaska Department of Fish and Game (ADFG) sample individual deliveries for state managed fisheries (Nichols *et al.* 2015). Overall catch delivered is reported through a (historically) paper and electronic catch reporting system. Total catch is estimated through a blend of catch reporting and observer data (Cahalan *et al.* 2014)

The distribution of directed cod fishing is distinct to gear type, Figure 2.7 shows the distribution of catch from 1990-2015 for the three major gear types. Figure 2.8 and Figure 2.9 show the distribution of catch for 2016 and 2017 through October 11, 2017 for the three major gear types. In the 1970's and early to mid-1980's the majority of Pacific cod catch in the Gulf of Alaska was taken by foreign vessels using longline. With the development of the domestic Gulf of Alaska trawl fleet in the late 1980's trawl vessels took an increasing share of Pacific cod and Pacific cod catch increased sharply to around 70,000 t throughout the 1990's. Although there had always been Pacific cod catch in crab pots, pots were first used to catch a measureable amount of Pacific cod in 1987. This sector initially comprised only a small portion of the catch, however by 1991 pots caught 14% of the total catch. Throughout the 1990s the share of the Pacific cod caught by pots steadily increased to more than a third of the catch by 2002 (Table 2.2 and Fig. 2.7). The portion of catch caught by the pot sector steeply increased in 2003 with incoming Steller sea lion regulations and halibut bycatch limiting trawl and by 2011 through 2017 the pot sector caught more than half the total catch of Pacific cod in the Gulf of Alaska.

In 2015 combined state and federal catch was 77,772 t (24%) below the ABC while in 2016 combined catch was 64,071 t (35%) below the ABC (Table 2.3). As of October 16, the 2017 combined fishery has only caught 45,364 t which is only 51% of the TAC.

The largest component of incidental catch of other targeted groundfish species in the Pacific cod fisheries by weight are skate species in combination followed by arrowtooth flounder and walleye pollock (Table 2.6). Rockfish, octopus, rock sole, sculpin species, and shark species also make up a major component of the bycatch in these fisheries. Incidental catch of non-target species in the GOA Pacific cod fishery are listed in Table 2.7.

<u>Longline</u>

For 1990-2015 the longline fishery has been dispersed across the Central and Western GOA, however more longline catch taken to the west of Kodiak, with some longline fishing occurring in Barnabus trough and a small concentration of sets along the Seward Peninsula (Fig. 2.7). The 2016 and 2017 fisheries show a similar pattern (Fig. 2.8 and Fig. 2.9), however the 2017 fishery shows a concentration in fishing in deeper waters in the Central GOA area (Fig. 2.10) and shallower waters in the Western GOA (Fig. 2.11) than in previous years. The longline fishery tends to catch larger fish on average than the other fisheries (Fig. 2.12). The mean size of Pacific cod caught in the longline fishery is 64cm (annual mean varies from 58cm to 70cm). There was a drop in the mean length of fish in the longline fishery since 1990, however this trend has been more variable over the last 10 years although the overall trend continues to move to smaller fish (Fig. 2.13). In the Central GOA the Longline fishery during the A season had a slower start than previous years, but eventually caught the A-season TAC by mid-April; a point reached in 2016 three weeks earlier (Fig. 2.18). The A season CPUE in the Central GOA longline fishery was substantially lower than the previous two years (Fig. 2.20) approximately matching the low CPUE encountered in 2008 when stock abundance had been at it previously lowest level (Fig. 2.22). The A- season longline fishery in the Western GOA appears to have started later than the previous 4 years, however although effort appears to be lower the CPUE appears similar to the high CPUE attained in 2015 and on average higher than 2016 (Fig. 2.19, Fig. 2.21, and Fig. 2.22).

<u>Pot</u>

The pot fishery is a relatively recent development (Table 2.2) and predominately pursued using smaller catcher vessels. The Alaska state managed fishery is predominantly conducted using pots with on average 84% of the state catch coming from pot fishing vessels. In 2016 60% of the overall GOA Pacific cod catch was made using pots. Pot fishing occurs close to the major ports of Kodiak, Sand Point and on either side of the Seward Peninsula (Fig. 2.7). In 2016 (Fig.2.8) this same pattern is observed while in 2017 (Fig. 2.9) low observer coverage makes it difficult to determine if fishing distribution was the same as previous years. From the observed vessels in 2017 there appears to have been less fishing to the southwest of Kodiak, however this may be due to low observer coverage. The pot fishery in the Central GOA appears to have moved to deeper water in 2017 than in 2016 or 2015 (Fig 2.10), while pot fishing in the Western GOA appears to be similar among the past three years.

The pot fishery generally catches fish greater than 40 cm (Fig. 2.14), but like the longline fishery there has been a declining trend in Pacific cod mean length in the fishery since 1998 with the smallest fish at less than 60cm on average caught during the 2016 fishery (Fig. 2.15). The 2017 fishery data show an increase in length, potentially due to a combination of the fishery moving to deeper water and an apparent lack of smaller fish in the population.

The pot fishery in the Central GOA was slower and did not take the full TAC for the A season (Fig. 2.18). The pot fishery in the Western GOA appears to have been slower than 2014 and 2015, but similar to 2016 (Fig. 2.19). CPUE during the A season (January-April) in both the Central and Western GOA was lower than the previous two years (Fig. 2.20 and Fig. 2.21), on par with CPUE during 2013 and 2008-2010 (Fig. 2.22).

<u>Trawl</u>

The Gulf of Alaska Pacific cod trawl fishery rapidly developed starting in 1987, quickly surpassing the catch from the foreign longline fishery pursued in the 1970’s to mid-1980s in 1987. The trawl fishery dominated the catch into the min-2000s, but was then somewhat replaced increases in pot fishing in the mid-2000’s. This transition to pot fishing was partially due to Steller sea lion regulations, halibut bycatch caps, and development of an Alaska state managed fishery. The distribution of catch from the trawl fishery for 1990-2015 shows it has been widely distributed across the Central and Western GOA (Fig. 2.7) with the highest concentration of catch coming from southeast of Kodiak Island in the Central GOA and around the Shumigan Islands in the Western GOA. In 2016 trawl fishing in the Western GOA shows a shift away from the Shumigan Islands further to the west around Sanak Island and near the Alaska Peninsula (Fig. 2. 81). Catch concentrations in the Central GOA for 2016 look much like the historic fishing patterns for this area (Fig.2.8). Trawl fishing in 2017 for the A season shows increased catch near

Sanak Island and substantially less catch to the southeast of Kodiak and lower catches in the Central GOA in general (Fig. 2.9).

The trawl fishery catches smaller fish than the other two gear types with fish as small as 10 cm appearing in the observed length composition samples (Fig. 2.16). The average size of Pacific cod caught by trawl in the 1980's was on average smaller than those caught later (Fig. 2.17). The trawl fishery shows an increase in average size in the 1990s with the maturation of the domestic fishery. The decline in the mean length from the mid-1990s until 2015 mimics that observed in the longline and pot fisheries with some prominent outliers (2005-2006). The years 2005 and 2006 shows little observed fishing in the B-season when smaller fish are more often encountered with this gear type. The mean size shows a sharp increase in 2016 and 2017. The change to deeper depth and a larger proportion of the catch coming from the Western GOA might partially explain this recent increase.

The directed A season trawl fishery in the Central GOA started much later than previous years, catch rates were lower and the fishery did not take the full TAC (Fig. 2.18). Effort and CPUE in 2017 was lower than the previous 9 years (Fig. 2.20 and Fig. 2.22). The Western GOA A season trawl fishery appears to have finished the trawl TAC at the same time as the previous three years (Fig. 2.21) and had better than average CPUE compared to the previous four years (Fig. 2.21 and Fig.2.23).

Other gear types, non-directed, and non-commercial catch

There is a small jig fishery for Pacific cod in the GOA, this is a primarily state managed fishery and there is no observer data documenting distribution. This fishery takes on average 2,400 t per year. In 2017 the jig fishery was nearly non-existent with catch at less than 150 t. Catch in both the Central and Western GOA was exceptionally low as were catch rates.

Pacific cod is also caught as bycatch in other commercial fisheries. Although historically the shallow water flatfish fishery caught the most Pacific cod, since 2014 Pacific cod bycatch in the Arrowtooth flounder target fishery has surpassed it (Table 2.8). The weight of Pacific cod catch summed for all other target fisheries was 3,239 t in 2016 a low for recent fisheries, 2017 will likely be lower. This following an all-time high of 10,780 t in 2015 with 1/3 of this from the Arrowtooth flounder target fishery.

Non-commercial catch of Pacific cod in the Gulf of Alaska is considered to be relatively small at less than 400 t; data are available through 2015 (Table 2.9). The largest component of this catch comes from the recreational fishery, generally taking one-third to one-half of the accounted for non-commercial catch.

Other fishery related indices for stock health

There is a long history of evaluating the health of a stock by its condition which examines changes in the weight to length relationship (Nash et al. 2006). Condition is measured in this document as the deviance from a log linear regression on weight by length for all Pacific cod fishery A season (January-April) data for 1992-2017. There is some variability in the length to weight relationships between Pacific cod captured in the Central and Western GOA fisheries and among gear types. However, there is a consistent trend in both areas for Pacific cod captured using longline and pot gear in there being lower condition during 2014-2016 for fish less than 80 cm (Fig. 2.23, Fig.2.24, Fig. 2.25, and Fig. 2.26).

Incidental catch of Pacific cod in other targeted groundfish fisheries is provided in Table 2.8 and noncommercial catch of Pacific cod are listed in Table 2.9.

Indices of fishery catch per unit effort (CPUE) can be informative to the health of a stock, however CPUE in directed fisheries can be hyper-stable with CPUE remaining high even at low abundance (Walters 2003). This phenomenon is believed to have contributed to the decline of the Northern Atlantic cod (*Gadus morhua*) on the eastern coast of Canada (Rose and Kulka 2011). Instead we show the occurrence of Pacific cod in other directed fisheries. We examine two disparate fisheries to evaluate trends in incidental catch of Pacific cod, the pelagic walleye pollock fishery and the bottom trawl shallow water flatfish fishery. The occurrence of Pacific cod in the pelagic pollock fishery appears to be an index of abundance that is particularly sensitive to 2 year old Pacific cod, which are thought to be more pelagic. The shallow water flatfish fishery tracks a larger portion of the adult population of Pacific cod. For the pollock fishery we track incidence of occurrence as proportion of hauls with cod (Fig. 2.27 and Fig. 2.28) and the number of Pacific cod per ton of pollock (Fig. 2.29). In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of target species catch were examined (Fig. 2.30). For all of these indices, the 2017 value is the lowest in the series (2000-2017). For the shallow water flatfish fishery 2016 was the second lowest value. It should be noted that none of these indices are controlled for gear, vessel, or fishing practice changes.

Surveys

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 fact that 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.

The 2017 survey was conducted with two chartered vessels that accomplished 536 stations. While the GOA Bottom Trawl Survey optimally employs three chartered vessels and targets 825 stations, the 2017 likely captured the trend and magnitude of the cod abundance in the GOA. The 2017 survey covered all strata; regions; and shelf, gully, and upper slope habitats to 700 m. The percent standard error of 12.8% was lower than the historic average of 16.7%. The 2017 survey was comparable to the 2013 survey that was also conducted with two vessels and achieved 548 stations. The 2013 Pacific cod survey estimate was almost five times higher than the 2017 survey.

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.11 and Fig. 2.31). For example, the estimates dropped by 48% between the 1996 and 1999 estimates but subsequent estimates were similar through 2005. The 2009 survey estimate spiked at 2 times the 2006 estimate. Subsequent surveys showed a decline through 2017. The 2017 estimates for abundance and biomass estimates were the lowest in the time series (a 71% drop in abundance and 58% drop in biomass compared to the 2015 estimate). The survey encounters fish as small as 5 cm and generally tracks large year classes as they grow (e.g., the 1996, 2005-2008, and 2012 year classes; Fig. 2.32). The mean length in the trawl survey generally increased from 1984-2005 with except for the 1997 and 2001 surveys (Fig. 2.33). The decline in mean length in 2007 and 2009 was apparently due to incoming 2005-2008 year classes. The mean length in the survey increased in the 2011 survey although still remained below the 1984-2005 overall average.

The distribution of Pacific cod in the survey has been highly variable (Fig. 2.34) with inconsistent peaks in CPUE. In 2017 the survey had the lowest average density of the time series, but also no high density peaks in CPUE were observed in any survey station. There were some higher than average densities for the 2017 survey located along the Alaska Peninsula and south of Unimak island, but for the most part CPUE was universally low throughout the Gulf of Alaska. The next lowest survey, 2007, had high spikes of density in the Central GOA west of Kodiak and along the Alaska Peninsula, as well as numerous mid-density spikes throughout the Central and Western GOA.

AFSC sablefish longline survey

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, biennial sampling of the AI in 1996, and biennial sampling of the eastern BS in 1997 (Rutecki et al. 1997). The domestic survey also samples major gullies of the GOA in addition to sampling the upper continental slope. The order in which areas are surveyed was changed in 1998 to reduce interactions between survey sampling and short, intense fisheries. Before 1998, the order was AI and/or BS, Western Gulf, Central Gulf, Eastern Gulf. Starting in 1998, the Eastern Gulf area was surveyed before the Central Gulf area. International Pacific halibut longline survey

A Relative Population Number (RPN) index of Pacific cod abundance and length compositions for 1990 through 2017 (Table 2.12 and Fig 2.35). 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). This RPN index mirrors the trend observed in the bottom trawl survey for 1990 through 2017 with a decline in abundance from 1990 through 2008 and a sharp increase (154%) in 2009 and continued increase through 2011 with the maturation of the large 2005-2008 year classes. In 2012-2013 there appears a decline in the abundance index concurrent with a drop in overall shelf temperature potentially due to changes in availability of Pacific cod in these years as the population moved to shallower areas. In 2014-2016 the index increases but this may reflect increased availability with warmer conditions. The index shows a sharp drop (53%) in abundance from 2016 to 2017.

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.36). The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990-2017 (Fig. 2.37), matching the trend observed in all three fisheries, but not in the bottom trawl survey. Changes in mean size appear consistent with changing availability in the survey due to bottom temperatures and changes in the overall population with large year classes. Smaller fish are encountered during this survey in warm years vs. cold years. There is a sharp decline in mean size in 2009 when the large 2005 year-class would be becoming available to this survey. The even steeper decline in average length in 2015 was encountered in the warmest year on record for the time series.

Since 1990, when the AFSC longline survey time series begins, there is an increasing trend in temperature, a decreasing trend in both AFSC longline RPN and mean length of Pacific cod in this survey (Fig. 2.38). Once linearly de-trended the RPN index and CFSR 10 cm bottom temperature index (See below) has a Pearson's correlation coefficient $R = 0.30$, (p-value of 0.12) interestingly enough, the mean size of Pacific cod caught in the survey has $r = -0.23$ and mean length with RPN $r = -0.49$ over the time series from 1990-2016.

International Pacific Halibut Commission (IPHC) longline survey

This 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 survey samples the slope and select gullies from 200-1000 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. However, Pacific cod taken in the IPHC survey are not measured for length. To compare, to IPHC relative population number's (RPN) were calculated using the same methods as the AFSC longline survey data (but using different depth strata). Stratum areas (km^2) from the RACE trawl surveys were used for IPHC RPN calculations. The most recent IPHC survey estimate available is from 2016.

The IPHC survey estimates of Pacific cod tracks well with both the AFSC sablefish longline and AFSC bottom trawl surveys (Table 2.13 and Fig. 2.39). There was an apparent drop in abundance from 1997-1999 with a stable but low population through to 2006. The population increases sharply starting in 2007, likely with the incoming large 2005 year class and continues to increase through 2009 as the large 2005-2008 year classes matured. The population then remained relatively stable through to 2014. The RPN index shows a steep decline in 2015 and 2016 consistent with the other two surveys. The 2016 RPN is the lowest on record for the 20-year time series.

Alaska Department of Fish and Game bottom trawl survey

The Alaska Department of Fish and Game (ADFG) has conducted bottom trawl surveys of nearshore areas of the Gulf of Alaska since 1987. Although these surveys are designed to monitor population trends of Tanner crab and red king crab, Pacific cod and other fish are also sampled. Standardized survey methods using a 400-mesh eastern trawl were employed from 1987 to the present. The survey is designed to sample at fixed stations from mostly nearshore areas from Kodiak Island to Unimak Pass, and does not cover the entire shelf area (Fig. 2.40 and Fig. 2.41). The average number of tows completed during the survey is 360. On average, 89% of these tows contain Pacific cod. Details of the ADFG trawl gear and sampling procedures are in Spalinger (2012).

To develop an index from these data, a simple delta GLM model was applied covering 1988-2017. Data were filtered to exclude missing latitude and longitudes and missing depths. This model is separated into two components: one that tracks presence-absence observations and a second that models factors affecting positive observations. For both components, a fixed-effects model was selected and includes year, geographic area, and depth as factors. Strata were defined according to ADFG district (Kodiak, Chignik, South Peninsula) and depth (< 30 fm, 30-70 fm, > 70 fm). The error assumption of presence-absence observations was assumed to be binomial but alternative error assumptions were evaluated for the positive observations (lognormal versus gamma). The AIC statistic indicated the lognormal distribution was more appropriate than the gamma (ΔAIC= 1988.6). Comparison of delta GLM indices with the area-swept estimates indicated similar trends. Variances were based on a bootstrap procedure, and CVs for the annual index values ranged from 0.07 to 0.13. These values underestimate uncertainty relative to population trends since the area covered by the survey is a small percentage of the GOA shelf area where Pacific cod have been observed.

The ADFG survey index follows the other three indices presented above with a drop in abundance between 1998 and 1999 (-45%) and relatively low abundance throughout the 2000s (Table 2.14 and Fig. 2.42 and Fig. 2.43). This survey differs from other indices as the estimates only increased in 2012 (an 89% increase from 2011), and then dropped off steadily afterwards to a record low in 2016. The 2017 survey index was 5% higher than the 2016 survey index with broadly overlapping confidence intervals for these two years.

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 1979-2006 (Fig. 2.44 and Table 2.15).

The mean depth of Pacific cod at 10 cm and 40cm was found to be 47.9 m and 103.4 m in the Central GOA and 41.9 m and 64.07 m in the Western GOA. The temperatures of the 10 cm and 40 cm Pacific cod in the CFSR indices are highly correlated ($R^2 = 0.88$) with the larger fish in deeper and slightly colder waters 7.49 °C vs. 6.00 °C in the Central GOA and 4.78 °C vs. 4.75 °C in the Western GOA. The shallower index is more variable (CV_{10cm} 0.10 vs. CV_{40cm}=0.07). There are high peaks temperature in 1981, 1987, 1998, 2015 and 2016 with 2015 being the highest in both the 10 cm and 40 cm indices. There are low valleys in temperature in 1982, 1989, 2009, 2012, and 2013. The coldest temperature in the 10cm index was in 2009 and in the 40cm index in 2012. There trend is insignificant for both indices.

Data

This section describes data used in the current assessment (Fig. 2.45). It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used are provided in Appendix 2.3. Descriptions of the trends in these data were provided above in the pertinent sections.

Data	Source	Type	Years included
Federal and state fishery catch, by gear type	AKFIN	metric tons	1977 – 2017
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2017
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2017
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 – 2017
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 – 2015
GOA NMFS bottom trawl survey mean length-at-age and conditional age-at-length	AFSC	mean value and number	1990 – 2015
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	Number, by cm bin	1990 – 2017
CFSR bottom temperature indices	National Center for Atmospheric Research	Temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2016

Fishery

Catch Biomass

Catches for the period 1991-2017 are shown for the three main gear types in Table 2.2, with the catches for 2017 presented through October 11, 2017. For the assessment model the Oct–Dec catch was estimated given the average fraction of annual catch by gear type and FMP subarea for this period in 2016. The fishery was set in three gear type, trawl (all trawl types), longline (longline and jig) and pot. The weight of catch of other commercial species caught in the Pacific cod targeted fisheries for 2013 through 2017 are shown in Table 2.6, and incidental catch of non-commercial species for 2007 – 2017 are shown in Table 2.7. Non-commercial catch of Pacific cod in other activities is provided in Table 2.9.

Catch Size Composition

Fishery size compositions are presently available by gear for at least one gear type in every year from 1977 through the first half of 2017. Size composition data are based on 1-cm bins ranging from 1 to 116 cm. As the maximum percent of fish larger than 110 cm over each year-gear type-season is less than 0.5%, the upper limit of the length bins was set at 116 cm, with the 116-cm bin accounting for all fish 116 cm and larger. The trawl fishery length composition data are provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx)

There are two changes (Described below) to the data in the Model 17.09.xx assessment model series proposed which were presented in the September plan team and included in Appendix 2.3.

(http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_3.pdf)

Size composition proportioning

For the 2016 assessment models and assessment model series Model17.08.xx, fishery length composition data were estimated based on the extrapolated number of fish in each haul for all hauls in a gear type for each year.

2016 Method: $p_{ygl} = \frac{\sum_h \frac{n_{yghl}}{\sum_l n_{yahl}} N_{ygh}}{\sum_h N_{yg}}$

Where *p* is the proportion of fish at length *l* for gear type *g* in year *y*, *n* is the number of fish measured in haul *h* at length *l* from gear type *g*, and year *y* and *N* is the total extrapolated number of fish in haul h for gear type *g*, and year *y*.

For 2017 for post-1991 length composition (series Model 17.09.xx) we propose estimating the length compositions using the total Catch Accounting System (CAS) derived total catch weight for each gear type, NMFS management area, trimester, and year. Data prior to 1991 were unavailable at this resolution so those size composition estimates are unchanged.

Model 17.09.xx method (post-1991): $p_{ygl} = \sum_{t,a} \left(\left(\frac{\sum_h \frac{n_{ytaghl}}{\sum_l n_{ytaghl}} N_{ytagh}}{\sum_h N_{ytag}} \right) \left(\frac{W_{ytag}}{\sum_{tag} W_{ytag}} \right) \right)$

Where *p* is the proportion of fish at length *l* for gear type *g* in year *y*, *n* is the number of fish measured in haul *h* at length *l* from gear type *g*, NMFS area *a*, trimester *t*, and year *y* and *N* is the total extrapolated number of fish in haul h for gear type *g*, NMFS area *a*, trimester *t*, and year *y*. The *W* terms come from the CAS database and represent total (extrapolated) weight for gear type *g*, NMFS area *a*, trimester *t*, and year *y*.

Addition of ADFG port sampling for Pot fishery data

In 2017 observer coverage changed as managers established electronic monitoring (EM) as a substitute for observer coverage. This is likely to reduce observer coverage of the GOA Pacific cod pot fishery to around 4% compared to 14.7% coverage in 2016 (Craig Faunce, personal comm. 25 July 2017). The EM program is currently unable to measure fish for length composition (and obviously is unable to include age structure sampling). In 2016 the pot fishery caught 59% of the total allocation of GOA Pacific cod with 75% of this caught in state waters. This leaves a large proportion of the catch without observer collected length composition data. To mitigate this loss of data, other sources of pot fishery length composition data are being considered. The ADFG has routinely collected length data from Pacific cod landings since 1997. As such, adding these data as a way to augment the pot fishery length composition data for the stock assessment is important.

The ADFG port sampling and NMFS at-sea observer methods are follow different sampling frames so combining them poses some challenges. We propose to use ADF&G data from the pot fishery for trimester/areas in which observer data were missing. The resolution of the ADF&G data required the assumption that all of the samples collected in an area/trimester were representative of the overall catch for that trimester/area.

Method for ADFG data: $p_{ytagl} = \frac{n_{ygl}}{\sum_l n_{yal}} \left(\frac{W_{ytag}}{\sum_{tag} W_{ytag}} \right)$

Where *p* is the proportion of fish at length *l* for gear type *g* in NMFS area *a* in trimester *t* for year *y*, *n* is the number of fish measured at length *l* from gear type *g* in trimester *t* of year *y*. W is the catch accounting total weight for gear type *g*, NMFS area *a*, trimester *t*, and year *y*.

Age composition

Otoliths for fishery age composition have been collected since 1982. In 2017 the Age and Growth laboratory at the AFSC read the ages for 1,334 otoliths from the 2015 and 2016 fishery. Although these ages are not yet included in the stock assessment models, they have been used to evaluate the fishery data. The raw data presented in Figure 2.46.

Surveys

NMFS Gulf of Alaska Bottom Trawl Survey

Abundance Estimates

Bottom trawl survey estimates of total abundance used in the assessment models examined this year are shown in Table 2.11 and Fig. 2.31, together with their respective coefficients of variation.

Length Composition

The relative length compositions used in the assessment models examined this year from 1984-2015 are shown in Figure 2.32 and provided in Appendix 2.2 in an Excel spreadsheet (http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx).

Age Composition

Age compositions (Fig. 2.47) and conditional length at age (Fig. 2.48) from each trawl survey since 1990 (except 2017) are available and included in this year's assessment models. The age compositions and conditional length at age data are provided in Appendix 2.2 in an Excel spreadsheet. (http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx)

A recent study by Kastelle *et al.* (2017) state that one of the specific reasons for their study was to investigate the apparent mismatch between the mean length at age (from growth-zone based ages) and length-frequency modal sizes in the BSAI Pacific cod stock assessments and to evaluate whether age determination bias could account for the mismatch. Mean lengths at age (either from raw age-length pairs or age-length keys) were reported to be smaller than the modal size at presumed age from length distributions. In general, for the specimens in their study, there was an increased probability of a positive bias in fish at ages 3 and 4 (Kastelle *et al.* 2017; Fig. 6, Table 2); that is, they were over-aged. In effect, this over-ageing created a bias in mean length at age, resulting in smaller estimates of size at a given age. When correcting for ageing bias by reallocating age-length samples in all specimens aged 2–5 in proportion to that seen in the true age distribution, mean size at ages 2–4 did indeed increase (Kastelle *et al.* 2017, Fig. 7). For example, there was an increase of 35 mm and 50 mm for Pacific cod aged 3 and 4, respectively. This correction brings the mean size at corrected age closer to modal sizes in the length compositions. While beyond the scope of their study, they postulate that the use of this correction to adjust the mean size at age data currently included in Pacific cod stock assessments should prove beneficial for rectifying discrepancies between mean length-at-age estimates and length-frequency modes.

Although not implemented this year, we will work with the age and growth lab in 2018 to add aging bias to the assessment model.

AFSC Longline Survey for the Gulf of Alaska

Relative Population Numbers Index and Length Composition
The AFSC longline survey for the Gulf of Alaska survey data on relative Pacific cod abundance together with their respective coefficients of variation used in the assessment models examined this year are shown in Table 2.12 and Fig. 2.35.

Length Composition
The length composition data for the AFSC longline survey data are shown in Figure 2.36 and provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx)

Environmental indices

CFSR bottom temperature indices
The CFSR bottom temperature indices for 10 cm Pacific cod were used in this assessment (see description above; Fig. 2.44 and Table 2.15).

Analytic Approach

Model Structure

This year's proposed models apply refinements to input data (fishery length composition estimates and including ADFG port sampling data). They also introduce a way to incorporate environmental linkages in the treatment of natural mortality to evaluate the impacts of the warm water temperatures exhibited in 2014-2016. Additionally, the treatment of the AFSC longline survey index is refined by adding a parameter to scale catchability with temperature. To see the history of models used in this assessment refer to A'mar and Palsson (2015). Stock Synthesis version 3.24U (Methot and Wetzel 2013; Methot 2013) was used to run all the model configurations in this analysis. For consistency, we include the 2016 accepted model (Model16.08.25) with updated 2016 and 2017 catch data as well as 2017 AFSC bottom trawl abundance and AFSC longline index and length composition data.

The new models first reviewed by the NPFMC GOA Groundfish Plan Team in September 2017 and this is shown in Appendix 2.1. At that meeting, the 2017 survey data were unavailable. However, the magnitude of the decline in new index values prompted presentations to the October 2017 Council meeting since it was clear that the decrease was well below any reasonable expectation. For this assessment, the drop was explored in three of the new model configurations by adding a natural mortality block for 2015-2016 (and supported by a number of ancillary observations in fisheries, the ecosystem, and biological characteristics). The models presented represent a subset of models deemed to be most informative for discussion and stock management.

All models presented were single sex age-based models with length-based selectivity. The models have data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the Auke Bay Longline survey indices). Length composition data were available for all three fisheries and both indices. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was modeled as varying about a mean with standard deviation fixed at sigma R = 0.44 (Barbeaux *et al.* 2016). All selectivities were fit using six parameter double-normal selectivity curves. Five additional model configurations were developed for this document (note Model 17.09.37 is experimental and meant for potential future consideration):

Model configurations:

Models	Natural mortality	Survey catchability	Length-based Selectivity
17.08.25	Fit with normal prior of 0.38 and σ = 0.1	Trawl Q fit with uniform prior Longline float	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery. 1978-1989, 1990-2012, 2013-2016, and 2017 for longline and trawl, 1978-2012, and 2013-2017 for pot. 1984-1995, 1996-2005, 2006-2017 for bottom trawl survey
17.09.25	Fit with log normal prior log(μ) = -0.81 and σ = 0.41	Same as 17.08.25	Same as 17.08.25
17.09.26	Two blocks one block including 1977-2014 and 2017 and one block for 2015-2016. The first block M fixed at the prior of 0.44 the second M's fit with log normal prior log(μ)= -0.81 and σ = 0.41	Same as 17.08.25	Same blocks as 17.xx.25, except selectivity allowed to be fit annually based on a dev with cv=0.2 for the 1978-1989 block.
17.09.31	Two blocks one block including 1977-2014 and 2017 and one block for 2015-2016. Both blocks M fit lognormal prior of log(μ)= -0.81 and σ = 0.1	Trawl Q fit with uniform prior Longline Q fit with prior and conditioned on temperature index	Same as 17.09.26
17.09.35 **F**17.09.36	Same as 17.09.31	Same as Model17.09.31	Same as 17.09.26 except added block for trawl and longline fisheries for 2005-2006
F17.09.37	Age and year specific Ms, Fit with knots at 0, 1, and 5 where M is allowed to change. Age 0 set at 0.75, 1 at 0.44 and age 5. Age 1 and age 5 conditioned on bottom temperature anomalies. Block 2015-2016 fixed for age 1 at 0.9 and fit with uniform prior for age 5.	Same as 17.09.31	Same as 17.09.36

F= Francis TA1.8 method tuned.

Time varying selectivity components:

Configuration	Component	Temporal Blocks/Devs.
xx.xx.25	Trawl and Longline Fishery	Blocks – 1977-1995, 1996-2005, and 2006-2016
	Pot Fishery	Blocks – 1977-2012 and 2013-2016
	Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2016
17.09.26	Longline Fishery	Annual varying 1978-1989
	Trawl Fishery	Blocks–1977-1995, 1996-2005, 2006-2016,2017
17.09.31	Pot Fishery	Blocks – 1977-2012 and 2013-2016
	Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2016
17.09.35	Longline Fishery	Annually variable 1978-1989
17.09.36	Trawl Fishery	Blocks – 1996-2004,2005-2006,2007-2016, 2017
17.09.37	Pot Fishery	Blocks – 1977-2012 and 2013-2016
	Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2016

Parameters Estimated Outside the Assessment Model

Natural Mortality

In the 1993 BSAI Pacific cod assessment (Thompson and Methot 1993), the natural mortality rate *M* was estimated to be 0.37. All subsequent assessments of the BSAI and GOA Pacific cod stocks (except the 1995 GOA assessment) have used this value for *M*, until the 2007 assessments, at which time the BSAI assessment adopted a value of 0.34 and the GOA assessment adopted a value of 0.38. Both of these were accepted by the respective Plan Teams and the SSC. The new values were based on Equation 7 of Jensen (1996) and ages at 50% maturity reported by (Stark 2007; see "Maturity" subsection below). In response to a request from the SSC, the 2008 BSAI assessment included further discussion and justification for these values.

For the 2016 reference model (Model 16.08.25) *M* was estimated using a normal prior with a mean of 0.38 and CV of 0.1. This September Dr. Thompson presented a new natural mortality prior based on a literature search (Table 2.1) for the Bering Sea stock assessment (Thomson et al. 2017). For the Gulf of Alaska stock we used the same methodology and literature search to devise a new prior for M. This resulted in a lognormal prior on M of -0.81 (μ=0.44) with a standard deviation of 0.44 for the Gulf of Alaska Pacific cod. Model 17.09.25 was fit with this prior on M.

Due to the drop in survey abundances between 2015 and 2016 it is suspected that natural mortality increased in 2015 and 2016. Model 19.09.26 introduces a block for 2015-2016 where M could be fit separately from all other years. $M_{standard}$ is fixed at 0.44 in this model while $M_{2015\text{-}2016}$ is fit with a lognormal prior of μ=-0.81 and a σ=0.41. Model 17.09.31 and Model 17.09.36 follow this same blocking of M, but M is fit for both periods with a lognormal prior of μ=-0.81 and σ=0.1. The use of special mortality periods have been proposed and approved for use in several Bering Sea crab assessments.

Model 17.09.37 is experimental and intended to explore the impact of temperature on *M* at different ages and over time. In this model *M* is fixed for age 0 at 0.75 (there is no information in the model to inform this value and therefore simply scales the age-0 estimates). $M_{standard}$ at ages 1-4 and ages 5-20 were fixed at 0.44, but a uniform parameter with a uniform parameter bounded at 0.1 and 2.0 was fit which scales M to the 10 cm CFSR temperature index was fit to each. $M_{2015\text{-}2016}$ for ages 1-4 were fit with a lognormal prior log(μ)= -0.1054 σ=0.05 and for ages 5-20 fit with a uniform prior between 0.1 and 2.0.

Catchability

For all models the catchability for the AFSC bottom trawl survey is fit with a non-informative prior. For Models 17.xx.25 and 17.09.26 the longline survey catchability is also unconstrained. For Models

17.09.31, Model 17.09.36, and Model 17.09.37 the AFSC longline survey catchability is scaled without constraint but a parameter (also unconstrained) is included to modify annual values based on the CFSR 10cm index through a linear relationship: $\log(Q_y) = log(\bar{Q} + T_y\beta)$ where Q_y is catchability for a given year $\bar{Q}$ is the expected catchability across all time and T_y is the annual CFSR index and β is the scaling parameter. In September this parameterization was explored for the trawl survey, with some success. This relationship appears degraded slightly when the 2017 survey data were introduced. However, because the AFSC longline survey is limited to deeper waters it was reasoned that a change in Pacific cod depth would impact the longline survey more than the trawl survey. Given that changes in Pacific cod depth have been observed with temperature (Fig. 2.4), we explored models with longline catchability scaled with the 10 cm CFSR index as well.

A simple linear analysis shows a significant relationship between the 10 cm CFSR index and the AFSC longline RPN index after a 4 degree polynomial trend on year (Y) is removed from the RPN index (see below). The evidence ratio (Burnham and Anderson 2011) shows that although the model with a quadratic or cubic polynomial on the 10 cm CFSR index provides a better fit, there is little difference from the linear fit.

Model	AIC	Δ_{AIC}	l_i	w_i	Evidence Ratio
x=Y	636.5	23.65	7.32E-06	0.000001	182,167.54
x=Y+Y^2	623.65	10.8	0.0045	0.000565	295.21
x=Y+Y^2+Y^3	622.78	9.93	0.0070	0.001163	143.31
x=Y+Y^2+Y^3+Y^4	617.32	4.47	0.1070	0.017832	9.35
x=Y+Y^2+Y^3+Y^4+Y^5	619.31	6.46	0.0396	0.006593	25.28
x=Y+Y^2+Y^3+Y^4+**I**	613.75	0.90	0.6376	0.106271	1.57
x=Y+Y^2+Y^3+Y^4+**I+I^2**	612.85	0	1.0000	0.166667	1.00
x=Y+Y^2+Y^3+Y^4+**I+I^2+I^3**	613.30	0.45	0.8004	0.133406	1.25

Figure I2.1 Plot of AFSC longline survey RPN with 4th degree polynomial and 4th degree polynomial with 10 cm CFSR index fit.

Variability in Estimated Age

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 R^2 of 0.88. This regression was retained in the present assessment.

Weight at Length

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

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

Maturity

A detailed history and evaluation of parameter values used to describe the maturity schedule for GOA Pacific cod was presented in the 2005 assessment (Thompson and Dorn 2005). A length-based maturity schedule was used for many years. The parameter values used for this schedule in the 2005 and 2006 assessments were set on the basis of a study by Stark (2007) at the following values: length at 50% maturity = 50 cm and slope of linearized logistic equation = –0.222. However, in 2007, changes in SS allowed for use of either a length-based or an age-based maturity schedule. Beginning with the 2007 assessment, the accepted model has used an age-based schedule with intercept = 4.3 years and slope = –1.963 (Stark 2007). The use of an age-based rather than a length-based schedule follows a recommendation from the maturity study's author (James Stark, ret., Alaska Fisheries Science Center, personal communication). The age-based parameters were retained in the present assessment.

Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual SS runs, based on the data and the parameters estimated independently) in the model include the von Bertalanffy growth parameters, annual recruitment deviations, initial fishing mortality, gear-specific fishery selectivity parameters, and survey selectivity parameters (Table 2.16).

The same functional form (pattern 24 for length-based selectivity) used in Stock Synthesis to define the fishery selectivity schedules in previous year's assessments was used this year for both the fishery and survey. This functional form, the double normal, 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 (selectivity parameters are referenced by these numbers in several of the tables in this assessment):

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)
6. Final selectivity (at maximum length/age)

All but the "beginning of peak region" parameter are transformed: The widths are log-transformed and the other parameters are logit-transformed.

In this year's models both fishery and survey selectivities were length-based. Uniform prior distributions were used for all selectivity parameters, except for *dev* vectors in models with annually varying selectivities which were constrained by input standard deviations ("sigma") of 0.2.

For all parameters estimated within individual SS runs, the estimator used was the mode of the logarithm of the joint posterior distribution, which was in turn calculated as the sum of the logarithms of the parameter-specific prior distributions and the logarithm of the likelihood function.

In addition to the above, the full set of year- and gear-specific fishing mortality rates were also estimated conditionally, but not in the same sense as the above parameters. The fishing mortality rates are determined exactly rather than estimated statistically because SS assumes that the input total catch data are true values rather than estimates, so the fishing mortality rates can be computed algebraically given the other parameter values and the input catch data.

Likelihood Components

The model includes likelihood components for trawl survey relative abundance, fishery and survey size composition, survey age composition, survey mean size at age, recruitment, parameter deviations, and "softbounds" (equivalent to an extremely weak prior distribution used to keep parameters from hitting bounds), initial (equilibrium) catch, and survey mean size at age.

In SS, emphasis factors are specified to determine which likelihood components receive the greatest attention during the parameter estimation process. For all models likelihood components were given an emphasis of 1.0 in the present assessment. For all models presented there were no parameters near bounds and the likelihoods appear well defined with the gradient of the objective function at less than 10-4. All models were examined by "jittering" starting parameters by 10% over 50 runs to evaluate if models had converged to local minima.

Use of Size and Age Composition Data in Parameter Estimation

Size and age composition data are assumed to be drawn from a multinomial distribution specific to a particular year and gear within the year. In the parameter estimation process, SS weights a given size composition observation (i.e., the size frequency distribution observed in a given year and gear) according to the emphasis associated with the respective likelihood component and the sample size specified for the multinomial distribution from which the data are assumed to be drawn. We set initial sample sizes for the fishery at the number of hauls sampled or 200 whichever is least, for the surveys both size and age composition sample sizes were initially set at 100. For all but two models (Model 17.09.36 and 17.09.37) we did not tune the models. For the two tuned models we implemented the Francis TA1.8 method (Francis 2011). Model 17.09.36 was tuned with a single iteration, all of the Francis weights diagnostics confidence intervals bracketed 1.0 for the length and age composition data. The same tuned weightings were used in Model 17.09.37.

Results

Model Evaluation

The 2016 final model with data from 2017, and new model configurations are presented. The new models differed in data from the 2016 model (Model 17.08.25) and data weighting for Models 17.09.36 and 17.09.37. Therefore, these models could not be directly compared across likelihoods or AIC. The model evaluation criteria included model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model estimates fit to the survey indices, the survey age composition and conditional age-at-length data, reasonable curves for fishery and survey selectivity, and retrospective pattern. All models presented adequately estimated the variance-covariance matrix. Model likelihoods and key parameter estimates are provided in Table 2.17. Likelihoods by fleet are provided in

Table 2.18. It should be noted that not all models can be compared directly using likelihoods or AIC due to differences in data and data weighting. Retrospective results, index RMSE and composition mean effective sample sizes are provided in Table 2.19.

Comparing and Contrasting Model Configurations

The Model 16.09.25 was the exact configuration as Model 16.08.25 with the addition of the 2017 catch and survey data. Models 17.09.25 had the same configuration, but the proportioning of fishery length composition and the addition of ADFG port sampling length composition data for the pot fishery. Models 17.09.25, 17.09.26, Model 17.09.31 and Model 17.09.35 can be compared directly as the underlying data and weighting are the same across models. Model 17.09.36 and 17.09.37 have the same data as the other models, however the data weighting is different such that comparisons of fits to the fishery length composition data are not comparable. The results from the GOA Pacific cod stock assessment has been particularly volatile with a wide-array of models presented over the past 17 years (A'mar and Palsson 2015). The models presented this year are well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig.2.49). The female spawning biomass and age-0 recruitment for all the models considered this year are provided in Figure 2.50. The fit to the size composition data did not change the length at age substantially between models (Fig. 2.51) and won't be considered in model selection.

<u>Model 17.08.25</u>

The 17.08.25 configuration model was the data and model configuration as used last year, but with the addition of the 2017 surveys and finalized 2016 and partial 2017 catch data. There was a substantial change in the spawning stock biomass for the entire time series (Fig. 2.52). Natural mortality and catchability are fit in the model, as well as dome-shaped selectivity on both surveys and fisheries. Most of the change in the scale of the recruitment time series was due to a change in the estimate of natural mortality (M) in the model. M was estimated at 0.44, below that estimated from last year of 0.47. Because of the low abundance estimates from the trawl and longline surveys in 2017, the model discounts length and age composition supporting the large 2012 year class and found a more likely fit at lower recruitment numbers. Therefore M can be lower without this large influx of 2012 fish, but requires the overall number of age-0 fish across the time series to be scaled down to compensate for the lower M. The residuals around the 2012 and 2013 year classes in the fishery length composition data become larger, but the cost in likelihood is regained in fitting the recent bottom trawl and longline survey data better. Catchability was estimated at 1.78, near the value from last year of 1.77, suggesting the NMFS bottom trawl survey overestimates fish abundance at the lengths of peak selectivity. For sizes between 10cm and 80cm this translates into an average catchability × selectivity = 0.90 compared to 0.99 estimated in 2016. The fit made little change in selectivity except a shift in the trawl and longline fishery selectivity to the right in the final time block (Fig. 2.53). The change in Q causes a slight shift upward in the overall estimate of abundance, while the shift in selectivity to the right causes the model to estimate fewer large fish remaining in the population in proportion to the young fish, causing an overall reduction in spawning stock biomass across the time series.

Retrospective analysis results were rather poor compared to last year (Mohn's ρ = 0.318 vs. Mohn's ρ = 0.09). The low abundance and RPN indices drive the model this year to consider the 2012 year class to be near average, however once these data are removed the model then selects a fit that estimates this year class to be well above average (Fig. 2.54) based on their prevalence in the fishery length composition and survey age composition data.

Overall this model seems to perform well, however the apparent anomaly that occurred between 2015 and 2017 with the steep reduction in overall abundance could not be predicted in this model nor is that process explicitly captured in this model. The estimates of stock status from this model once the 2017 data are incorporated appear to be reasonable. However the 2012 year-class estimates are much lower than in previous assessments. These year-class strength estimates reflect the integration of variable natural mortality that likely occurred over ages and time (following cohorts) given the constant natural mortality assumed. That is, the year-class estimates reflect the resulting contribution to the spawning (and fishable) biomass rather than the actual number of juvenile pre-recruit fish observed. Available evidence from many sources suggest that the 2012 year class was highly abundant at ages 1-3. The lower estimate in this model is an indication that there was higher mortality on this age class that exceeded the 0.44 M estimated in the model. Although this natural mortality isn't explicitly taken into account in the model, the estimates of the current status of the stock is likely closer to the current actual status than last year's projection. However, even though the current model predicts there to be a much lower abundance in 2018 than last year's model, because there is disagreement between the high proportion of this age class in the age and size composition data and the low overall abundance estimates in the recent survey data, the model continues to predict an estimate of the survey index at a point higher than the survey index observation.

<u>Model 17.09.25</u>
This model is Model 17.08.25 with a change in the way fishery length composition data were proportioned and the augmentation of the pot fishery length composition data with ADFG port sampling data when there were data missing by year/area/trimester. Natural mortality was also fit in the model as a log normal using the Thompson (2017) prior of $\log(\mu)$=-0.81 with a σ of 0.41. Natural mortality remained at 0.44 in this model while catchability decreased to 1.67, slightly dropping the average catchability × selectivity for sizes 10cm – 80cm to 0.89. Likelihood profiles of M appear to be well defined (Fig.2.56), length and age composition data pushing the MLE to higher values, while the index data to lower values. A likelihood profile over M and Q show the fit with rather steep minimum (Fig. 2.57) with a broad likelihood field with some points that could act as local minima, specifically one near M = 0.38 and Q= 1.0 where older models had assumed to be at the MLE. There were only small changes in the fishery selectivity between models as the fishery length composition distributions did not change substantially (see Appendix 2.1). The model fit to the data are similar, however the fit to the longline survey RPN index improved slightly and slightly degraded to the bottom trawl survey abundance index (Table 2.18). The largest change in fit, outside of the fishery length composition which can't be compared directly, was an improvement of fit to both the bottom trawl survey age and length composition data (more than 20 points each). The fit to the longline survey length composition was impacted only slightly. The main changes to the model results was a slight decrease in the estimate of the 1990, 1999, 2002, 2008 and 2011 year classes and slight increase in the 2005-2007, 2009 and 2010 year classes and subsequent small change in spawning biomass (Fig. 2.55).

Examination of data impacts within the model were conducted where the AFSC bottom trawl survey and AFSC longline survey data were removed from the model (Fig.2.58). The impact of taking out the bottom trawl survey was an increase in recruitment with an increase in M to 0.46 from 0.44 and an affective change in the survey Q to 1.91. Taking out the bottom trawl survey also inflates the overall biomass estimates for 1977-2000 and ends in a higher spawning biomass in 2017. Removing the AFSC longline survey from the model results in little change in estimates of M and Q, recruitment varies only slightly from the run with the longline survey included, most notably the 2011 and 2012 year class estimates are smaller. Impacts on spawning biomass are primarily manifested in the final 5 years with lower biomass estimates overall.

The retrospective analysis (Fig.2.59) show substantial improvements over Model 17.08.25. The Mohn's ρ was approximately 1/3 of that from Model 17.08.25 and improvements to each of the measures of retrospective performance for both the spawning biomass and recruitment estimates (Table 2.19). The female spawning biomass retrospective performance was well within acceptable standards (< 0.2) proposed by Thompson (2016). Overall model results were similar between this model and Model 17.08.25 and the 2012 year class remains an issue in the retrospective analysis where its abundance is greatly inflated as the 2017 data are removed from the model. This causes a high estimate of Mohn's ρ for age-0 recruits (0.9) for this model.

Model 17.09.26

There are two main differences in Model 17.09.26 from Model 17.09.25. There is a time block on M for 2015-2016 which allows M to be fit for these years. Trawl and longline selectivity is allowed to vary annually for 1977-1989, modeled with an annual deviation of 0.2 on the fit parameters. In addition M in the model is fixed for all years except for the 2015-2016 block at the Thompson (2017) prior of 0.44, and allowed to be fit in the 2015-2016 block as lognormal with log(μ)=-0.81 and σ = 0.41. This was an addition of 65 parameters over Model 17.09.25, 63 of which were annual deviation in fishery selectivity.

	Model17.09.25	Model17.09.25 W/Sel. change	Model17.09.25 W/M Block	Model17.09.26
Parameters	134	191	135	192
Likelihoods				
Total	1672.59	1624.40	1643.03	1598.34
Survey	24.84	24.81	9.15	8.41
Length Composition	1102.86	1052.32	1099.83	1047.31
Age composition	547.62	538.96	540.65	538.34

Because data and weighting were the same between Model 17.09.25 and Model 17.09.26, AICs and likelihoods could be compared. The overall fit to the data was improved with a change in AIC of -8.14. Fitting the model in a stepped fashion show each of the components changed from Model 17.09.25 Improved the model, but in different ways. The addition of the annually varying selectivity improved the fit to the trawl and longline fishery length composition while the addition of the block on natural mortality improved the fit to the surveys. In general, every component of the model when both these changes were implemented showed an improvement in fit (Table 2.17 and Table 2.18), except the survey length composition data which remained effectively the same with only a +0.04 change in a likelihood from 132.74 to 132.78 and the pot fishery length composition with a -1.65 change in likelihood from 211.3 to 209.65. Allowing annually varying trawl and longline selectivity in 1977-1989 provided a better fit to the early trawl and longline fishery length composition data (Fig. 2.60) and caused the model to fit much lower recruitment in 1977-1980, higher recruitment in 1981 and 1982 (Fig. 2.62). M for the 2015-2016 block increase to 0.88 and catchability dropped to 1.57 for all years. This resulted in an average catchability × selectivity for sizes 10cm – 80cm of 0.87. The increase in *M* caused an increase age-0 fish in 2006-2016 over the Model 17.09.25 estimates therefore fitting the length and age composition better for the 2013-2017 while also fitting the steep increase in abundance in 2009 and subsequent drop in abundance observed in the 2017 AFSC bottom trawl and longline surveys better (Fig. 2.61) in comparison to previously described models. Although the model fit to the AFSC longline survey RPN index is improved over previous models, the fit remains somewhat problematic as the model does not follow the dip in the index between 2011 and 2015 and none of the models fit the high (but uncertain) 2009 estimate from the bottom trawl survey.

Retrospective patterns in the recommended model were much better than previous models with a Mohn's ρ = -0.004 for female spawning biomass and 0.004 for recruitment. This model had the best retrospective index values of all models presented this year (Table 2.19). However, the index measures the mean and plots of the retrospective reveal wide deviances from the end year estimate as data were removed (Fig. 2.63). The end year spawning biomass and end year number at age-0 varied between higher and lower than the final run as years of data were removed without a consistent trend. All of the retrospective runs estimate the 2012 year class to be weaker than the end model suggesting that Model 17.09.25 may be overestimating M in the 2015-2016 block.

Model 17.09.31

Model 17.09.31 differs from Model 17.09.26 in that both natural mortality blocks are fit with a more constrained lognormal distribution having a prior with log(μ)=-0.81 and σ =0.1, and a parameter modeled with a uniform prior was used to scale longline catchability with the CFSR bottom temperature index anomalies.

Because data and weightings were the same for Model 17.09.25, Model 17.09.26 and Model 17.09.31 AICs and likelihoods could be compared directly. Model 17.09.31 had an additional 68 parameters over Model 17.09.25 and 3 parameters over Model 17.09.26 and changed the AIC by –32.50 and -24.22, respectively. All data components had an improved fit over Model 17.09.25 and, excepting the AFSC longline survey length composition data, Model 17.09.26 (Table 2.17 and Table 2.18). The difference in fit to the length composition data between Model 17.09.26 and Model 17.09.31 were nearly negligible for all components except the longline fishery data which had an overall improvement of 13.9 LL; the other components changed by less than 3 points each. Similarly the change in harmonic mean of the effective N between Model 17.09.26 and Model 17.09.31 length composition data were negligible except for the longline data (Table 2.18). The fits to the AFSC bottom trawl and AFSC longline surveys were greatly improved in Model 17.09.31 with the addition of the temperature index on longline catchability (Table 2.18 and Fig. 2.64). Like all previous models the increase in mean size in 2005 and 2006 in the trawl fishery is not fit (Fig. 2.60). This apparent change in mean size is due to early fishery closures that year which restricted the trawl fishery to the A-season when the fishery can target larger fish in spawning aggregations. The predicted values for the longline survey in Model 17.09.31 for 2010-2017 show a marked improvement in fit with the expected values rising to a peak in 2010 with a dipping plateau between 2010 and 2015, then a sharp drop to 2017 (Fig. 2.59). This compared to the shallow rise then fall of abundance in Model 17.09.26 which misses 3 of the 8 RPN confidence intervals. This additional flexibility in fitting the longline survey also improved the trawl survey fit to the 2009 and 2015 abundance estimates over Model 17.09.26.

Natural mortality in Model 17.09.31 was estimated for the standard years at 0.48 and in 2015-2016 at 0.69. This increase in natural mortality caused the overall estimates for age-0 fish to be increased (Fig. 2.61) and the reduced estimate of M for 2015-2016 decreased the estimate of the 2012 year class in relation to other year classes over Model 17.09.26 (Fig. 2.65). Catchability for the AFSC bottom trawl survey dropped to 1.48, this resulted in an average catchability × selectivity for sizes 10cm – 80cm of 0.78 in this survey. AFSC longline survey catchability ranged from 1.4 to 2.7 (Fig. 2.64) with increase catchability in warm years and lower catchability in cold years. This matches data from the bottom trawl survey showing Pacific cod moving deeper in warm years (Fig. 2.4), making them more available to this survey which has, on average, deeper stations than the AFSC bottom trawl survey.

The retrospective indices were degraded from Model 17.09.26 and, although slightly better, similar to Model 17.09.25. The difference in the retrospectives compared to Model 17.09.26 was in the larger difference in the estimated 2005-2012 year classes in comparison to other year classes as data are removed. In Model 17.09.31 once the 2017 data are removed the 2012 year class estimate increases to over a 100% difference from the estimate with the 2017 data vs. an ~20% decrease in Model 17.09.26. Although the overall differences in end year estimates are smaller than in Model 17.09.26 the ρ values end up being higher because there is a small positive bias in the retrospective while in Model17.09.26 the retrospective estimates bracket the final estimate evenly.

Model 17.09.35 and 17.09.36

Model 17.09.35 and Model 17.09.36 differed from Model 17.09.31 in that a time block was added to the longline and trawl fishery selectivities for 2005-2006. This block was added to address the lack of fit to the length composition data during these two years when the fishery was closed earlier than normal and a B-season fishery was greatly curtailed. In Model 17.09.36 differs from Model 17.09.35 in that size composition multinomial sample sizes were tuned using the Francis TA1.8 method (Francis 2011).

The AIC between Model 17.09.31 and 17.09.35 changes by -58 (Table 2.17). The only substantial difference between the two models were an improvement to the fit to the trawl fishery (-28 LL) and longline fishery (-8 LL) length composition (Table 2.18 and Fig.2.67). The improvement to the trawl fishery was primarily due to a better fit to the 2005 and 2006 length composition data as expected. The three other length composition datasets were improved minimally. There was a slight degradation to the fit to the trawl survey index (< +1 LL) and age composition (< +2 LL) and an insubstantial improvement to the longline survey index (< -1 LL; Table 2.18 and Fig. 2.66). Harmonic mean effective Ns for the length composition data reveal similar trend with a larger effective Ns in the all length composition components, but overall a rather small improvement to the model fit.

In essence the improvement in fit did not translate into substantive differences in model results (Fig. 2.66). Besides the change in selectivity for 2005-2006, the M's shifted upward and Q downward by less than 0.01. These small changes made a small upward adjustment in recruitment across the entire time series. However the change in selectivity caused the 2001-2003 to be estimated slightly higher in relation to other recruitment years, decreasing the decline in spawning biomass observed in 2005-2008 compared to Model 17.09.31.

The Francis tuning adjustments implemented were 0.387, 0.594, and 0.425 for the trawl, longline, and pot fishery length composition data and no adjustment for the AFSC bottom trawl or longline survey length or age composition data. The tuning caused the both Ms to shift downward by < 0.01 to values very near those fit in Model 17.09.31 and catchability to be fit at a higher value, Q = 1.56 for the trawl survey and between 1.5 and 1.8 in the longline survey. The tuning minimally improved the fit to the AFSC bottom trawl survey and longline length and age composition data measured both by a decreased in negative log likelihood and an increase in the harmonic mean effective sample size (Table 2.18 and Table 2.19). The harmonic means of the effective sample size for the fishery size compositions decrease as one would expect with the decrease in weight in the multinomial. Interesting however is that the models fit the AFSC bottom trawl survey marginally better (< 0.7 LL) and the AFSC longline surveys worse with an increase of 2.29 LL. The change to the AFSC longline survey fits were primarily to the 1998, 2003, 2010, and 2015 values which were at the peaks in temperature and therefore longline catchability. The change in model fit to the early part of the fishery length composition data increase the 1977 and 1978 spawning stock biomass and decreased the peak spawning biomass in 1988-1995 in relation to the overall time series impacting the estimate of B100

Retrospectives for Models17.09.35 were slightly worse and for Model 17.09.36 slightly better than Model 17.09.31 (Table 2.19 and Fig. 2.68), however the retrospective results for the spawning biomass series for all three models were within acceptable limits. Like the other models we still had increase uncertainty around the 2012 year class as the 2017 survey data were removed. All of the models (except Model 17.09.26) consistently overestimated the 2012 year class as data years were removed from the model.

<u>Model 17.09.37</u>
Model 17.09.37 differs from Model 17.09.36 in how natural mortality was parameterized. In this model M is fixed for age 0 at 0.75, then linearly modeled between knots with knots at age 1, and age 5. Two parameters fit with a uniform prior scaled the age 1 and age 5 natural mortalities with the 10 cm CFSR bottom temperature index. In addition a time block was added to natural mortality for 2015-2016 to allow additional change to M in these years when natural mortality was theorized to have been higher than normal. Model 17.09.37 was introduced this year simply as an introduction to the concept of variable M conditioned on the environment. The early life history of Pacific cod and apparent sensitivity to temperature make this species a prime for exploring this model type. If vetted properly this model could be expanded as an enhance model to predict impacts of climate change on GOA cod and more easily incorporate larval surveys and other early life history indices in the model.

Model 17.09.37 has an improved AIC over Model 17.09.36 of -35.68 and the best fit of all the models to the AFSC trawl survey index. The fit to the model showed a highly dynamic M (Table 2.20 and Fig. 2.69) with higher natural mortality in the warm years and much lower natural mortality in the cold years. For age-1 this varied from a high in 2015 of 1.72 (during the warm anomaly nicknamed the "Blob") to a low of 0.27 in 2009 (coincident with the first year of the very large 2008 year class). At above age-5 M varied much less with a high in 2015 of 0.5 and low of 0.34 in 2009. The average natural mortality for age-1 to age 14 over 1977-2017 was estimated at M = 0.45. The variable M had the greatest improvement to fit on the AFSC bottom trawl survey index. There were only marginal improvements to the AFSC longline RPN index and length and age composition data. Index RMSE improved for both surveys but the harmonic mean effective N for all but the trawl survey length composition were smaller than in Model 17.09.36. Catchability in both the AFSC bottom trawl and longline surveys increase over Model 17.09.36. Catchability in the AFSC bottom trawl survey was estimated at 1.73 resulting in the average catchability × selectivity for sizes 10cm – 80 cm of 1.00.

The retrospective indices for Spawning stock biomass were in essence the same as Model 17.09.36 (Fig. 2.72), however the retrospective indices for the recruitment time series was somewhat improved (Table 2.19) with estimates for the 2012 year class remaining within 95% confidence intervals for the entire retrospective series.

Impacts on the model results show a less variable recruitment index as the variability in initial abundance was modeled as changes in natural mortality (Table 2.20 and Fig. 2.71). However, the 2012 year class is estimated to be as large as the 1977 year class. Due to the lower overall average M and higher Q the spawning stock biomass is over the time series is estimated to be lower. This model likely provides a more realistic view of the processes impacting recruitment, however our ability to project the model results is limited for short term (i.e. 2-15 year projections) for use in management

Selection of Final Model

Comparing likelihoods or AIC among all the models was appropriate for Models 17.09.25, 17.09.26, 17.09.31, and 17.09.35. Although there was considerable difference in model configuration, particularly concerning how natural mortality was handled for 2015-2016, fits and model results ended up being very similar. Using the AIC statistic Model 17.09.35 had the best fit. The largest improvement in fit was largely due to due to the better fit in the 1977-1989 when annually varying selectivity was implemented for these years in the fishery. The largest improvement in fit to the abundance indices was due to the addition of the time block on fitting natural mortality in 2015-2016. This drop may have been over-fit in Model 17.09.26 as this is the only model where 2012 recruitment decreases in the retrospective analysis. Model 17.09.35 and Model 17.09.36 differ simply in fishery length composition multinomial weighting. The non-tuned model (Model 17.09.35) fits and results were between those fits and results generated from the two tuning methods commonly used. The McAlister and Ianelli (1997) method tended to result in a model with higher weights on the size composition data, while the Francis TA1.8 (2011) method placed less weight on these data. The McAlister and Ianelli method resulted in a worse fit to both the indices and much tighter fits to the composition data. There is not a consensus on which method is best for Stock Synthesis like models, as the un-tuned model ends up being a compromise between the two, the authors feel this is the better option at this time. It should be noted that results from the three methods were comparable. We therefore recommend using Model 17.09.35 as the reference model for 2018. All Stock Synthesis files for Model 17.09.35 are provided in Appendix 2.3.

Model 16.09.35 diagnostics and Suggestions for Future Improvement

<u>Survey Indices</u>

Model 16.09.35 fit to the NMFS bottom trawl survey was within error bounds of the survey estimates for all but the 2009 and 2017 survey (Fig. 2.66). Given the available length and age composition data, the model was not able to increase abundance enough between 2007 and 2009 to match the large increase in abundance between these two surveys and the model could also not fit the sharp drop in abundance between 2015 and 2017 and retain a good fit to the longline survey RPN index which had a relatively high value for 2016. Comparison of total biomass predictions and AFSC bottom trawl survey abundance estimates are relatively closely matched for the 1996-2017 values with predictions at 1.38 times the survey estimates (Fig. 2.75), an effective “catchability” of 0.71.

Model 17.09.35 fits the AFSC longline index well (Fig. 2.66). The improvement was primarily due to fitting it with the 10cm CFSR bottom temperature index. This addition allowed the model to increase overall biomass in warm years and decrease it in cold year, better fitting the spikes and valleys observed in the index as well as the overall decreasing trend observed with the warming trend in the temperature index for 1990-2016. An exploratory model with the IPHC longline index included using selectivity from the bottom trawl survey showed essentially no difference in model fit and results once the temperature index was used to scale the AFSC longline survey catchability (Fig.2.73). A standardized IPHC RPN index was then nearly identical to the predicted values from the bottom trawl survey for 2006-2016 from Model 17.09.35 (Fig. 2.74). The IPHC longline survey RPN index will likely be added to the assessment model in 2018 as it is an annual model and will help offset the uncertainty in this model due to the AFSC bottom trawl survey being biannual.

<u>Length Composition</u>
Selectivities in Model 17.09.35 were allowed to be dome-shaped, except for the 1990-2017 longline fisheries and 2013-2017 trawl fisheries (Fig. 2.76). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.79). For the trawl fishery the model predictions (Fig. 2.67 and Fig. 2.78) although matching the mean length well, tended to underestimate the high peaks of the distributions and overestimate either side of the peaks. The addition of the 2005-2006 block on the fit selectivity parameters allowed the model to fit these two years better than any of the alternative models without the time block. This improved the fit not only to these year, but the surrounding years as well. Predictions of the longline fishery length composition (Fig. 2.67 and Fig. 2.79) were well fit but similarly underestimated the high peaks of some of the distributions, but matched the mean length very well. In addition when the distributions tended to be bimodal, the model tended to predict a single mode between the two modes. Predictions of the pot fishery length composition (Fig. 2.80) were also very well fit, again, like the trawl and longline fisheries the high peaks of the distributions tended to be underestimated. The mean length for the pot fishery data were well matched for all years. For the fishery length composition, there really is no need for improvement, residuals were small even for the minimal discrepancies noted above for the peak modes.

Model 17.08.35 matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.81), however small fish (sub-27 cm) high modes although identified were not always matched in magnitude. The sub-27cm modes in 1996, 2007, and 2009 were estimated lower than observed while a predicted mode for sub-27cm fish in 2011 was not observed in the data. A few peak modes were underestimated, but in general the larger fish were well predicted by the model. In future years, we may use models similar to Model 17.09.37 with age and year specific M to examine how these missed peaks correlate with mortality events and how these impact overall model performance.

Although the selectivity for Model 17.09.35 Auke Bay Laboratory length composition data (Fig. 2.82) were not time varying, the predictions matched the data well. The 2015 prediction was the only one that didn't fit within the 95% confidence bounds of the mean length. This was likely due to smaller fish moving to deeper waters in this very warm year. For this survey in the future fitting the selectivity parameters on the CFSR temperature index, similar to how catchability is parameterized, should be explored.

<u>Age Composition and Length-at-Age</u>
Even though the shelf survey age composition data were fit using the length composition selectivity (Fig. 2.76) in Model 17.09.35, age composition predictions matched the data well (Fig. 2.83). Mean age predictions all fell within the confidence bounds of the data (Fig. 2.84).

Model 17.09.35 has non-time varying growth (Fig. 2.85). Fits to the length-at-age data are within the error bounds for most ages (Fig. 2.86), however there appears to be some inter-annual variability that was not captured in this model. For instance Pacific cod in 2011 and 2015 were predicted in Model 17.09.35 to be larger at age than the data show for the oldest fish, while 2005 the opposite was true. This may be improved with annually varying growth, however data for pre-1990 data are not available, and therefore modeling inter-annual variability prior to 1990 is not possible.

Mean length and weight at age from Model 17.09.35 are provided in Table 2.24.

Time Series Results

Definitions
The biomass estimates presented here will be defined in two ways: 1) total biomass was defined as age 0+ biomass, consisting of the biomass of all fish aged 0 years or greater in a given year; and 2) spawning biomass was defined as the biomass of all spawning females in a given year. The recruitment estimates presented here was defined as numbers of age-0 fish in a given year; actual recruitment to fishery and survey depends on selectivities as estimated (noting that there are no indices involving age-0 Pacific cod). All results presented are from Model 17.09.35.

Biomass
Estimates of total biomass were on average 141% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 585,807 t in 1989 (Fig. 2.87) to 237,086 in 2006 and then an increase to another peak in 2010 of 345,269 t then decrease continuously through 2018. With average recruitment in 2017 total biomass would be expected to begin to increase again in 2019 (note that there is no information currently on the 2017 recruitment size). Spawning biomass (Table 2.23) shows a similar trend of decline since the late 1980s with a peak in 1990 at 190,465 t to a low in 2008 of 54, 470 t. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes in 2012 of 89,920 t, after which the decline continued to lowest level of 35,824 t projected for 2018. Projections from last year's model showed an increase in spawning biomass as the large 2012 and 2013 year classes mature, but then decrease starting in 2018 due to poor recruitment since 2014 (Barbeaux et al 2016, Table 2.15). This year's model takes into account the new survey indices which show a steep decline in abundance and biomass since 2015, suggesting a substantial increase in natural mortality for these two year classes in 2015 and 2016. This decrease in these two year classed greatly reduced the current spawning biomass estimate and further reduces the projection into 2019 and 2020. With future fishing in 2018 and 2019 limited to 17,000 t the projected spawning biomass are projected to be near $B_{20\%}$ at 34,443 t and 33,796 t.

Numbers at age and length are given in Appendix 2.2 and shown in Figure 2.88 and available online at: (http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx)

Recruitment and Numbers at Age
The recruitment predictions in Model 17.09.35 (Table 2.22, Fig. 2.89 and Fig. 2.90) show large 1977, 1984, and 2012 year-classes with more than 0.9 billion (at age-0) fish for each (0.945 billion for 1977, 0.975 for 1984 and 0.902 billon for 2012) although uncertainty on the 1977 and 1984 year-class estimates were large (σ_{1977} = 0.255 and σ_{1984} = 0.221). Large year-classes (<0.7 billion age-0) were also estimated for 1982, 1985, 1987, 1989, 1990, 2006, and 2008. Between 1990 and 2010 the average recruitment was estimated at 0.5 billion, 29% lower than the 1977-1989 mean recruitment of 0.705 billion and 10% lower than the 1977-2016 mean recruitment of 0.557 billion. Note that in models where *M* was not fit separately for 2015-2016 the 2012 year class is 11% above the 1977-2015 mean, while in Model 17.09.35, where M is fit separately for 2015-2016, the 2012 year class is 60% above the 1977-2015 mean (Fig. 2.91).

Fishing Mortality
Fishing mortality appears to have increased steadily with the decline in abundance from 1990 through a peak in 2008 with continued high fishing mortality through 2016 in all models examined (Table 2.25). This period saw both a decline in recruitment paired with increases in catch. The largest increase in catch has

been in the pot fishery, which also shows the largest increase in continuous F (Fig. 2.94). The phase plane plot (Fig. 2.93) shows that F was estimated to have been above the control rule advised levels but below $F_{35\%}$ for 2008 and 2017 and biomass was below $B_{35\%}$ in 2008 and 2009 and again 2016 and 2017 and projected to be below through 2019.

Retrospective analysis

Estimates of spawning biomass for Model 17.09.35 with an ending year of 2007 through 2017 are not consistently biased from 1984 through 2000, have a consistent negative adjustment from 2009-2015 and a positive adjustment post-2015 as more data are included (Fig. 2.67). Relative differences in estimates of spawning biomass and recruitment show the same pattern for the more recent years.

MCMC results

MCMC were conducted with 1,000,000 iterations with 350,000 burn-in and thinned to every 500th iteration leaving 1,300 iterations for constructing the posterior distributions. Geweke (1992) and Heidelberger and Welch (1983) MCMC convergence tests, as implemented in the *coda* R library (Plummer *et al.* 2006), concluded adequate convergence in the chain (Fig. 2.94). Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Table 2.26 and Fig. 2.95). Posterior shows a 0.054% probability of the spawning stock biomass being below $B_{20\%}$ from the projection model (Fig. 2.96).

Harvest Recommendations

Amendment 56 Reference Points

Amendment 56 to the GOA Groundfish Fishery Management Plan (FMP) defines the "overfishing level" (OFL), the fishing mortality rate used to set OFL (F_{OFL}), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (F_{ABC}) may be less than this maximum permissible level, but not greater. Because reliable estimates of reference points related to maximum sustainable yield (MSY) are currently not available but reliable estimates of reference points related to spawning per recruit are available, Pacific cod in the GOA have generally been managed under Tier 3 of Amendment 56. Tier 3 uses the following reference points: $B_{40\%}$, equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing; $F_{35\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 35% of the level that would be obtained in the absence of fishing; and $F_{40\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 40% of the level that would be obtained in the absence of fishing. The following formulae apply under Tier 3:

3a) Stock status: $B/B_{40\%} > 1$

$F_{OFL} = F_{35\%}$

$F_{ABC} \leq F_{40\%}$

3b) Stock status: $0.05 < B/B_{40\%} \leq 1$

$F_{OFL} = F_{35\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

$F_{ABC} \leq F_{40\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

3c) Stock status: $B/B_{40\%} \leq 0.05$

$F_{OFL} = 0$

$F_{ABC} = 0$

Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. These reference points are estimated as follows, based on this year's model, Model 17.09.36:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	58,984 t	67,411 t	168,528 t

For a stock exploited by multiple gear types, estimation of $F_{35\%}$ and $F_{40\%}$ requires an assumption regarding the apportionment of fishing mortality among those gear types. For this assessment, the apportionment was based on this year's model's estimates of fishing mortality by gear for the five most recent complete years of data (2011-2016). The average fishing mortality rates for implied that total fishing mortality was divided among the three main gear types according to the following percentages: trawl 30%, longline 20%, and pot 50%. This apportionment results in estimates of $F_{35\%}$ and $F_{40\%}$ equal to 0.824 and 0.657.

Specification of OFL and Maximum Permissible ABC

Spawning biomass for 2018 is estimated by this year's model to be 36,106 t. This is below the $B_{40\%}$ value of 67,411 t, thereby placing Pacific cod in sub-tier "b" of Tier 3. Given this, the model estimates OFL, maximum permissible ABC, and the associated fishing mortality rates for 2018 and 2019 as follows (2019 values are predicated on the assumption that 2018 catch will be 18,000 t, below maximum permissible ABC):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2018	23,565	19,401
Harvest amount	2019	21,416	17,634
Fishing mortality rate	2018	0.42	0.34
Fishing mortality rate	2019	0.40	0.32

The age 0+ biomass projections for 2018 and 2019 from this year's model are 170,565 t and 197,711 t, respectively.

ABC Recommendation

Since 2008 the GOA Plan Team and SSC has recommended setting the ABC at the maximum permissible level under Tier 3. Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2017 are provided in Table 2.27.

However, following this practice, this year's maximum ABC for 2018 would push the stock below $B_{20\%}$ in 2019, therefore we recommend reducing the recommended ABC to 18,000 to maintain the stock above $B_{20\%}$ in 2019 (Fig. 2.97). Similarly, the maximum ABC for 2019 would push the stock below $B_{20\%}$ in 2020, we therefore recommend setting the ABC for 2019 at 17,000 t a value which keeps the SSB above $B_{20\%}$ in 2020.

Area Allocation of Harvests

For the past several years, ABC has been allocated among regulatory areas on the basis of the three most recent surveys. The previous proportions based on the 2009-2013 surveys were 33% Western, 64% Central, and 3% Eastern. In the 2013 assessment, the random effects model was used for the 2014 ABC apportionment. Using this method with the trawl survey biomass estimates through 2017, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	44.9%	45.1%	10.0%	100%
2018 ABC	8,082	8,118	1,800	18,000
2019 ABC	7,633	7,667	1,700	17,000

Standard Harvest and Recruitment Scenarios and Projection Methodology

A standard set of projections for population status under alternatives were conducted to comply with Amendment 56 of the FMP. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2017 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2017 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2017 (here assumed to be 48,940 t). In each subsequent year, the fishing mortality rate is prescribed based on the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. This year the recruitments were pulled from Model 17.09.35 with the 2015-2016 natural mortality block was set at the standard M value (Fig. 2.91 and Table 2.28). This is thought to be consistent with past practices for models with single Ms throughout. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2018, are as follow ("*max* F_{ABC} " refers to the maximum permissible value of F_{ABC} under Amendment 56):

Scenario 1: In all future years, *F* is set equal to *max* F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)

Scenario 2: In all future years, *F* is set equal to the author's recommend level. Due to current conditions of strong recruitment and a projected increasing biomass, the recommendation is set equal to the maximum permissible ABC.

Scenario 3: In all future years, *F* is set equal to the 2011-2016 average *F*. (Rationale: For some stocks, TAC can be well below ABC, and recent average *F* may provide a better indicator of F_{TAC} than F_{ABC}.)

Scenario 4: In all future years, *F* is set equal to the $F_{75\%}$. (Rationale: This scenario was developed by the NMFS Regional Office based on public feedback on alternatives.

Scenario 5: In all future years, *F* is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA' s requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follows (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):

Scenario 6: In all future years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be above half of its B_{MSY} level in 2017 and above its B_{MSY} level in 2027 under this scenario, then the stock is not overfished.)

Scenario 7: In 2018 and 2019, F is set equal to max FABC, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2019 or 2) above 1/2 of its MSY level in 2019 and expected to be above its MSY level in 2029 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 13 years from 2017 in Model 17.06.35 (Table 2.29). All scenarios including scenario 5 (no fishing) project the stock to be below $B_{35\%}$ until 2022, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2023. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.97) will be below $B_{35\%}$ in 2018 through 2023 due to poor recruitment and high natural mortality post-2008. Under an assumption of mean recruitment, the stock recovers above $B_{35\%}$ by 2023.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2017 at 40,329 will be above its MSY value in 2027 at 63,043 t and therefore is not overfished.

Projections 7 with fishing at the OFL after 2019 results in an expected spawning biomass of 62,643 t by 2029. These projections illustrate the impact of the low recruitment in 2014 and 2015. For example, under all scenarios, the spawning biomass is expected to continue to drop due to the low recruitments post-2008 and high mortality of the 2011-2013 recruitments and decreasing influence of the high 2005-2008 year classes and then levels off as the projection relies on mean recruitment.

Under Scenarios 6 (Fig. 2.97) and 7 of the 2017 Model 17.09.35 the projected spawning biomass for Gulf of Alaska Pacific cod is not currently overfished, nor is it approaching an overfished status.

Ecosystem Considerations

Ecosystem Effects on the Stock

Food-web dynamics in the Gulf of Alaska (GOA) are structured by climate-driven changes to circulation and water temperature, which can impact the distribution of key predators in the system and mediate trophic interactions. Recent evaluation finds evidence for strong food-web responses to perturbation in the GOA and indicates a dominance of destabilizing forces in the system that suggest a "dynamic ecosystem structure, perhaps more prone to dramatic reorganization than the [Bering Sea], and perhaps inherently less predictable" (Gaichas et al., 2015).

Predation is a major structuring pressure in the GOA ecosystem. Prey and predators of Pacific cod have been described or reviewed by Albers and Anderson (1985), Livingston (1989, 1991), Lang et al. (2003), Westrheim (1996), Yang (2004), and Gaichas et al. 2015. The composition of Pacific cod prey varies spatially and with changing environmental conditions. In terms of percent occurrence, some of the most important items in the diet of Pacific cod in the BSAI and GOA have been polychaetes, amphipods, and crangonid shrimp. In terms of numbers of individual organisms consumed, some of the most important dietary items have been euphausids, miscellaneous fishes, and amphipods. In terms of weight of organisms consumed, some of the most important dietary items have been walleye pollock, fishery offal, yellowfin sole, and crustaceans (including Pandalidae and Chionoecetes bairdi). Predators of Pacific cod include Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin. Major trends in the most important prey or predator species can be expected to affect the dynamics of Pacific cod (Gaichas et al. 2015).

The marine heat wave of 2014-2016 in the Northeast Pacific was unusual in the degree of temperature increase, the maintenance of warm water through the winters and the depth to which the warm temperatures reached (Bond et al 2015). Metabolic demand for ectothermic fish like Pacific cod is largely a function of thermal experience and tends to increase exponentially with increasing temperatures. Fish can minimize metabolic costs through behaviors such as movement to thermally optimal temperatures, or can increase consumption of food energy to meet increasing metabolic demands. The former requires access to thermally optimal temperatures, which may have been impacted by the recent marine heat wave. The latter requires sufficient access to abundant or high energy prey resources. Thus, if either is limiting, metabolic costs may exceed energetic consumption and decreases in growth or increases in mortality may occur.

In fact, for Pacific cod in the GOA during the anomalously warm years of 2014-2016, prey demand was elevated above long-term mean estimates, and peaked in 2016, according to adult bioenergetic model estimates of relative energetic demand (Fig. 2.98). Based on water temperatures at preferred depth, metabolic demand was greatest for 10 cm fish and >40 cm fish but lowest for 30 cm fish (Fig. 2.98). Bioenergetic model estimates of Pacific cod growth and respiration also suggest poor thermal conditions for growth in 1998 (following the record El Niño of 1997/98) and 2016 (top panel Fig. 2.99) that were driven by high metabolic demand during those years (bottom panel, Fig. 2.99). Prey energetic demand based on mean energy densities and annual shifts in diet composition show moderate changes in diet energy density over time, with highest cumulative diet energy densities in 2013, which occurred at the end of a 7 year cold temperature stanza in the GOA, and slightly lower values in 2015 near the long-term mean (Fig. 2.100). Stomach fullness of Pacific cod sampled from the GOA summer bottom trawl survey was lowest to date in 2015 (Fig. 2.101), and diet composition varied from previous years, with a 47.8 % drop in *Chionoecetes bairdi* relative to previous years (Figs. 2.102 and 2.103) and an absence of capelin which had been abundant, particularly in smaller Pacific cod, during 2011 and 2013. The proportion of *C. bairdi* in the diets of 40-80 cm cod dropped from the long-term mean of about 13.8% to 6.6% in 2015, but increased again to mean levels in 2017. The average specific weight of diets in 2017 increased from a historical low in 2015 to above average for 40-80 cm fish, but remained low for 20-40 cm fish (Fig. 2.102).

The increase in metabolic demand in 2015 has two important implications: (1) Pacific cod would have had to consume an additional 6-12% of prey per day ($g\ g^{-1}d^{-1}$) over average (i.e., based on mean estimates for years 1980-2014) to maintain growth and body condition, or (2) Pacific cod would have had to access energetic reserves leading to net body mass loss. The protracted warm conditions from 2014-2016 may have exceeded both adaptive options, potentially leading to starvation and mortality. In addition, other ectothermic fish species would be expected to have similarly elevated metabolic demands during the warm conditions, increasing the potential for broad scale prey limitations.

There are a few lines of evidence to support this potential mechanism for declines in Pacific cod abundance, including low fish condition observed in 2015 (i.e., fish that were lighter than average for a given length; Zador et al. 2017), lowest potential growth based on mean relative foraging rates reported in Holsman and Aydin (2015; Fig 2.99 top), highest recorded metabolic demands in 2015 (Fig. 2.99, bottom), below average diet energy density (lowest since 2007) based on diet composition of survey collected stomach samples (Fig. 2.101), and reports in 2015-2106 of widespread mortality events from starvation for avian and marine mammal predators that share prey resources with Pacific cod in the GOA. Also of important note is the potential absence of capelin (an important prey item) in the diets of Pacific cod from 2015 (Fig. 2.101), and the overall lower mean stomach fullness for fish in 2015 (height of columns in Fig. 2.101; note that these data are aggregated across regions and fish sizes). Considered collectively, these lines of evidence suggest that persistent anomalously warm conditions that extended from surface waters to depth, may have contributed to high mortality rates for juvenile and adult Pacific cod from the years 2014-2016. Additional analysis of these patterns is needed to further evaluate spatial differences in energetic demand and potential factors influencing Pacific cod survival across the region.

Fishery Effects on the Ecosystem

Potentially, fisheries for Pacific cod can have effects on other species in the ecosystem through a variety of mechanisms, for example by relieving predation pressure on shared prey species (i.e., species which serve as prey for both Pacific cod and other species), by reducing prey availability for predators of Pacific cod, by altering habitat, by imposing bycatch mortality, or by "ghost fishing" caused by lost fishing gear.

Incidental Catch of Nontarget Species

Incidental catches of nontarget species in each year 2007-2016 are shown Table 2.7. In terms of average catch over the time series, only sea stars account for more than 250 t per year.

Steller Sea Lions

Sinclair and Zeppelin (2002) showed that Pacific cod was one of the four most important prey items of Steller sea lions in terms of frequency of occurrence averaged over years, seasons, and sites, and was especially important in winter. Pitcher (1981) and Calkins (1998) also showed Pacific cod to be an important winter prey item in the GOA and BSAI, respectively. Furthermore, the size ranges of Pacific cod harvested by the fisheries and consumed by Steller sea lions overlap, and the fishery operates to some extent in the same geographic areas used by Steller sea lion as foraging grounds (Livingston (ed.), 2002).

The Fisheries Interaction Team of the Alaska Fisheries Science Center has been engaged in research to determine the effectiveness of recent management measures designed to mitigate the impacts of the Pacific cod fisheries (among others) on Steller sea lions. Results from studies conducted in 2002-2003 were summarized by Conners et al. (2004). These studies included a tagging feasibility study, which may evolve into an ongoing research effort capable of providing information on the extent and rate to which Pacific cod move in and out of various portions of Steller sea lion critical habitat. Nearly 6,000 cod with spaghetti tags were released, of which approximately 1,000 had been returned as of September 2003.

Seabirds

The following is a summary of information provided by Livingston (ed., 2002): In both the BSAI and GOA, the northern fulmar (*Fulmarus glacialis*) comprises the majority of seabird bycatch, which occurs primarily in the longline fisheries, including the hook and line fishery for Pacific cod Shearwater (*Puffinus* spp.) distribution overlaps with the Pacific cod longline fishery in the Bering Sea, and with trawl fisheries in general in both the Bering Sea and GOA. Black-footed albatross (*Phoebastria nigripes*) is taken in much greater numbers in the GOA longline fisheries than the Bering Sea longline fisheries, but is not taken in the trawl fisheries. The distribution of Laysan albatross (*Phoebastria immutabilis*) appears to overlap with the longline fisheries in the central and western Aleutians. The distribution of short-tailed albatross (*Phoebastria albatrus*) also overlaps with the Pacific cod longline fishery along the Aleutian chain, although the majority of the bycatch has taken place along the northern portion of the Bering Sea shelf edge (in contrast, only two takes have been recorded in the GOA). Some success has been obtained in devising measures to mitigate fishery-seabird interactions. For example, on vessels larger than 60 ft. LOA, paired streamer lines of specified performance and material standards have been found to reduce seabird incidental take significantly.

Fishery Usage of Habitat

The following is a summary of information provided by Livingston (ed., 2002): The longline and trawl fisheries for Pacific cod each comprise an important component of the combined fisheries associated with the respective gear type in each of the three major management regions (BS, AI, and GOA). Looking at each gear type in each region as a whole (i.e., aggregating across all target species) during the period 1998-2001, the total number of observed sets was as follows:

Gear	BS	AI	GOA
Trawl	240,347	43,585	68,436
Longline	65,286	13,462	7,139

In the BS, both longline and trawl effort was concentrated north of False Pass (Unimak Island) and along the shelf edge represented by the boundary of areas 513, 517 (in addition, longline effort was concentrated along the shelf edge represented by the boundary of areas 521-533). In the AI, both longline and trawl effort were dispersed over a wide area along the shelf edge. The catcher vessel longline fishery in the AI occurred primarily over mud bottoms. Longline catcher-processors in the AI tended to fish more over rocky bottoms. In the GOA, fishing effort was also dispersed over a wide area along the shelf, though pockets of trawl effort were located near Chirikof, Cape Barnabus, Cape Chiniak and Marmot Flats. The GOA longline fishery for Pacific cod generally took place over gravel, cobble, mud, sand, and rocky bottoms, in depths of 25 fathoms to 140 fathoms.

Impacts of the Pacific cod fisheries on essential fish habitat were further analyzed in an environmental impact statement by NMFS (2005).

Gulf of Alaska Pacific cod Economic Performance Report for 2016

Pacific cod is a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries. Pacific cod typically accounts for just under 30% of the GOA's FMP groundfish harvest and over 20% of the total Pacific cod catch in Alaska. Total catch of Pacific cod in the GOA was 64 thousand t and retained catch 63 thousand t, down 18% in 2016 from 2015. Retained catch is below the recent high of 79 thousand t in 2014, and is just under the 2007-2011 average of 63 thousand t (Table 2.30). Catches in 2017 are expected to be below 2016 with a 10% reduction in the 2017 TAC. Preliminary stock assessment estimates as of Oct. 2017 suggest a substantial reduction in the 2018 catch specifications. Ex-vessel revenues in 2016 were down 18% to $41 million with the reduction in catch (Table 2.30). The products made from GOA Pacific cod had a first-wholesale value was $90 million in 2016, which was down 12% from 2015 and below the 2007-2011 average of $102 million (Table 2.30, Table 2.31, and Table 2.32).

The fishery for cod is an iconic fishery with a long history, particularly in the North Atlantic. Global catch was consistently over 2 million t through the 1980s, but began to taper off in the 1990s as cod stocks began to collapse in the northwest Atlantic Ocean. Over roughly the same period, the U.S. catch of Pacific cod (caught in Alaska) grew to approximately 250 thousand tons where it remained throughout the early to mid-2000s. European catch of Atlantic cod in the Barents Sea (conducted mostly by Russia, Norway, and Iceland) slowed and global catch hit a low in 2007 at 1.13 million t. U.S. Pacific cod's share of global catch was at a high at just over 20% in the early 2000s. Since 2007 global catch has grown to 1.85 million t in 2014 as catch in the Barents Sea has rebounded and U.S. catch has remained strong at over 300 thousand t since 2011. European Atlantic cod and U.S. Pacific cod remain the two major sources supplying the cod market over the past decade accounting for roughly 75% and 20%, respectively. Atlantic cod and Pacific cod are substitutes in the global market. Because of cod's long history, global demand is present in a number of geographical regions, but Europe and the U.S. are the primary consumer markets for many of the Pacific cod products. The market for cod is also indirectly affected by activity in the pollock fisheries which experienced a similar period of decline in 2008-2010 before rebounding. Cod and pollock are commonly used to produce breaded fish portions. Alaska caught Pacific cod in the GOA became certified by the Marine Stewardship Council (MSC) in 2010, a NGO based third-party sustainability certification, which some buyers seek. Changes in global catch and production account for much of the broader time trends in the cod markets. In particular, the average first-wholesale prices peak approximately $1.90 per pound in 2008 and subsequently declined precipitously to approximately $1.50

per pound in 2009-2010 as markets priced in consecutive years of approximately 100 thousand t increases in the Barents Sea cod catch in 2009-2011; coupled with reduced demand from the recession.

The Pacific cod total allowable catch (TAC) is allocated to multiple sectors. In the GOA, sectors are defined by gear type (hook and line, pot, trawl and jig) and processing capacity (catcher vessel (CV) and catcher processor (CP)). Within the sectoral allocations the fisheries effectively operate as open access with limited entry. Almost all of the GOA Pacific cod fisheries is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch. Approximately 40% is caught by the trawl, 40% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. In recent years approximately 60% of the retained catch volume and value is in the Central Gulf fisheries, 40% in the Western Gulf, and 1-2% occurring in other region of the GOA. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch. The 2016 retained catch in the GOA decreased 18% to 63 thousand t in part due to a reduction in the TAC. In most years the fisheries harvest the entire TAC, however, in 2016 only approximately 90% of the TAC was harvested, poor fishing conditions were a potential contributing factor. The ex-vessel value totaled $41 million in 2016, which was down from $50 million in 2015. Ex-vessel prices were basically unchanged at $0.29 per pound in 2016. Catch from the fixed gear vessels (which includes hook-and-line and pot gear) typically receive a slightly higher price from processors because they incur less damage when caught, has recently been about $0.04 per pound.

The first-wholesale value of Pacific cod products was down 12% to $90.2 million in 2015. Despite lower prices through 2014 and 2015 revenues were strong as result of increased catch levels. In contrast, 2016 prices were up and revenues are down because of reduced production volume. The two primary product forms produced from cod in the GOA are fillets and H&G, which comprise approximately 55% and 30% of the value on average, though the relative share can fluctuate year over year depending on relative prices and processing decisions. The average price of GOA Pacific cod products in 2016 increased 29% to $1.89 driven by an increase 23% in fillet prices to $3.36 per pound. Media reports indicate that Pacific cod prices were soft in early 2016 with weak demand from Japan, an important market for Pacific cod. By the middle of the year prices had begun to rise with strong demand from the U.S., Japan, and other markets. High prices of common fish protein substitutes such as salmon were also cited as contributing to the strong cod demand. Strong demand globally coupled with tight supply have resulted in high prices continuing throughout 2017. H&G prices were comparatively weaker and first wholesale prices dropped 13% to $1.09 which likely contributed to the reduction in H&G production.

U.S. exports of cod are roughly proportional to U.S. cod production. More than 90% of the exports are H&G, much of which goes to China for secondary processing and re-export. China’s rise as re-processor is fairly recent. Between 2001 and 2011 exports to China have increased nearly 10 fold. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Approximately 30% of Alaska’s cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 20% of global production and the GOA is approximately 20% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. However, strong demand and tight supply in 2017 from the U.S. and globally have contributed to high prices. With the Barents Sea quota reduced by 13% 2018 the global cod supply is expected to remain constrained relative to recent levels which could result in continued high price levels through 2018.

Data Gaps and Research Priorities

Understanding of the above ecosystem considerations would be improved if future research were directed toward closing certain data gaps. Such research would have several foci, including the following: 1) ecology of the Pacific cod stock, including spatial dynamics, trophic and other interspecific relationships, and the relationship between climate and recruitment; 2) behavior of the Pacific cod fishery, including spatial dynamics; 3) determinants of trawl survey catchability and selectivity and relationship with environmental covariates; 4) age determination and effects of aging error and bias on model parameters including natural mortality; 5) ecology of species taken as bycatch in the Pacific cod fisheries, including estimation of biomass, carrying capacity, and resilience; and 6) ecology of species that interact with Pacific cod, including estimation of biomass, carrying capacity, and resilience.

Literature Cited

Albers, W. D., and P. J. Anderson. 1985. Diet of Pacific cod, *Gadus macrocephalus*, and predation on the northern pink shrimp, *Pandalus borealis*, in Pavlof Bay, Alaska. Fish. Bull., U.S. 83:601-610.

Alderdice, D.F. and Forrester, C.R., 1971. Effects of salinity, temperature, and dissolved oxygen on early development of the Pacific cod (*Gadus macrocephalus*). Journal of the Fisheries Board of Canada, 28(6), pp.883-902.

A'mar, T. and W. Pallson 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

A'mar, T., Thompson, G., Martin, M., and W. Palsson. 2012. 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. 183-322. 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.

Betts, M., H. D. G. Maschner, and D. S. Clark 2011. Zooarchaeology of the 'Fish That Stops', in Madonna L. Moss and Aubrey Cannon, eds., *The Archaeology of North Pacific Fisheries*, University of Alaska Press, Fairbanks, Alaska, 188.

Boldt, J. (editor). 2005. Ecosystem Considerations for 2006. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua (2015), Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett., 42, 3414–3420

Cahalan, J., J. Gasper, and J. Mondragon. 2014. Catch sampling and estimation in the federal groundfish fisheries off Alaska, 2015 edition. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-286, 46 p.

Calkins, D. G. 1998. Prey of Steller sea lions in the Bering Sea. Biosphere Conservation 1:33-44.

Faunce, C., J. Sullivan, S. Barbeaux, J. Cahalan, J. Gasper, S. Lowe, and R. Webster. 2017. Deployment performance review of the 2016 North Pacific Groundfish and Halibut Observer Program. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-358, 75 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.

Fournier, D., and C. P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 38:1195-1207.

Fournier, D.A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68: 1124-1138.

Gaichas, S., Aydin, K.Y. & Francis, R.C. 2015. Wasp waist or beer belly? Modeling food web structure and energetic control in Alaskan marine ecosystems, with implications for fishing and environmental forcing. Progress in Oceanography, 138: 1–17. https://doi.org/10.1016/j.pocean.2015.09.010

Geweke, J. Evaluating the accuracy of sampling-based approaches to calculating posterior moments. In Bayesian Statistics 4 (ed JM Bernado, JO Berger, AP Dawid and AFM Smith). Clarendon Press, Oxford, UK.

Greer-Walker, M. 1970. Growth and development of the skeletal muscle fibres of the cod (*Gadus morhua L.*). Journal du Conseil 33:228-244.

Gregory, R. S., C. Morris, and B. Newton. In review. Relative strength of the 2007 and 2008 year-classes, from nearshore surveys of demersal age 0 Atlantic cod in Newman Sound, Bonavista Bay. Can. Sci. Advis. Sec. Res. Doc. series./xxx.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-146.

Heidelberger P and Welch PD. Simulation run length control in the presence of an initial transient. Opns Res., 31, 1109-44 (1983)

Hiatt, T., R. Felthoven, M. Dalton, B. Garber-Yonts, A. Haynie, K. Herrmann, D. Lew, J. Sepez, C. Seung, L. Sievanen, and the staff of Northern Economics. 2007. Stock Assessment and Fishery Evaluation Report for the Groundfish Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the Groundfish Fisheries off Alaska, 2006. Economic and Social Sciences Research Program, Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, Washington 98115-6349. 353 p.

Holsman, KK and K Aydin. (2015). Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Mar Ecol Prog Ser doi: 521:217-23510.3354/ meps11102

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.

Lang, G. M., C. W. Derrah, and P. A. Livingston. 2003. Groundfish food habits and predation on commercially important prey species in the Eastern Bering Sea from 1993 through 1996. Alaska Fisheries Science Center Processed Report 2003-04. Alaska Fisheries Science Center, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 351 p.

Laurel, B.J., Hurst, T.P., Copeman, L.A. and Davis, M.W., 2008. The role of temperature on the growth and survival of early and late hatching Pacific cod larvae (Gadus macrocephalus). Journal of Plankton Research, 30(9), pp.1051-1060.

Livingston, P. A. 1989. Interannual trends in Pacific cod, Gadus macrocephalus, predation on three commercially important crab species in the eastern Bering Sea. Fish. Bull., U.S. 87:807-827.

Livingston, P. A. 1991. Pacific cod. *In* P. A. Livingston (editor), Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1984 to 1986, p. 31-88. U.S. Dept. Commer, NOAA Tech. Memo. NMFS F/NWC-207.

Livingston, P. A. (editor). 2003. Ecosystem Considerations for 2003. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Livingston, P.A., Aydin, K., Buckley, T.W., Lang, G.M., Yang, M-S., Miller, B.S. (2017) Quantifying food web interactions in the North Pacific - a data-based approach. Environmental Biology of Fishes 100:443-470. doi: 10.1007/s10641-017-0587-0

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

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78, 1069-1079.

Methot, R. D. 1986. Synthetic estimates of historical abundance and mortality for northern anchovy, *Engraulis mordax*. NMFS, Southwest Fish. Cent., Admin. Rep. LJ 86-29, La Jolla, CA.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Methot, R. D. 1998. Application of stock synthesis to NRC test data sets. *In* V. R. Restrepo (editor), Analyses of simulated data sets in support of the NRC study on stock assessment methods, p. 59-80. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-30.

Methot, R. D. 2000. Technical description of the stock synthesis assessment program. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-43, 46 p.

Methot, R. D. 2005a. Technical description of the Stock Synthesis II Assessment Program. Unpubl. manuscr. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 54 p.

Methot, R. D. 2005b. User manual for the assessment program Strock Synthesis 2 (SS2), Model Version 1.19. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2007. User manual for the integrated analysis program Stock Synthesis 2 (SS2), Model Version 2.00c. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2013. User Manual for Stock Synthesis, Model Version 3.24q. Unpublished manuscript. 150 p.

Methot, R. D., and Wetzell, C. R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Rsch. 142:86-99.

National Marine Fisheries Service (NMFS). 2005. Final environmental impact statement for essential fish habitat identification and conservation in Alaska. National Marine Fisheries Service, Alaska Region. P.O. Box 21668, Juneau, AK 99802-1668.

Nichol, D. G., T. Honkalehto, and G. G. Thompson. 2007. Proximity of Pacific cod to the sea floor: Using archival tags to estimate fish availability to research bottom trawls. *Fisheries Research* 86:129-135.

Nichols, N. W., P. Converse, and K. Phillips. 2015. Annual management report for groundfish fisheries in the Kodiak, Chignik, and South Alaska Peninsula Management Areas, 2014. Alaska Department of Fish and Game, Fishery Management Report No. 15-41, Anchorage.

Ona, E., and O. R. Godø. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer 189: 159–166.

Pitcher, K. W. 1981. Prey of Steller sea lion, *Eumetopias jubatus*, in the Gulf of Alaska. Fishery Bulletin 79:467-472.

Martyn Plummer, Nicky Best, Kate Cowles and Karen Vines (2006). CODA: Convergence Diagnosis and Output Analysis for MCMC, R News, vol 6, 7-11

Raring, N. W., E. A. Laman, P. G. von Szalay, and M. H. Martin. 2016. Data report: 2011 Gulf of Alaska bottom trawl survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-330, 231 p. doi:10.7289/V5/TM-AFSC-330.

Rose, G.A. and Kulka, D.W., 1999. Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (*Gadus morhua*) declined. Canadian Journal of Fisheries and Aquatic Sciences, 56(S1), pp.118-127.

Saha, S., and Coauthors, 2010: The NCEP climate forecast system reanalysis. Bull. Amer. Meteor. Soc., 91, 1015-1057.

Savin, A. B. 2008. Seasonal distribution and Migrations of Pacific cod *Gadus macrocephalus* (Gadidae) in Anadyr Bay and adjacent waters. Journal of Ichythyology 48:610-621.

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.

Sinclair, E.S. and T. K. Zeppelin. 2002. Seasonal and spatial differences in diet in the western stock of Steller sea lions (*Eumetopias jubatus*). Journal of Mammalogy 83(4).

Smith, R.L., Paul, A.J. and Paul, J.M., 1990. Seasonal changes in energy and the energy cost of spawning in Gulf of Alaska Pacific cod. Journal of Fish Biology, 36(3), pp.307-316.

Spies I. 2012. Landscape genetics reveals population subdivision in Bering Sea and Aleutian Islands Pacific cod. *Transactions of the American Fisheries Society* 141:1557-1573.

Stark, J. W. 2007. Geographic and seasonal variations in maturation and growth of female Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska and Bering Sea. Fish. Bull. 105:396–407.

Thompson, G., T. A'mar, and W. Palsson. 2011. 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. 161-306. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Thompson, G. G., and M. E. Conners. 2007. Report of the Pacific cod technical workshop held at the Alaska Fisheries Science Center, April 24-25, 2007. Unpubl. manuscr., Alaska Fisheries Science Center, Resource Ecology and Fisheries Management Division, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 56 p.

Thompson, G. G., and M. W. Dorn. 2005. 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. 155-244. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., M. Dorn, and D. Nichol. 2006. 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. 147-220. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, D. Nichol, S. Gaichas, and K. Aydin. 2007a. Assessment of the Pacific cod stock in the Eastern Bering Sea and Aleutian Islands Area. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions, p. 209-327. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2007b. 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. 169-194. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2009. 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. 165-352. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2010. 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. 157-328. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and R. D. Methot. 1993. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

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. 1994. 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 1995, 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.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2002. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 89-167. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2004. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 131-232. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Ueda, Y., Y. Narimatsu, T. Hattori, M. Ito, D. Kitagawa, N. Tomikawa, and T. Matsuishi. 2006. Fishing efficiency estimated based on the abundance from virtual population analysis and bottom-trawl surveys of Pacific cod (Gadus macrocephalus) in the waters off the Pacific coast of northern Honshu, Japan. Nippon Suisan Gakkaishi 72:201-209.

Vollenweider, J.J., Heintz, R.A., Schaufler, L. & Bradshaw, R. 2011. Seasonal cycles in whole-body proximate composition and energy content of forage fish vary with water depth. Marine Biology, 158(2): 413–427. https://doi.org/10.1007/s00227-010-1569-3

Walters, C., 2003. Folly and fantasy in the analysis of spatial catch rate data. Canadian Journal of Fisheries and Aquatic Sciences, 60(12), pp.1433-1436.

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.

Westrheim, S. J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092. 390 p.

Yang, M-S. 2004. Diet changes of Pacific cod (Gadus macrocephalus) in Pavlof Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 102:400-405.

Zador et al. 2017. Ecosystem considerations for the Gulf of Alaska. 2017 SAFE report.

Tables

Table 2.1. Studies of Pacific cod natural mortality and statistics on the combined values. The column labeled "Used?" indicates whether the value was used in developing this year's assessment model prior on natural mortality.

Area	Author	Year	Value	ln(value)	Used?	Statistics	
EBS	Low	1974	0.375	-0.981	Y	mu:	-0.815
EBS	Wespestad et al.	1982	0.7	-0.357	Y	sigma:	0.423
EBS	Bakkala and Wespestad	1985	0.45	-0.799	Y	Arithmetic:	0.484
EBS	Thompson and Shimada	1990	0.29	-1.238	Y	Geometric:	0.443
EBS	Thompson and Methot	1993	0.37	-0.994	Y	Harmonic:	0.405
EBS	Shimada and Kimura	1994	0.96	-0.041	Y	Mode:	0.370
EBS	Shi et al.	2007	0.45	-0.799	Y	L95%:	0.193
EBS	Thompson et al.	2007	0.34	-1.079	Y	U95%:	1.015
EBS	Thompson	2016	0.36	-1.022	Y		
GOA	Thompson and Zenger	1993	0.27	-1.309	Y		
GOA	Thompson and Zenger	1995	0.5	-0.693	Y		
GOA	Thompson	2007	0.38	-0.968	Y		
GOA	Barbeaux et al.	2016	0.47	-0.755	N		
BC	Ketchen	1964	0.595	-0.519	Y		
BC	Fournier	1983	0.65	-0.431	Y		

Table 2.2. Catch (t) for 1991 through 2017 by jurisdiction and gear type (as of 2017-10-10)

	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	16,537	20,114	429	58,845	826	14,604	4,045	19,475	78,320
2011	16,453	16,547	29,231	722	62,952	995	16,675	4,627	22,297	85,249
2012	20,071	14,466	21,237	722	56,496	862	15,939	4,613	21,414	77,910
2013	21,698	12,863	17,010	476	52,046	1,087	14,154	1,303	16,544	68,591
2014	26,794	14,747	19,956	1,046	62,543	1,006	18,442	2,838	22,286	84,829
2015	22,260	12,741	20,643	408	56,053	468	19,717	2,807	22,993	79,045
2016	15,210	8,151	19,245	346	42,952	806	18,606	1,708	21,120	64,071
2017*	12,666	7,632	11,786	67	32,152	127	13,023	62	13,212	45,364

Table 2.3 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 2017 is current through 2017-10-11. 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	76,301	77,900	77,900	-
1992	80,073	63,500	63,500	87,600
1993	55,709	56,700	56,700	78,100
1994	46,649	50,400	50,400	71,100
1995	68,085	69,200	69,200	126,000
1996	68,064	65,000	65,000	88,000
1997	67,840	69,115	81,500	180,000
1998	61,520	66,060	77,900	141,000
1999	67,928	67,835	84,400	134,000
2000	54,266	59,800	76,400	102,000
2001	41,533	52,110	67,800	91,200
2002	42,307	44,230	57,600	77,100
2003	52,461	40,540	52,800	70,100
2004	56,569	48,033	62,810	102,000
2005	47,538	44,433	58,100	86,200
2006	47,822	52,264	68,859	95,500
2007	51,895	52,264	68,859	97,600
2008	58,666	50,269	64,493	88,660
2009	52,633	41,807	55,300	66,000
2010	77,623	59,563	79,100	94,100
2011	84,385	65,100	86,800	102,600
2012	77,195	65,700	87,600	104,000
2013	67,394	60,600	80,800	97,200
2014	83,687	64.738	88,500	107,300
2015	77,771	75,202	102,850	140,300
2016	64,071	71,925	98,600	116,700
2017*	45,364	64,442	88,342	105,378

*As of 10/11/2017

Table 2.4. History of GOA Pacific cod allocations by regulatory area (in percent)

Year(s)	Western	Central	Eastern
1977-1985	28	56	16
1986	40	44	16
1987	27	56	17
1988-1989	19	73	8
1990	33	66	1
1991	33	62	5
1992	37	61	2
1993-1994	33	62	5
1995-1996	29	66	5
1997-1999	35	63	2
2000-2001	36	57	7
2002	39	55	6
2002	38	56	6
2003	39	55	6
2003	38	56	6
2004	36	57	7
2004	35.3	56.5	8.2
2005	36	57	7
2005	35.3	56.5	8.2
2006	39	55	6
2006	38.54	54.35	7.11
2007	39	55	6
2007	38.54	54.35	7.11
2008	39	57	4
2008	38.69	56.55	4.76
2009	39	57	4
2009	38.69	56.55	4.76
2010	35	62	3
2010	34.86	61.75	3.39
2011	35	62	3
2011	35	62	3
2012	35	62	3
2012	32	65	3
2013	38	60	3
2014	37	60	3
2015	38	60	3
2016	41	50	9
2017	41	50	9
2018	44.9	45.1	10

Table 2.5 Estimated retained-and discarded GOA Pacific cod from federal waters (source: AKFIN; *as of 2017-10-11)

Year	Discarded	Retained	Grand Total
1991	1,427	74,873	76,301
1992	3,920	76,827	80,747
1993	5,886	50,602	56,488
1994	3,122	44,363	47,485
1995	3,546	65,439	68,985
1996	7,555	60,725	68,280
1997	4,828	63,647	68,476
1998	1,732	60,389	62,121
1999	1,645	66,970	68,614
2000	1,378	53,130	54,508
2001	1,904	39,715	41,619
2002	3,715	38,631	42,345
2003	2,485	50,097	52,582
2004	1,268	55,355	56,624
2005	1,043	46,541	47,584
2006	1,852	46,045	47,897
2007	1,448	50,813	52,261
2008	3,307	55,707	59,014
2009	3,944	49,252	53,196
2010	2,871	75,449	78,320
2011	2,083	83,166	85,249
2012	973	76,937	77,910
2013	4,623	63,968	68,591
2014	5,231	79,598	84,829
2015	1,734	77,311	79,045
2016	895	63,177	64,071
2017*	522	44,842	45,364

Table 2.6 Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2013 – 2017 for GOA Pacific cod as target species (AKFIN; as of 2017-10-20)

	2013		2014		2015		2016		2017	
Species	D	R	D	R	D	R	D	R	D	R
flounder, arrowtooth	862	576	818	499	448	659	560	809	205	258
flounder, starry	0	4	0	3	0	4	0	3		3
greenling, atka mackerel	21	0	7	0	146	11	31	8	349	32
halibut, Pacific	0	26	5	30	28	35	5	15	8	20
octopus, North Pacific	109	212	673	511	524	376	154	204	28	131
Pacific sleeper shark	14		2		18		9		0	
perch, Pacific ocean	7	5	0	14	104	62	781	15	46	29
pollock, walleye	105	750	87	1422	108	1002	58	346	308	464
rockfish, dusky	17	6	10	39	11	16	60	19	75	13
rockfish, harlequin	0	0	0	0	1	2	3		1	
rockfish, northern	48	62	13	59	12	35	61	17	36	8
rockfish, quillback	0	4	0	4	0	21	0	15	0	8
rockfish, redstripe		1		0		1		0	0	0
rockfish, rougheye	0	1	1	3	0	3	1	2	7	2
rockfish, shortraker	1	3	3	1	0	3	1	1	4	2
rockfish, silvergray	0	0	0	0		1	0	1		0
rockfish, thornyhead (idiots)	5	3	3	16	5	4	3	7	11	20
rockfish, yelloweye (red snapper)	6	13	16	11	7	20	13	17	36	29
sablefish (blackcod)	31	16	12	45	39	36	100	31	65	20
sculpin, bigmouth	20		6		25		20		15	
sculpin, general	2	5	1	7	0	3	1	11	1	2
sculpin, great	66		65		92		158		321	
sculpin, other large	192		206		229		163		155	
sculpin, plain	1				1		3			
sculpin, yellow irish lord	192		257		278		502	0	392	
shark, spiny dogfish	45	0	375	0	111	0	341	0	214	
skate, Alaskan		0		1		0		2		0
skate, Aleutian		3		8		4		8		5
skate, big	212	399	660	180	569	203	384	253	394	151
skate, longnose	82	266	94	321	148	465	335	154	209	86
skate, other	794	8	876	50	998	77	910	63	730	27
skate, Whiteblotched								0		1
sole, butter	0	186	0	69	0	48	0	45	0	10
sole, dover	0	6	0	9	0	15	1	4	0	0
sole, English		15	0	9		7	0	3		1
sole, flathead	6	179	15	180	13	241	6	245	12	99
sole, rex	17	95	12	73	8	113	23	147	3	16
sole, rock	4	586	8	514	8	655	13	514	20	550
sole, yellowfin			0	0	1			0	0	0
squid, majestic	0	1		0	0	1	0	1	0	0

Table 2.7 Incidental catch (t or birds by number) of non-target species groups by GOA Pacific cod fisheries, 2013-2017 (as of 2017-10-20).

	2013	2014	2015	2016	2017
Benthic urochordata		0.1	4.3	0.0	1.3
Birds	99	123	99	163	129
Bivalves	1.7	1.6	1.4	0.7	1.2
Brittle star unidentified	0.1	0.0	0.0	0.0	0.0
Corals Bryozoans - Corals Bryozoans Unidentified	0.1	1.5	1.2	0.4	1.2
Corals Bryozoans - Red Tree Coral		0.1	0.5		
Eelpouts	0.2	0.1	0.3	0.1	0.1
Eulachon		0.2	0.0		0.0
Giant Grenadier	80.0	183.8	107.3	83.5	14.3
Greenlings	1.2	1.4	2.6	4.7	5.6
Grenadier - Rattail Grenadier Unidentified	17.4	15.6	0.1	1.2	
Hermit crab unidentified	1.9	0.4	2.8	0.6	0.1
Invertebrate unidentified	0.4	0.5	0.2	1.1	0.0
Misc crabs	2.9	2.9	1.0	1.0	0.8
Misc crustaceans	0.0	0.0	0.5		0.0
Misc fish	90.4	120.5	108.4	152.5	146.4
Misc inverts (worms etc)			0.0		
Other osmerids				0.0	
Pacific Hake				0.0	
Pacific Sand lance		0.0			0.0
Pandalid shrimp			0.0	0.0	
Polychaete unidentified	0.0			0.0	
Scypho jellies	1.6	1.2	4.0	21.5	0.9
Sea anemone unidentified	6.6	6.8	5.7	21.2	12.2
Sea pens whips	2.3	2.9	1.8	0.7	0.5
Sea star	551.7	872.0	1218.4	892.3	360.7
Snails	2.4	24.0	11.8	14.6	9.2
Sponge unidentified	0.4	0.3	1.3	1.6	1.8
State-managed Rockfish	40.2	13.6	14.6	47.1	73.3
Stichaeidae	0.1				0.3
urchins dollars cucumbers	1.2	1.4	4.2	2.0	4.4

Table 2.8 Pacific cod catch (t) in other target Gulf of Alaska groundfish fisheries. *Data for 2017 is as of 10/20/2017.

Year	Shallow Water Flatfish - GOA	Arrowtooth Flounder	Pollock - bottom	Rockfish	Halibut	Rex Sole - GOA	Pollock - midwater	Flathead Sole	Sablefish	Other Species	Deep Water Flatfish - GOA	Atka Mackerel	Total
2003	1,598	844	110	1,787	281	588	166	274	87	325	38		6,097
2004	806	504	222	1,735	257	175	171	194	51	120	106		4,341
2005	1,234	636	207	931	226	115	145	153	95	22	6		3,772
2006	1,278	944	647	521	253	271	62	38	144	8	1		4,166
2007	2,421	901	217	251	423	409	58	131	129			1	4,941
2008	3,367	1,593	459	445	488	238	120	125	156	0			6,991
2009	4,196	611	394	631	938	592	158	279	88	10			7,897
2010	2,742	719	1,309	734	578	390	188	286	73	24	8		7,052
2011	924	1,736	1,338	560	1,273	155	162	94	86	2	16	9	6,354
2012	1,040	934	935	404	233	174	332	134	40	0			4,225
2013	2,626	1,038	850	584	1,954	203	192	102	129	0	9	15	7,701
2014	2,267	3,030	2,810	624	1,132	273	476	64	100	1	2		10,780
2015	711	1,383	1,089	785	453	162	622	1	117	12			5,335
2016	224	1,345	623	365	279	25	227	39	101			10	3,239
2017*	117	1,117	476	223	232	6	35	2	62	2		5	2,275

Table 2.9 Noncommercial fishery catch (in kg); total source amounts less than 1 mt were omitted (AFSC for GOA bottom trawl survey values; AKFIN for other values, as of 2017-10-28)

Source	2009	2010	2011	2012	2013	2014	2015
Annual Longline Survey	30,987	33,224	27,069	30,505	22,734	33,370	39,824
Bait for Crab Fishery					16,444	7,348	1,616
Golden King Crab Pot Survey				12			
Gulf of Alaska Bottom Trawl Survey			29,393		26,221		18,945
IPHC Annual Longline Survey		142,300	124,356	85,595	123,197	138,091	77,044
Large-Mesh Trawl Survey	958	11,702	17,015	20,500	18,577	13,090	8,072
Salmon EFP 13-01					2,647	8,316	
Scallop Dredge Survey	14				8		0
Shelikof Acoustic Survey		14					
Shelikof and Chirikof EIT				4			
Shumagin and Sanak EIT				583			
Shumigans Acoustic Survey		1,030					
Small-Mesh Trawl Survey		1,887	1,654	2,662	1,678	1,424	1,412
Sport Fishery		113,660	155,527	143,762	131,133	199,263	183,813
Spot Shrimp Survey			3			12	10
Structure of Gulf of Alaska Forage Fish Communities		136					
Western Gulf of Alaska Pollock Acoustic Cooperative Survey		59					
Total	31,959	304,011	355,017	283,622	342,639	400,913	330,736

Table 2.10 Pacific cod catch (t) in other target Gulf of Alaska groundfish fisheries. *Data for 2017 is as of 10/20/2017.

Year	Shallow Water Flatfish - GOA	Arrowtooth Flounder	Pollock - bottom	Rockfish	Halibut	Rex Sole - GOA	Pollock - midwater	Flathead Sole	Sablefish	Other Species	Deep Water Flatfish - GOA	Atka Mackerel	Total
2003	1,598	844	110	1,787	281	588	166	274	87	325	38		6,097
2004	806	504	222	1,735	257	175	171	194	51	120	106		4,341
2005	1,234	636	207	931	226	115	145	153	95	22	6		3,772
2006	1,278	944	647	521	253	271	62	38	144	8	1		4,166
2007	2,421	901	217	251	423	409	58	131	129			1	4,941
2008	3,367	1,593	459	445	488	238	120	125	156	0			6,991
2009	4,196	611	394	631	938	592	158	279	88	10			7,897
2010	2,742	719	1,309	734	578	390	188	286	73	24	8		7,052
2011	924	1,736	1,338	560	1,273	155	162	94	86	2	16	9	6,354
2012	1,040	934	935	404	233	174	332	134	40	0			4,225
2013	2,626	1,038	850	584	1,954	203	192	102	129	0	9	15	7,701
2014	2,267	3,030	2,810	624	1,132	273	476	64	100	1	2		10,780
2015	711	1,383	1,089	785	453	162	622	1	117	12			5,335
2016	224	1,345	623	365	279	25	227	39	101			10	3,239
2017*	117	1,117	476	223	232	6	35	2	62	2		5	2,275

Table 2.11 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 2.12 AFSC's longline survey Relative Population Number (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			
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 2.13 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			
2007	18,196.23	0.19			

Table 2.14 ADFG trawl survey deltaGLM biomass index and CVs for Pacific cod.

Year	Index	CV	Year	Index	CV
1988	2.85	0.09	2005	1.08	0.09
1989	3.79	0.09	2006	0.93	0.09
1990	2.82	0.08	2007	1.11	0.08
1991	1.93	0.14	2008	1.28	0.07
1992	2.93	0.08	2009	1.29	0.07
1993	2.37	0.09	2010	1.09	0.07
1994	2.13	0.08	2011	1.40	0.07
1995	2.36	0.11	2012	2.65	0.09
1996	2.39	0.09	2013	2.00	0.10
1997	2.57	0.08	2014	1.37	0.10
1998	2.32	0.09	2015	1.24	0.10
1999	1.28	0.07	2016	0.85	0.11
2000	1.00	0.08	2017	0.90	0.11
2001	0.88	0.08			
2002	1.11	0.07			
2003	0.89	0.08			
2004	1.37	0.07			

Table 2.15 CFSR bottom temperature index for 10 cm and 40 cm Pacific cod for 1979-2016.

Year	10cm	40cm	Year	10cm	40cm
1979	5.798	5.111	1999	5.100	5.015
1980	5.488	5.024	2000	5.183	4.878
1981	6.454	5.460	2001	5.476	5.081
1982	4.747	4.645	2002	4.824	4.447
1983	5.636	5.329	2003	5.833	5.438
1984	5.367	5.314	2004	5.235	5.089
1985	5.219	5.232	2005	5.503	5.320
1986	5.342	5.085	2006	5.299	5.059
1987	6.061	5.412	2007	4.752	4.377
1988	5.481	5.031	2008	4.849	4.645
1989	4.728	4.509	2009	4.383	4.396
1990	4.847	4.561	2010	5.736	5.164
1991	4.967	4.648	2011	5.038	4.775
1992	5.462	4.965	2012	4.755	4.275
1993	5.135	4.794	2013	4.716	4.741
1994	5.058	4.888	2014	5.465	5.004
1995	4.592	4.688	2015	6.468	5.668
1996	5.106	4.864	2016	6.075	5.005
1997	5.123	4.959			
1998	6.270	5.575			

Table 2.16 Number of parameters by category for model configurations presented.

	M17.xx.25	M17.09.26	M17.09.31	M17.09.36	M17.09.37
Recruitment					
Early Rec. Devs (1962-1977)	16	16	16	16	16
Main Rec. Devs (1978-2014)	37	37	37	37	37
Late Rec. Devs (2015-2017)	3	3	3	3	3
Future Rec. Devs. (2018-2022)	5	5	5	5	5
R_0	1	1	1	1	1
R_1 offset	1	1	1	1	1
Natural mortality	1	1	2	2	4
Growth	5	5	5	5	5
Catchability					
Q_{trawl}	1	1	1	1	1
$Q_{longline}$			1		
$Q_{longline}$ env. offset			1		
Initial F	2	2	2	2	2
Selectivity					
Trawl Survey	18	16	18	16	16
Longline survey	5	5	5	5	5
Trawl Fishery	13	55 (39 dev)	55 (39 dev)	59 (39 dev)	59 (39 dev)
Longline Fishery	11	36 (24 dev)	36 (24 dev)	40 (24 dev)	40 (24 dev)
Pot Fishery	8	8	8	8	8
Total	127	192	195	202	204

Table 2.17 Model fit statistics and results. Note that likelihoods between model series are not completely comparable.

	M17.08.25	M17.09.25	M17.09.26	M17.09.31	M17.09.35	M17.09.36	M17.09.37
AIC	3918.88	3613.18	3604.90	3580.68	3522.78	2774.70	2739.02
Likelihoods							
Total	1822.44	1672.59	1610.45	1595.34	1559.39	1185.35	1165.51
Survey	26.01	24.84	5.98	-0.24	0.80	2.38	-5.51
Length Composition	1228.27	1102.86	1057.78	1045.43	1005.46	643.05	640.83
Age Composition	569.36	547.62	541.79	538.02	531.37	534.00	531.97
Recruitment	-7.86	-8.02	-2.99	-6.05	-4.14	-1.07	-1.20
Parameter priors	0.00	0.00	1.21	10.10	11.64	9.76	2.96
Parameter Devs.	0.025	0.022	4.85	4.80	4.80	3.81	3.94
Parameters							
R_0 billions	360.16	355.93	372.54	501.12	531.37	470.62	493.61
Steepness	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Natural Mortality	0.44	0.44	0.44|0.88	0.48|0.69	0.49|0.71	0.48|0.69	See text
$q_{Shelf}\|q_{longline}$	1.78	1.67	1.57	1.48|1.4 - 2.7	1.47|1.4-2.7	1.56|1.5 - 2.8	1.73|1.7 - 3.0
L_{min}	5.72	6.82	6.74	7.04	7.08	7.13	7.09
L_{max}	117.76	123.67	120.28	124.25	124.14	123.98	122.99
Von Bert K	0.13	0.12	0.12	0.11	0.11	0.11	0.11
Results							
Model							
SSB_{1978} (t)	120,656	111,802	65,599	72,447	74,472	79,064	82,088
Projection							
$SSB_{100\%}$ (t)	184,887	185,832	190,511	169,261	168,583	164,520	
SSB_{2017} (t)	44,468	43,289	36,534	40,102	40,442	37,632	
$SSB_{2017\%}$	24.1%	23.3%	19.2%	23.7%	24.0%	22.8%	
SSB_{2018}(t)	39,177	38,804	31,694	35,159	36,209	33,334	
$SSB_{2018\%}$	21.2%	20.9%	16.7%	20.8%	21.5%	20.3%	
$F_{35\%}$	0.496	0.570	0.459	0.749	0.657	0.704	
$F_{40\%}$	0.609	0.707	0.558	0.944	0.824	0.887	
2018							
ABC (t)	15,904	16,547	0	17,669	19,401	15,965	
F_{ABC}	0.25	0.283	0	0.370	0.336	0.338	
OFL (t)	19,090	19,989	11,027	21,579	23,564	19,512	
F_{OFL}	0.31	0.349	0.209	0.462	0.417	0.423	
2019							
ABC (t)	14,528	15,858	0	16,758	17,634	15,907	
F_{ABC}	0.238	0.277	0	0.362	0.318	0.342	
OFL (t)	17,795	19,147	14,208	19,745	21,415	18,760	
F_{OFL}	0.291	0.340	0.240	0.436	0.395	0.411	

Table 2.18 Likelihood components by fleet for all proposed models.

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
Model17.08.25	Age_like	569.36	-	-	-	569.36	-
Model17.09.26	Age_like	541.79	-	-	-	541.79	-
Model17.09.31	Age_like	538.02	-	-	-	538.02	-
Model17.09.35	Age_like	540.80	-	-	-	540.80	-
Model17.09.36	Age_like	534.00	-	-	-	534.00	-
Model17.09.37	Age_like	531.97	-	-	-	531.97	-
Model17.08.25	Catch_like	1.26E-09	3.49E-10	4.54E-10	4.57E-10	-	-
Model17.09.25	Catch_like	4.33E-09	1.40E-09	1.47E-09	1.46E-09	-	-
Model17.09.26	Catch_like	3.58E-09	1.15E-09	1.18E-09	1.26E-09	-	-
Model17.09.31	Catch_like	1.10E-09	3.56E-10	3.64E-10	3.81E-10	-	-
Model17.09.35	Catch_like	3.04E-10	9.47E-11	1.07E-10	1.03E-10	-	-
Model17.09.36	Catch_like	1.03E-09	3.19E-10	3.62E-10	3.52E-10	-	-
Model17.09.37	Catch_like	1.01E-08	3.07E-09	3.44E-09	3.56E-09	-	-
Model17.08.25	Length_like	1,228.27	407.87	258.52	203.99	163.68	194.21
Model17.09.25	Length_like	1,102.86	326.09	235.01	211.30	132.74	197.71
Model17.09.26	Length_like	1,057.78	299.72	223.42	209.65	132.78	192.22
Model17.09.31	Length_like	1,045.43	302.39	209.52	207.23	132.04	194.26
Model17.09.35	Length_like	1,005.46	274.13	200.89	208.00	132.85	189.60
Model17.09.36	Length_like	643.05	110.49	123.57	90.13	130.97	187.89
Model17.09.37	Length_like	640.83	108.66	125.22	90.13	129.47	187.36
Model17.08.25	Surv_like	26.01	-	-	-	7.53	18.48
Model17.09.25	Surv_like	24.84	-	-	-	7.60	17.25
Model17.09.26	Surv_like	5.98	-	-	-	-5.54	11.52
Model17.09.31	Surv_like	-0.24	-	-	-	-0.85	0.61
Model17.09.35	Surv_like	0.80	-	-	-	0.33	0.47
Model17.09.36	Surv_like	2.38	-	-	-	-0.38	2.76
Model17.09.37	Surv_like	-5.51	-	-	-	-8.22	2.71

Table 2.19 Retrospective analysis, index RMSE, harmonic mean effective N for length and age compositions, and recruitment variability for assessed models.

	M17.08.25	M17.09.25	M17.09.26	M17.09.31	M17.09.35	M17.09.36	M17.09.37
Retrospective							
Female spawning biomass							
Mohn's ρ	0.107	0.110	-0.004	0.099	0.137	0.091	0.094
Woods Hole ρ	-0.001	0.033	-0.013	0.030	0.062	0.034	0.028
RMSE	0.052	0.059	0.057	0.060	0.073	0.057	0.052
Recruitment (age -0)							
Mohn's ρ	1.002	0.902	-0.011	0.506	0.546	0.487	0.278
Woods Hole ρ	0.090	0.100	0.002	0.075	0.109	0.071	0.054
RMSE	0.219	0.213	0.158	0.174	0.186	0.177	0.158
Index RMSE							
Shelf	0.35	0.34	0.31	0.31	0.32	0.32	0.28
ABL Longline	0.35	0.35	0.33	0.31	0.32	0.33	0.32
Size Comp							
Har. Mean EffN							
Trawl	277.53	284.94	326.70	327.07	330.98	313.98	321.47
Longline	492.20	409.03	454.58	460.67	471.70	464.57	457.33
Pot	716.21	487.01	481.58	494.57	501.93	487.30	479.35
Trawl Survey	355.99	328.07	332.96	331.74	332.73	336.49	323.35
ABL Longline	292.43	289.26	302.10	297.40	305.29	309.60	302.45
*Mean input N*Adjustment*							
Trawl	152.25	124.8	124.8	124.8	124.8	48.30	48.30
Longline	158.18	117.42	117.42	117.42	117.42	69.75	69.75
Pot	177.46	135.54	135.54	135.54	135.54	57.60	57.60
Trawl Survey	100	100	100	100	100	100	100
ABL Longline	100	100	100	100	100	100	100
Age Comp							
Trawl Survey	3.47	3.50	3.49	3.50	3.50	3.50	3.49
Mean input N							
Trawl Survey	2.58	2.49	2.49	2.49	2.49	2.49	2.49
Rec. Var. (1977-2016)							
Std.dev(ln(No. Age 1))	0.41	0.41	0.42	0.41	0.40	0.39	0.35

Table 2.20 Natural mortality by age and year fit in Model 17.09.37, red are high values, blue low.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1977	0.75	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
1978	0.75	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
1979	0.75	0.58	0.56	0.54	0.52	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1980	0.75	0.49	0.48	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
1981	0.75	0.82	0.76	0.71	0.66	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
1982	0.75	0.33	0.34	0.35	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
1983	0.75	0.53	0.52	0.50	0.49	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
1984	0.75	0.46	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
1985	0.75	0.42	0.42	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
1986	0.75	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
1987	0.75	0.66	0.63	0.60	0.57	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
1988	0.75	0.49	0.48	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
1989	0.75	0.32	0.34	0.35	0.36	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
1990	0.75	0.34	0.36	0.37	0.38	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
1991	0.75	0.37	0.38	0.38	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
1992	0.75	0.48	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
1993	0.75	0.40	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
1994	0.75	0.39	0.39	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
1995	0.75	0.30	0.32	0.33	0.35	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
1996	0.75	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
1997	0.75	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
1998	0.75	0.74	0.70	0.66	0.61	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
1999	0.75	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
2000	0.75	0.41	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
2001	0.75	0.48	0.48	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
2002	0.75	0.34	0.35	0.36	0.37	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
2003	0.75	0.59	0.57	0.55	0.53	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2004	0.75	0.42	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
2005	0.75	0.49	0.48	0.48	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
2006	0.75	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
2007	0.75	0.33	0.34	0.35	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
2008	0.75	0.35	0.36	0.37	0.38	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
2009	0.75	0.27	0.29	0.31	0.32	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
2010	0.75	0.56	0.54	0.53	0.51	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
2011	0.75	0.38	0.39	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2012	0.75	0.33	0.34	0.35	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
2013	0.75	0.32	0.33	0.35	0.36	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
2014	0.75	0.48	0.48	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
2015	0.75	1.72	1.41	1.11	0.80	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2016	0.75	1.39	1.15	0.92	0.68	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
2017	0.75	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

Table 2.21 Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model, Model 16.08.25, Model 17.08.25, Model 17.09.25, Model17.09.26. Highlighted are the 1977 and 2012 year classes.

	Last Year's Model		M17.08.25		M17.09.25		M17.09.26	
Year	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev
1977	1.560	0.456	1.077	0.298	0.996	0.279	0.623	0.106
1978	0.473	0.178	0.312	0.116	0.302	0.111	0.188	0.051
1979	0.729	0.233	0.487	0.151	0.463	0.144	0.245	0.054
1980	0.801	0.235	0.546	0.154	0.519	0.149	0.443	0.071
1981	0.480	0.147	0.332	0.097	0.316	0.095	0.388	0.067
1982	0.554	0.168	0.379	0.110	0.370	0.110	0.554	0.079
1983	0.628	0.179	0.442	0.122	0.424	0.120	0.404	0.069
1984	0.912	0.224	0.674	0.159	0.664	0.161	0.631	0.072
1985	0.735	0.174	0.548	0.124	0.546	0.127	0.553	0.057
1986	0.562	0.133	0.413	0.094	0.407	0.096	0.406	0.042
1987	0.692	0.156	0.514	0.111	0.526	0.119	0.530	0.043
1988	0.573	0.132	0.427	0.094	0.436	0.100	0.437	0.040
1989	0.726	0.162	0.541	0.116	0.553	0.124	0.552	0.044
1990	0.668	0.148	0.496	0.105	0.532	0.118	0.536	0.042
1991	0.491	0.110	0.368	0.079	0.369	0.083	0.371	0.034
1992	0.429	0.094	0.324	0.068	0.316	0.069	0.313	0.028
1993	0.409	0.087	0.309	0.063	0.304	0.065	0.303	0.026
1994	0.421	0.088	0.320	0.064	0.326	0.068	0.327	0.026
1995	0.502	0.101	0.384	0.074	0.373	0.076	0.374	0.025
1996	0.351	0.073	0.268	0.054	0.276	0.058	0.275	0.022
1997	0.320	0.066	0.244	0.048	0.254	0.053	0.255	0.020
1998	0.392	0.079	0.299	0.057	0.306	0.062	0.308	0.021
1999	0.542	0.105	0.417	0.077	0.395	0.077	0.398	0.024
2000	0.446	0.085	0.349	0.064	0.337	0.065	0.337	0.021
2001	0.232	0.048	0.181	0.036	0.182	0.037	0.180	0.017
2002	0.265	0.052	0.206	0.039	0.190	0.038	0.189	0.017
2003	0.255	0.049	0.201	0.037	0.179	0.036	0.180	0.018
2004	0.389	0.072	0.304	0.054	0.284	0.055	0.288	0.025
2005	0.591	0.108	0.464	0.081	0.493	0.092	0.502	0.037
2006	0.668	0.121	0.520	0.089	0.556	0.102	0.584	0.040
2007	0.531	0.104	0.419	0.077	0.449	0.087	0.468	0.040
2008	0.754	0.142	0.563	0.097	0.512	0.096	0.574	0.042
2009	0.348	0.071	0.239	0.045	0.255	0.050	0.311	0.033
2010	0.401	0.080	0.255	0.046	0.277	0.053	0.383	0.041
2011	0.752	0.153	0.431	0.075	0.341	0.065	0.609	0.072
2012	1.099	0.235	0.460	0.082	0.449	0.086	0.951	0.124
2013	0.570	0.148	0.197	0.042	0.189	0.043	0.400	0.076
2014	0.261	0.078	0.083	0.022	0.089	0.025	0.160	0.038
2015	0.416	0.186	0.116	0.036	0.137	0.044	0.278	0.085
2016	0.546	0.269	0.109	0.034	0.117	0.038	0.187	0.053
2017			0.360	0.176	0.356	0.175	0.373	0.166
1998			0.299	0.057	0.306	0.062	0.308	0.021
Mean 1977-2015	0.562		0.380		0.375		0.400	
Stdev(Ln(x))		0.407		0.499		0.480		0.42

Table 2.22 Age-0 recruitment and standard deviation of age-0 recruits by year for 2017 models. Highlighted are the 1977 and 2012 year classes.

	M17.09.31		**M17.09.35**		**M17.09.36**		**M16.09.37**	
Year	**Age-0x10^9**	**St.dev.**	**Age-0x10^9**	**Stdev**	**Age-0x10^9**	**Stdev**	**Age-0x10^9**	**St.dev.**
1977	0.890	0.234	0.945	0.255	0.796	0.232	1.077	0.233
1978	0.274	0.094	0.290	0.101	0.276	0.101	0.362	0.118
1979	0.366	0.113	0.388	0.122	0.333	0.114	0.439	0.119
1980	0.654	0.172	0.695	0.187	0.543	0.160	0.707	0.151
1981	0.577	0.157	0.612	0.169	0.545	0.158	0.523	0.097
1982	0.835	0.210	0.881	0.227	0.711	0.195	0.772	0.125
1983	0.601	0.158	0.631	0.169	0.550	0.154	0.568	0.102
1984	0.929	0.206	0.975	0.221	0.827	0.198	0.880	0.111
1985	0.800	0.168	0.841	0.181	0.723	0.163	0.792	0.100
1986	0.583	0.122	0.611	0.132	0.557	0.125	0.599	0.078
1987	0.755	0.150	0.797	0.162	0.693	0.148	0.579	0.058
1988	0.628	0.128	0.660	0.138	0.567	0.125	0.431	0.049
1989	0.804	0.159	0.842	0.171	0.712	0.153	0.579	0.057
1990	0.781	0.152	0.826	0.165	0.723	0.154	0.624	0.059
1991	0.526	0.104	0.550	0.112	0.487	0.105	0.444	0.046
1992	0.434	0.084	0.450	0.090	0.407	0.086	0.354	0.036
1993	0.415	0.079	0.430	0.084	0.402	0.083	0.359	0.037
1994	0.455	0.084	0.474	0.090	0.446	0.090	0.430	0.040
1995	0.522	0.093	0.542	0.099	0.507	0.098	0.579	0.045
1996	0.385	0.071	0.398	0.076	0.336	0.068	0.416	0.042
1997	0.356	0.065	0.369	0.070	0.331	0.066	0.441	0.049
1998	0.426	0.075	0.441	0.080	0.402	0.077	0.400	0.030
1999	0.549	0.093	0.576	0.103	0.501	0.095	0.526	0.037
2000	0.466	0.078	0.505	0.090	0.461	0.086	0.502	0.035
2001	0.252	0.046	0.280	0.054	0.262	0.053	0.275	0.028
2002	0.265	0.047	0.294	0.054	0.253	0.049	0.292	0.031
2003	0.250	0.045	0.276	0.052	0.237	0.047	0.225	0.026
2004	0.398	0.069	0.431	0.078	0.391	0.074	0.361	0.038
2005	0.669	0.112	0.697	0.121	0.602	0.111	0.498	0.050
2006	0.760	0.125	0.799	0.136	0.728	0.130	0.581	0.051
2007	0.627	0.110	0.639	0.114	0.589	0.111	0.471	0.047
2008	0.722	0.122	0.727	0.126	0.660	0.119	0.553	0.050
2009	0.363	0.066	0.370	0.069	0.328	0.064	0.318	0.037
2010	0.408	0.074	0.425	0.079	0.382	0.073	0.316	0.042
2011	0.567	0.106	0.603	0.116	0.531	0.105	0.503	0.073
2012	0.826	0.161	0.902	0.180	0.809	0.164	1.083	0.151
2013	0.379	0.090	0.421	0.102	0.362	0.090	0.839	0.187
2014	0.166	0.046	0.182	0.052	0.161	0.046	0.392	0.108
2015	0.256	0.085	0.278	0.094	0.245	0.084	0.348	0.104
2016	0.193	0.062	0.208	0.068	0.185	0.060	0.162	0.042
2017	0.501	0.241	0.531	0.257	0.471	0.229	0.494	0.220
Mean 1977-2015	0.528		0.565		0.489		0.515	
Stdev(ln(age-0))		0.436		0.426		0.415		0.393

Table 2.23 Estimated female spawning biomass (t) from the 2016 assessment and this year's assessment from Models 16.08.25, 17.09.25, 17.09.35, and 17.09.26

	Last Year's Model		Model17.09.25		Model17.09.35		Model 17.09.36	
	Sp.Bio	St.dev	Sp.Bio	St.dev	Sp.Bio	St.dev	Sp.Bio	St.dev
1977	132,285	30,821	102,570	21,665	67,950	12,982	73,840	15,092
1978	143,660	31,718	111,800	22,316	74,475	13,342	79,065	15,470
1979	140,575	30,038	109,885	21,382	71,785	12,529	75,645	14,655
1980	140,510	28,713	109,485	20,545	72,545	12,284	74,065	13,763
1981	160,675	31,350	122,405	22,274	82,590	14,613	78,750	14,980
1982	195,575	35,342	148,765	25,273	98,600	17,205	90,960	17,096
1983	208,360	35,003	160,155	25,484	101,520	17,580	93,490	17,417
1984	210,755	33,449	163,180	24,814	101,765	17,838	92,320	17,287
1985	214,060	31,229	168,700	23,667	116,150	18,910	103,920	17,910
1986	211,320	27,717	170,640	21,470	138,020	19,415	123,810	18,344
1987	203,960	24,308	167,775	19,195	157,635	19,245	141,275	18,130
1988	202,310	21,719	169,500	17,473	171,305	18,348	154,070	17,233
1989	208,230	19,750	179,045	16,270	186,405	17,373	168,640	16,220
1990	204,735	17,454	180,240	14,755	190,465	15,852	173,590	14,813
1991	184,630	15,274	164,825	13,268	176,205	14,214	161,395	13,344
1992	167,680	13,742	152,205	12,301	164,150	13,138	150,510	12,335
1993	153,455	12,756	141,505	11,740	154,270	12,518	140,655	11,741
1994	154,515	12,172	145,570	11,484	159,545	12,248	145,365	11,535
1995	155,935	11,135	150,385	10,725	164,135	11,395	150,590	10,882
1996	140,470	9,572	137,310	9,300	148,525	9,751	137,025	9,498
1997	121,770	8,053	119,685	7,825	127,535	8,063	118,795	8,042
1998	104,710	6,952	103,025	6,739	108,470	6,867	102,635	7,023
1999	94,670	6,373	92,985	6,144	97,520	6,265	94,050	6,524
2000	84,750	6,031	82,820	5,792	87,170	5,917	84,805	6,180
2001	77,685	5,553	76,405	5,369	80,405	5,476	77,775	5,684
2002	75,600	5,140	75,050	4,985	78,825	5,112	75,995	5,275
2003	78,190	5,022	77,170	4,811	81,325	5,048	78,160	5,143
2004	80,825	4,965	78,285	4,696	83,360	5,145	79,645	5,163
2005	76,535	4,462	73,545	4,262	79,250	4,899	75,880	4,894
2006	67,700	3,660	65,080	3,582	71,040	4,306	68,275	4,270
2007	57,805	3,040	54,680	3,055	61,235	3,818	58,325	3,713
2008	51,225	2,876	46,749	2,928	54,470	3,718	50,985	3,568
2009	53,605	3,357	48,385	3,380	57,740	4,201	53,310	4,006
2010	69,070	4,222	65,345	4,245	75,775	5,124	70,015	4,881
2011	77,630	5,057	76,045	5,004	86,915	5,897	81,005	5,682
2012	81,330	5,957	79,420	5,529	89,920	6,314	84,585	6,143
2013	85,110	6,543	79,500	5,589	88,915	6,312	84,030	6,152
2014	81,115	6,412	72,250	5,011	81,125	5,996	76,420	5,815
2015	75,485	7,088	57,105	4,486	69,555	6,518	64,505	6,176
2016	91,210	10,037	50,785	4,606	56,455	4,941	52,355	4,717
2017	98,479		50,165	5,118	47,326	4,375	44,295	4,153
2018			**38,804**		**35,824**		**33,334**	

Table 2.24 Estimated beginning year weight and length at age from Model 17.09.35.

Age	Weight (kg)	Length (cm)	Age	Weight (kg)	Length (cm)
0	0.000	0.5	11	7.249	88.5
1	0.023	13.5	12	8.264	92.4
2	0.152	25.4	13	9.239	95.8
3	0.443	36.0	14	10.155	98.8
4	0.911	45.4	15	10.993	101.5
5	1.545	53.9	16	11.741	103.9
6	2.319	61.4	17	12.395	106.1
7	3.204	68.1	18	12.957	108.0
8	4.167	74.1	19	13.434	109.8
9	5.179	79.5	20	14.377	114.0
10	6.214	84.3			

Table 2.25 Estimated fishing mortality in Apical F and Total exploitation for Model 17.09.35.

	Sum Apical F				Sum Apical F		
Year	F	σ	**Total Exploitation**	**Year**	F	σ	**Total Exploitation**
1977	0.018	0.005	0.012	2001	0.464	0.038	0.169
1978	0.085	0.016	0.063	2002	0.478	0.036	0.162
1979	0.116	0.025	0.070	2003	0.618	0.043	0.192
1980	0.281	0.063	0.125	2004	0.664	0.046	0.224
1981	0.194	0.037	0.127	2005	0.688	0.052	0.211
1982	0.141	0.026	0.104	2006	0.729	0.053	0.236
1983	0.184	0.034	0.117	2007	0.799	0.066	0.265
1984	0.126	0.025	0.072	2008	1.098	0.105	0.268
1985	0.107	0.024	0.037	2009	0.914	0.086	0.202
1986	0.156	0.033	0.058	2010	1.061	0.096	0.261
1987	0.111	0.044	0.067	2011	0.992	0.086	0.265
1988	0.098	0.012	0.064	2012	0.831	0.076	0.262
1989	0.120	0.019	0.082	2013	0.599	0.059	0.250
1990	0.321	0.031	0.136	2014	0.865	0.090	0.314
1991	0.369	0.034	0.152	2015	1.039	0.120	0.272
1992	0.424	0.040	0.164	2016	0.994	0.114	0.291
1993	0.310	0.028	0.116				
1994	0.250	0.021	0.100				
1995	0.362	0.028	0.153				
1996	0.393	0.030	0.172				
1997	0.457	0.035	0.193				
1998	0.501	0.038	0.191				
1999	0.661	0.052	0.232				
2000	0.588	0.047	0.210				

Table 2.26 Model 17.09.35 parameters and reference estimates MLE and MCMC derived.

	MLE estimates		MCMC posterior distribution		
	MLE	σ	50%	2.5%	97.5%
$M_{Standard}$	0.4902	0.0230	0.48313	0.4366	0.5305
$M_{2015-2016}$	0.7136	0.0612	0.69752	0.5944	0.8259
Von Bert K	0.1134	0.0063	0.11835	0.1071	0.1320
Lmin	7.0841	0.5169	6.81304	5.6691	7.7914
Lmax	124.1370	4.2083	120.864	113.6449	128.4407
$Ln(Q_{Trawl\ survey})$	0.3853	0.0841	0.3827	0.1986	0.5518
$Ln(Q_{ll\ survey})$	0.6638	0.0562	0.6496	0.5034	0.7810
$Ln(Q_{ll\ survey\ envir.\ link})$	0.3244	0.0718	0.3152	0.2082	0.4312
$FSSB_{1978}$	74,475	13,342	79,491	57,478	116,790
$FSSB_{2018}$	40,535	4,621	40,420	32,399	50,171
Recr_1977	945,230	255,260	981,085	594,797	1,742,443
Recr_2012	901,690	180,440	844,229	581,060	1,296,929
$SSB_{2018}/B_{100\%}$	24.04%	2.74%	23.98%	19.22%	29.76%

Table 2.27 Biological reference points from GOA Pacific cod SAFE documents for years 20012017

Year	**$SB_{100\%}$**	**$SB_{40\%}$**	**$F_{40\%}$**	**SB_{y+1}**	**ABC_{y+1}**
2001	212,000	85,000	0.41	82,000	57,600
2002	226,000	90,300	0.35	88,300	52,800
2003	222,000	88,900	0.34	103,000	62,810
2004	211,000	84,400	0.31	91,700	58,100
2005	329,000	132,000	0.56	165,000	68,859
2006	259,000	103,000	0.46	136,000	68,859
2007	302,000	121,000	0.49	108,000	66,493
2008	255,500	102,200	0.52	88,000	55,300
2009	291,500	116,600	0.49	117,600	79,100
2010	256,300	102,500	0.42	124,100	86,800
2011	261,000	104,000	0.44	121,000	87,600
2012	234,800	93,900	0.49	111,000	80,800
2013	227,800	91,100	0.54	120,100	88,500
2014	316,500	126,600	0.50	155,400	102,850
2015	325,200	130,000	0.41	116,600	98,600
2016	196,776	78,711	0.53	105,378	88,342
2017	168,583	67,433	0.80	35,973	18,972

Table 2.28 Number of fish at age-0 from Model 17.09.35 with the M 2015-2016 block fixed at the standard M value used in projection model.

Year	Age-0	Year	Age-0
1977	297,389	2000	352,861
1978	568,910	2001	310,628
1979	172,883	2002	173,066
1980	232,497	2003	181,594
1981	417,153	2004	169,764
1982	368,632	2005	260,850
1983	536,216	2006	423,040
1984	383,023	2007	475,978
1985	594,276	2008	380,924
1986	513,220	2009	417,733
1987	371,982	2010	205,744
1988	485,264	2011	221,401
1989	401,433	2012	279,878
1990	512,310	2013	383,801
1991	503,920	2014	169,596
1992	336,392	2015	75,461
1993	275,087	2016	117,276
1994	262,377	2017	97,815
1995	289,001		
1996	330,958		
1997	243,571		
1998	225,773		
1999	269,297		

Table 2.29 Results for the projection scenarios from Model 17.09.35. Female spawning stock biomass (SSB) SSB, fishing mortality (F), and catch for the 7 projection scenarios.

SSB	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2017	40,442	40,442	40,442	40,442	40,442	40,442	40,442
2018	36,106	36,209	36,267	36,302	37,432	35,792	36,106
2019	33,926	34,424	34,733	34,928	41,981	32,328	33,926
2020	33,505	33,876	34,331	34,624	46,363	31,466	33,204
2021	40,029	39,973	40,901	41,247	56,332	37,726	38,450
2022	54,221	54,179	57,222	57,637	76,350	51,464	51,675
2023	64,144	64,117	72,982	73,527	98,027	60,067	60,086
2024	68,074	68,066	84,020	84,730	116,734	62,641	62,629
2025	69,612	69,610	91,301	92,167	131,988	63,385	63,378
2026	70,108	70,108	95,707	96,699	143,643	63,504	63,502
2027	69,863	69,863	97,858	98,942	151,799	63,126	63,125
2028	69,620	69,620	98,909	100,053	157,445	62,887	62,886
2029	69,430	69,430	99,380	100,562	161,244	62,737	62,737
2030	69,542	69,542	99,795	100,998	163,965	62,877	62,877
F							
2017	0.82	0.82	0.82	0.82	0.82	0.82	0.82
2018	0.34	0.31	0.29	0.29	0.00	0.42	0.34
2019	0.31	0.31	0.29	0.29	0.00	0.37	0.31
2020	0.30	0.32	0.29	0.29	0.00	0.36	0.38
2021	0.38	0.37	0.29	0.29	0.00	0.44	0.45
2022	0.51	0.51	0.29	0.29	0.00	0.61	0.62
2023	0.59	0.59	0.29	0.29	0.00	0.71	0.71
2024	0.61	0.61	0.29	0.29	0.00	0.73	0.73
2025	0.62	0.62	0.29	0.29	0.00	0.74	0.74
2026	0.62	0.62	0.29	0.29	0.00	0.74	0.74
2027	0.62	0.62	0.29	0.29	0.00	0.73	0.73
2028	0.62	0.62	0.29	0.29	0.00	0.73	0.73
2029	0.62	0.62	0.29	0.29	0.00	0.73	0.73
2030	0.62	0.62	0.29	0.29	0.00	0.73	0.73
Catch							
2017	48,940	48,940	48,940	48,940	48,940	48,940	48,940
2018	19,401	18,000	17,206	16,730	0	23,565	19,401
2019	17,168	17,000	16,562	16,180	0	19,247	17,168
2020	15,980	17,187	16,134	15,804	0	17,996	20,067
2021	24,148	24,076	19,295	18,891	0	26,657	27,643
2022	43,988	43,952	26,711	26,119	0	49,414	49,746
2023	58,950	58,905	34,370	33,622	0	65,421	65,429
2024	64,721	64,709	39,754	38,931	0	70,337	70,305
2025	66,575	66,574	43,076	42,229	0	71,469	71,454
2026	67,007	67,007	44,962	44,113	0	71,461	71,457
2027	66,671	66,672	45,849	45,012	0	70,856	70,855
2028	66,400	66,400	46,222	45,398	0	70,479	70,479
2029	66,168	66,168	46,374	45,559	0	70,297	70,297
2030	66,282	66,282	46,539	45,727	0	70,463	70,463

Table 2.30 Gulf of Alaska Pacific cod catch and ex-vessel data. Total and retained catch (thousand metric tons), ex-vessel value (million US$) and price (US$ per pound), hook and line and pot gear share of catch, inshore sector share of catch, number of vessel; 2007-2011 average and 2012-2016.

	Avg 07-11	2012	2013	2014	2015	2016
Total catch K mt	65.6	77.9	68.6	84.8	79	64.1
Retained catch K mt	62.7	76.9	63.9	79.5	77.2	63.1
Ex-vessel value M $	$51.3	$59.6	$37.2	$52.1	$50.0	$41.0
Ex-vessel price lb $	$0.371	$0.352	$0.264	$0.297	$0.293	$0.294
Hook & line share of catch	27%	27%	21%	23%	20%	17%
Pot gear share of catch	48%	48%	49%	48%	52%	60%
Central Gulf share of catch	61%	66%	58%	59%	60%	53%
Shoreside share of catch	88%	91%	92%	91%	92%	92%
Vessels #	437.2	504	350	341	382	358

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.31 Gulf of Alaska Pacific cod first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound), fillet and head and gut volume (thousand metric tons), value share, and price (US$ per pound), inshore share of value; 2007-2011 average and 2012-2016.

		Avg 07-11	2012	2013	2014	2015	2016
All Products	**volume K mt**	27.58	34.09	23.80	31.07	32.00	21.65
All Products	**value M $**	$102.1	$113.6	$94.2	$118.1	$102.9	$90.2
All Products	**price lb $**	$1.68	$1.51	$1.80	$1.72	$1.46	$1.89
Fillets	**volume K mt**	7.23	9.08	9.70	9.85	6.39	7.87
Fillets	**value share**	48.2%	50.1%	71.3%	57.1%	36.2%	64.6%
Fillets	**price lb $**	$3.09	$2.84	$3.14	$3.10	$2.64	$3.36
Head & Gut	**volume K mt**	12.50	15.37	6.63	13.95	19.05	8.43
Head & Gut	**value share**	37.5%	35.4%	15.6%	32.6%	51.1%	22.4%
Head & Gut	**price lb $**	$1.39	$1.19	$1.01	$1.25	$1.25	$1.09

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.32 Cod U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, and Europe's share of global production; U.S. export volume (thousand metric tons), value (million US$), and price (US$ per pound); U.S. cod consumption (estimated), and share of domestic production remaining in the U.S. (estimated); and the share of U.S. export volume and value for head and gut (H&G), fillets, China, Japan, and Germany and Netherlands; 2007-2011 average and 2012-2017.

		Avg 07-11	2012	2013	2014	2015	2016	2017 (thru July)
Global cod catch K mt		1,272	1,600	1,831	1,853	1,764	-	-
U.S. P. cod share of global catch		19.7%	20.7%	17.0%	17.7%	18.1%	-	-
Europe share of global catch		72.3%	73.2%	76.7%	75.9%	74.8%	-	-
Pacific cod share of U.S. catch		96.7%	98.6%	99.3%	99.3%	99.5%	-	-
U.S. cod consumption K mt (est.)		80	97	104	114	107	113	-
Share of U.S. cod not exported		25%	30%	31%	31%	26%	29%	-
Export volume K mt		90.3	111.1	101.8	107.3	113.2	105.2	67.7
Export value M US$		$286.3	$363.6	$308.0	$314.2	$335.0	$311.7	$208.0
Export price lb US$		$1.439	$1.485	$1.373	$1.328	$1.342	$1.344	$1.393
Frozen (H&G)	**volume Share**	68%	80%	91%	92%	91%	94%	94%
	value share	68%	80%	89%	91%	90%	92%	92%
Fillets	**volume Share**	13%	9%	4%	2%	3%	3%	5%
	value share	16%	11%	5%	4%	4%	4%	6%
China	**volume Share**	27%	46%	51%	54%	53%	55%	59%
	value share	25%	43%	48%	51%	51%	52%	57%
Japan	**volume Share**	18%	16%	13%	16%	13%	14%	12%
	value share	18%	16%	13%	16%	14%	15%	13%
Netherlands & Germany	**volume Share**	11%	8%	8%	9%	8%	5%	3%
	value share	12%	9%	9%	10%	8%	5%	3%

Notes: Pacific cod in this table is for all U.S. Unless noted, `cod' in this table refers to Atlantic and Pacific cod. Russia, Norway, and Iceland account for the majority of Europe's cod catch which is largely focused in the Barents sea.

Source: FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau, http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.

Figures

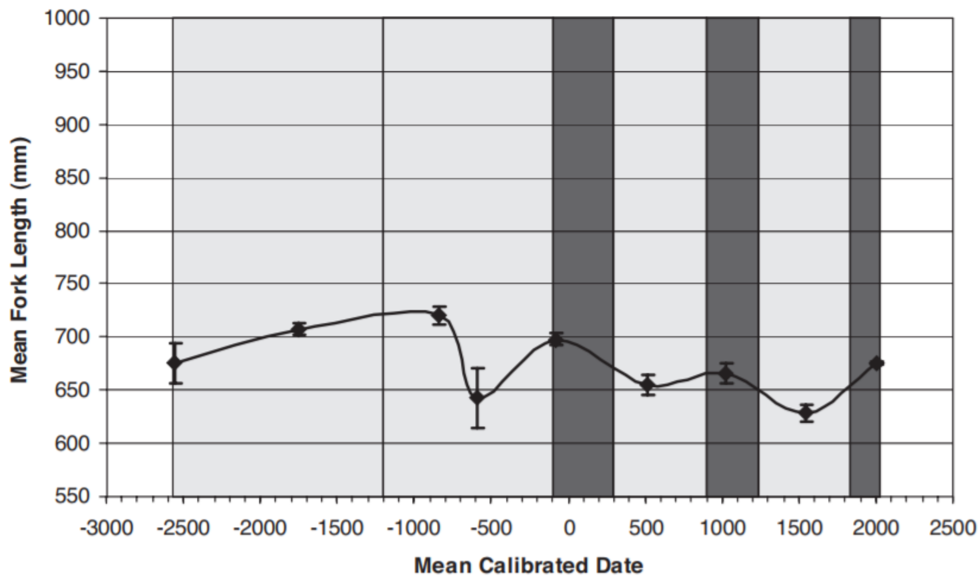


Figure 2.1 Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier environments, which are generally more productive, while the darkly shaded boxes represent warmer and generally less productive environments. Dates are presented as calibrated means; (From Betts *et al.* 2011; Figure 11.4).

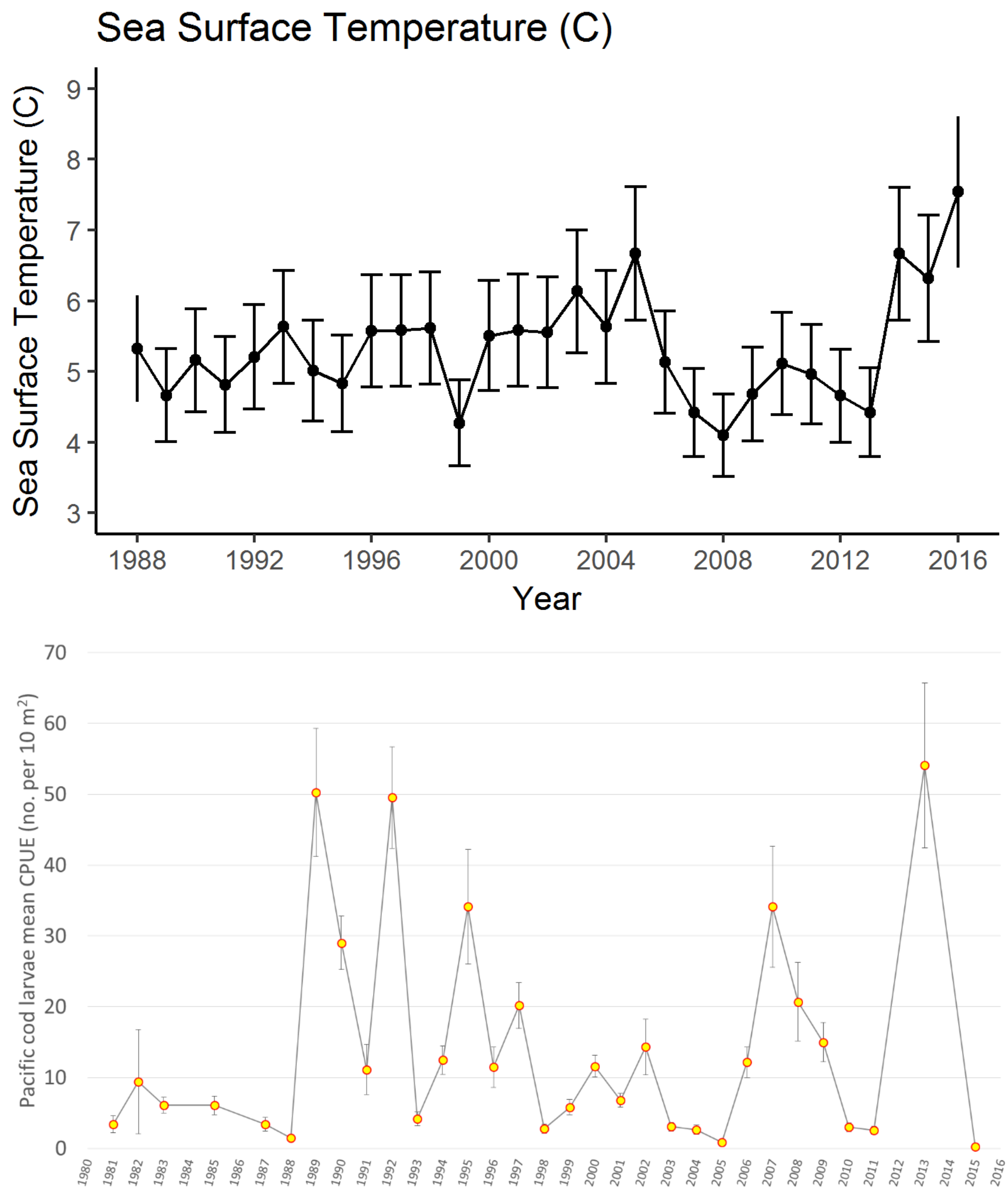


Figure 2.2. Sea surface temperatures (top) and larval abundance from late spring icthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area.

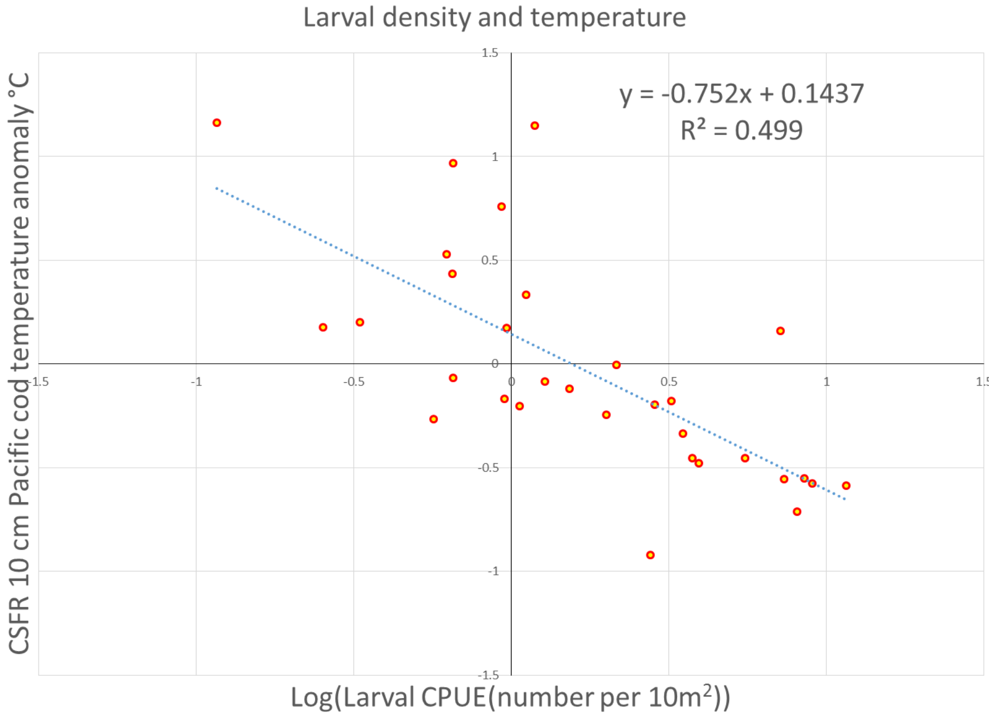


Figure 2.3 Log larval area weighted CPUE from late spring icthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area by mean annual temperature at 48m bottom depth in the Central GOA from the CFSR reanalysis data.

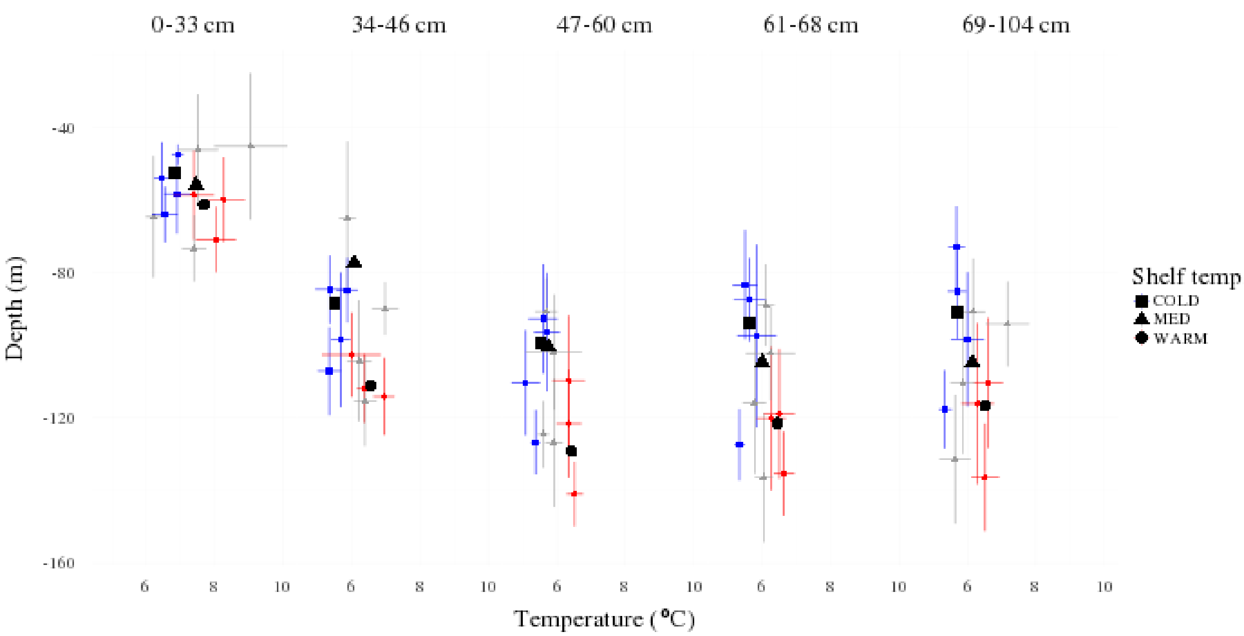


Figure 2.4 Annual centers of distribution of Pacific cod by temperature and depth for five size categories from the GOA bottom trawl survey. The red and blue points are greater or less than 0.66 standard deviations from the 1996-2017 bottom temperature mean for the Central GOA.

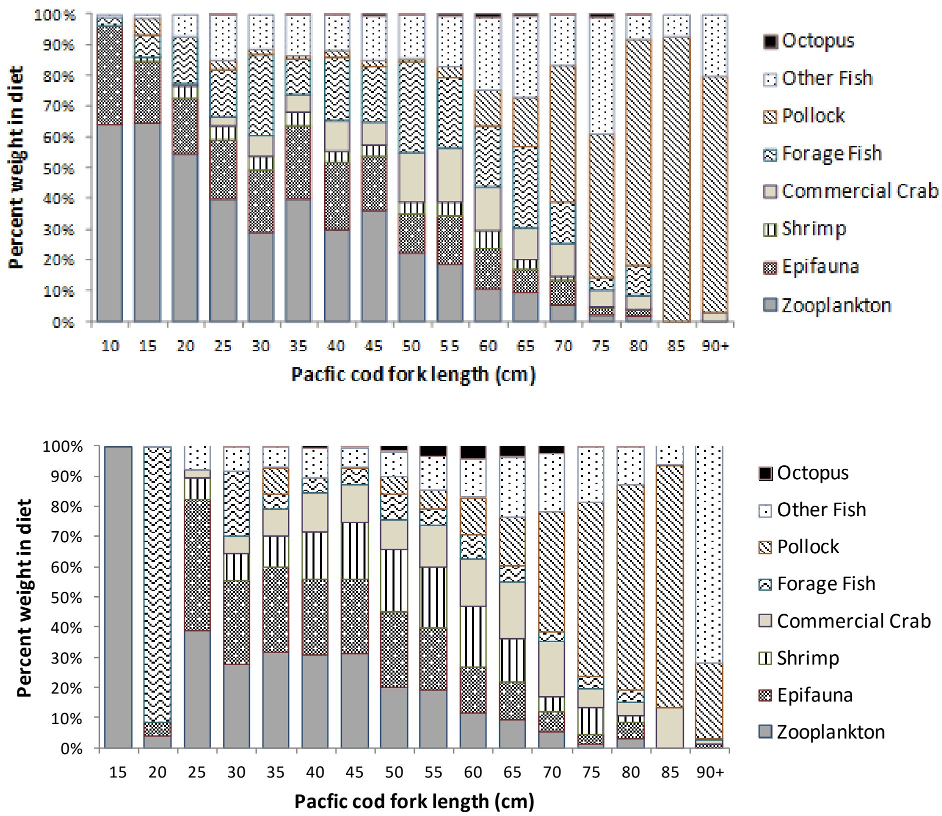


Figure 2.5 Percent diet by weight in Pacific cod stomachs sampled in water <100m (top) and >100m (bottom), all years and seasons, for Gulf of Alaska.

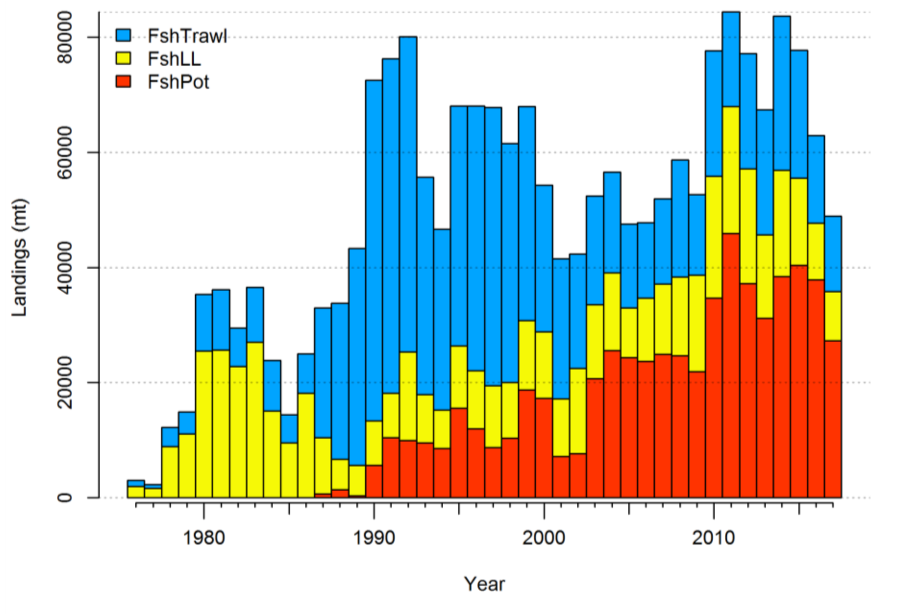


Figure 2.6 Gulf of Alaska Pacific cod catch from 1977-2017. Note that 2017 catch was estimated.

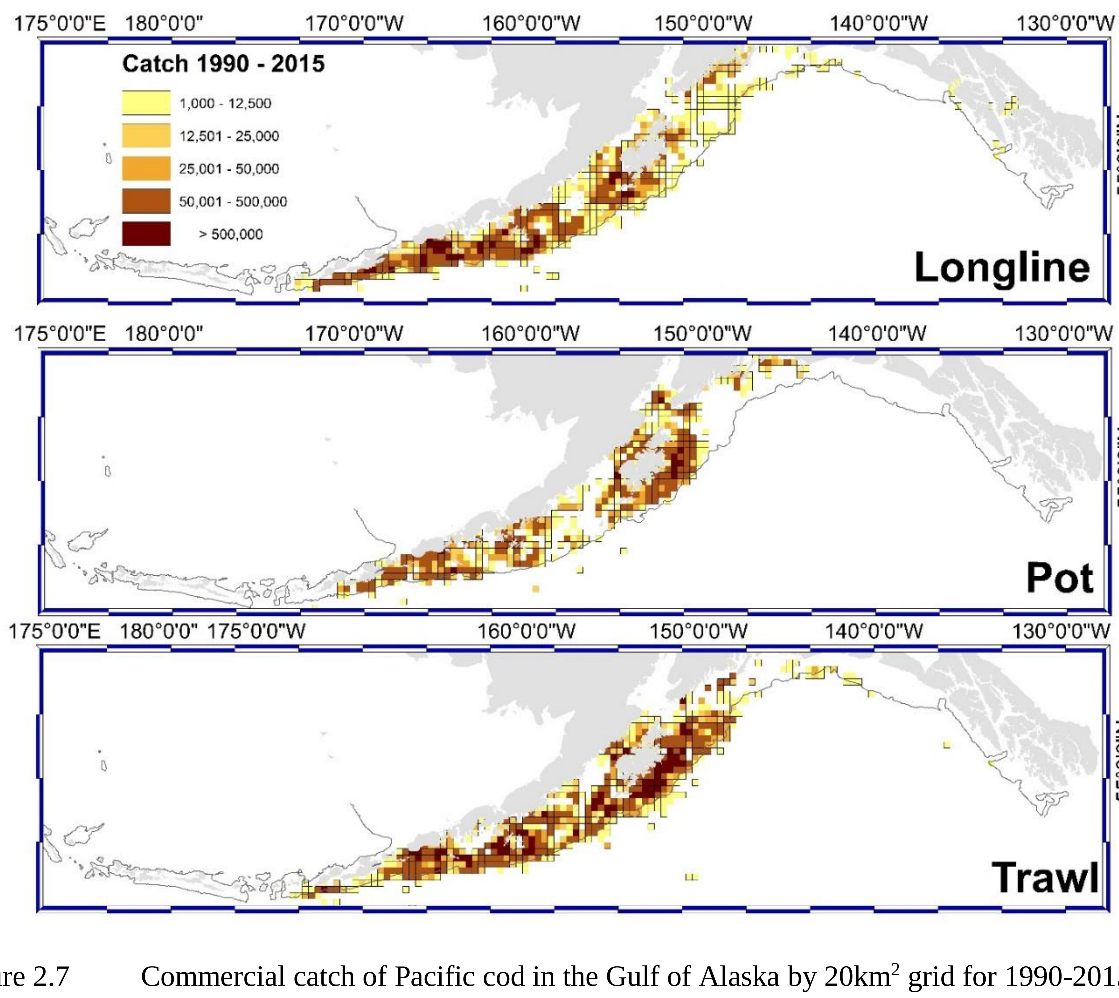


Figure 2.7 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2015.

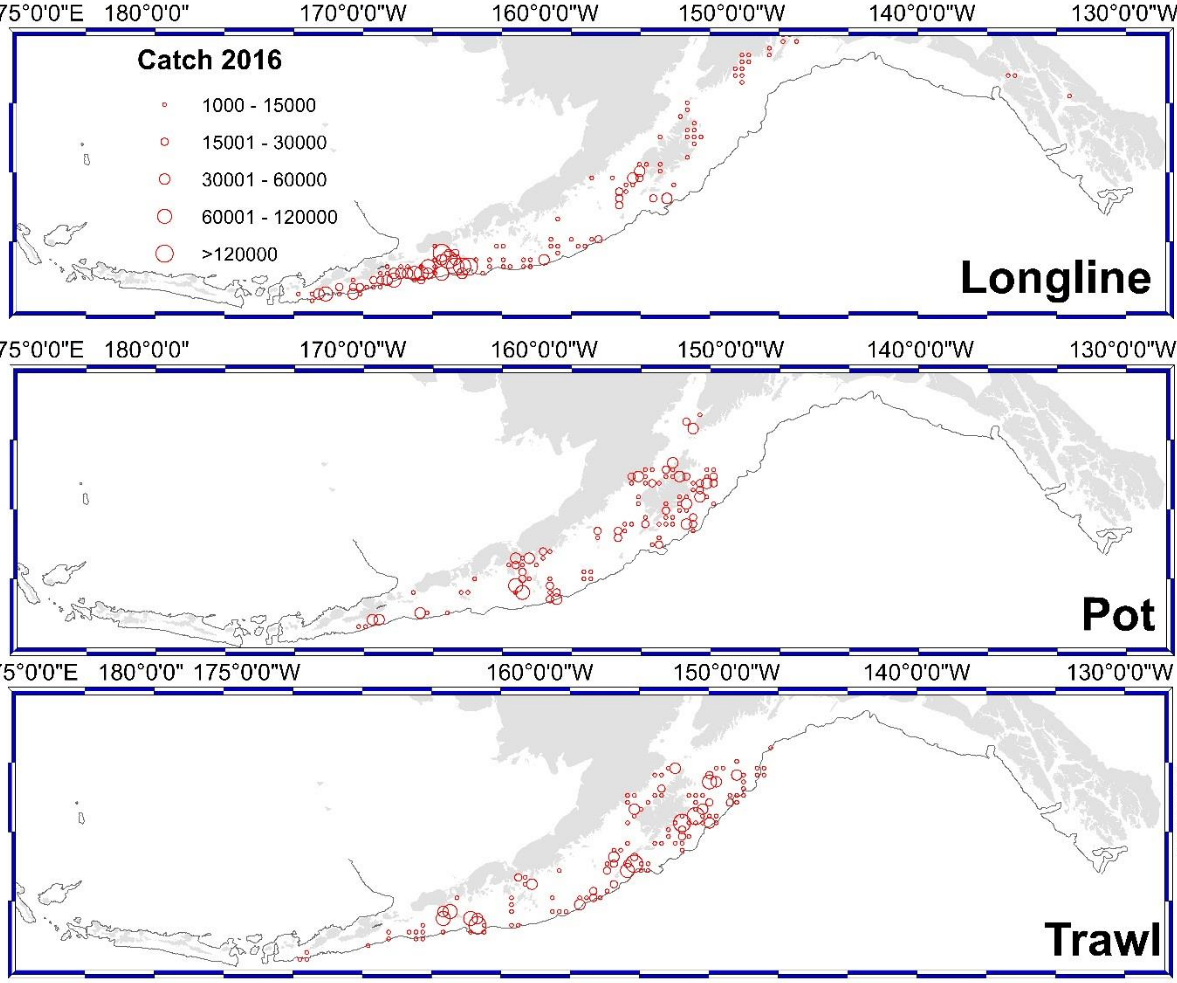


Figure 2.8 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2016.

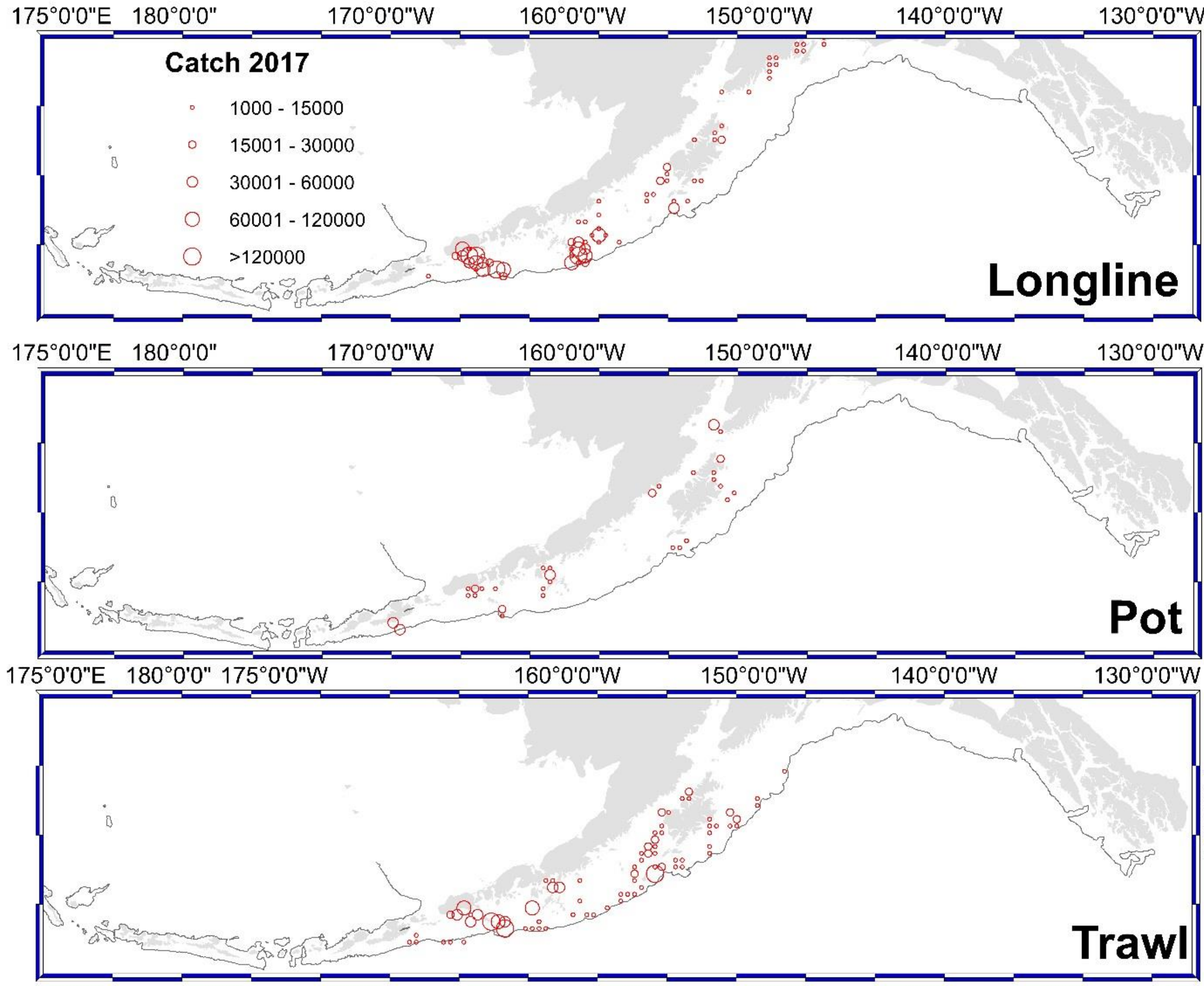


Figure 2.9 Commercial catch of Pacific cod in the Gulf of Alaska by $20km^2$ grid for 2017 as of October 11, 2017.

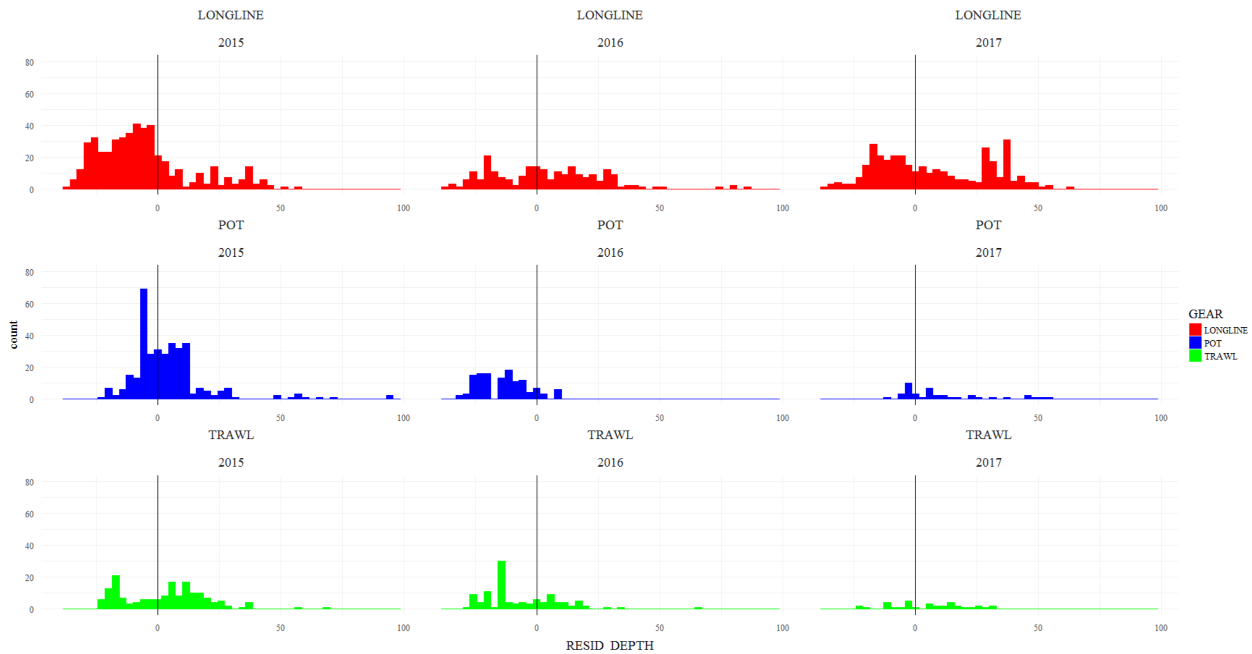


Figure 2.10 Central GOA difference in fishing depth from the three year mean (2015-2017) of observed hauls for January-August for the three major gear types.

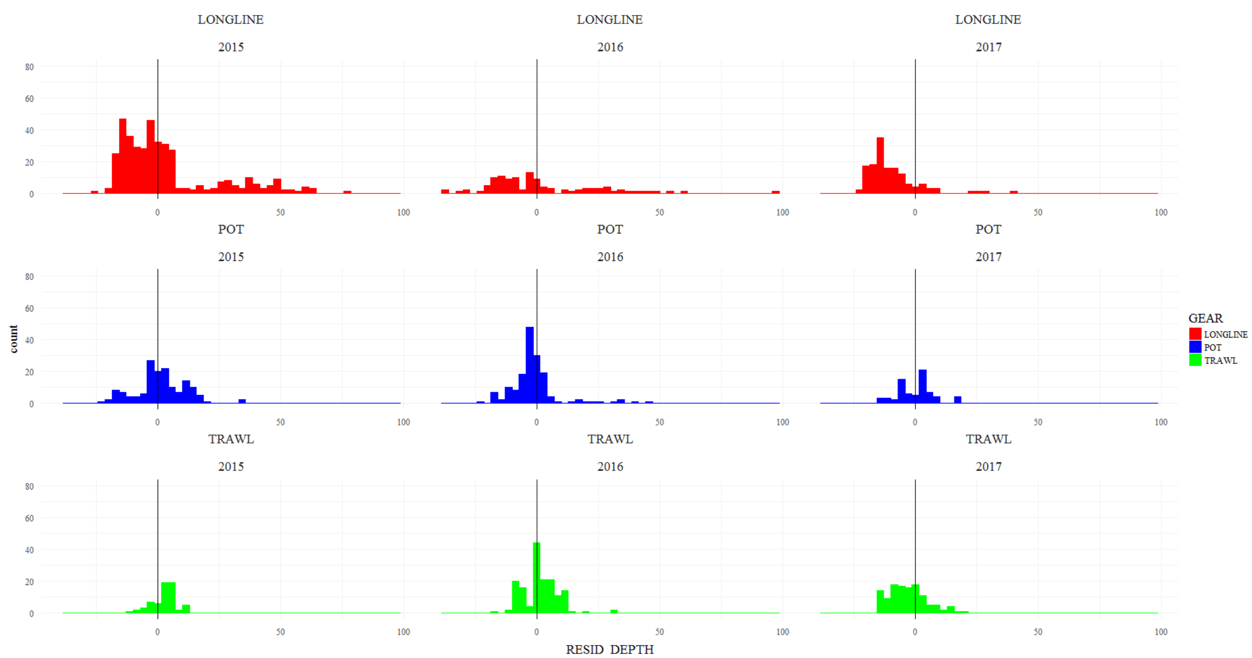


Figure 2.11 Western GOA difference in fishing depth from the three year mean (2015-2017) of observed hauls for January-August for the three major gear types.

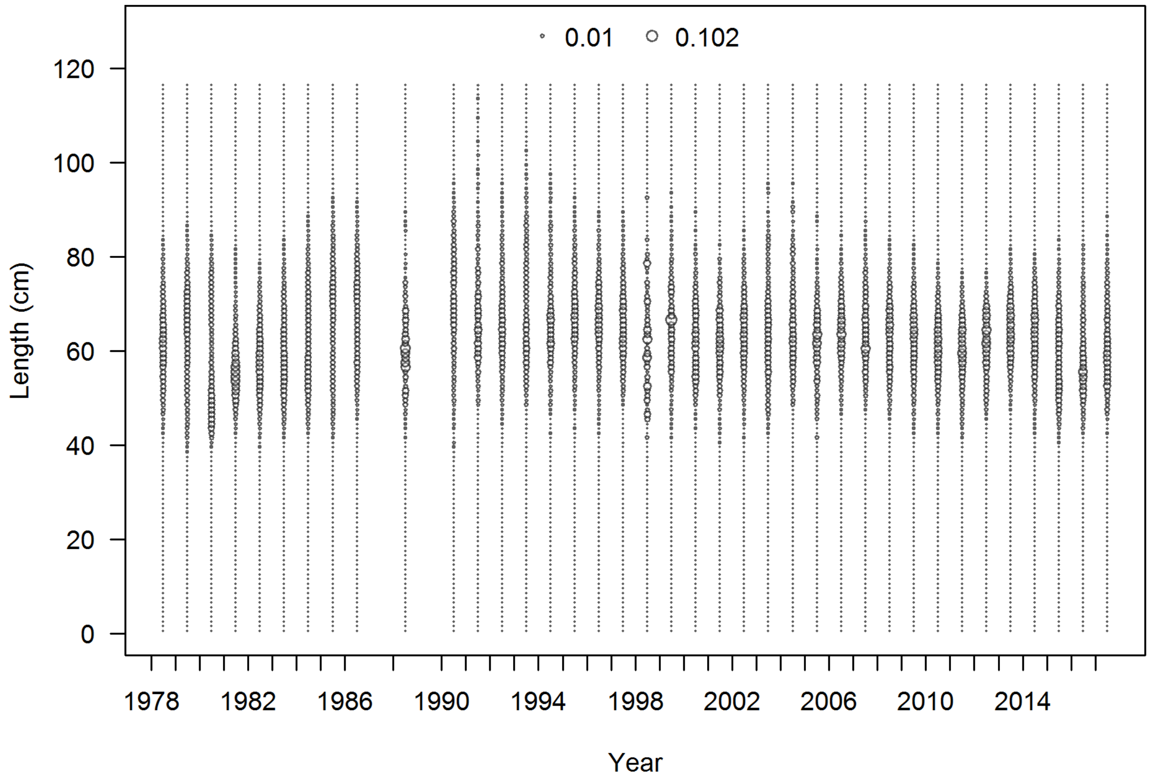


Figure 2.12 Pacific cod length composition by annual proportion from the Gulf of Alaska longline fishery (max=0.1).

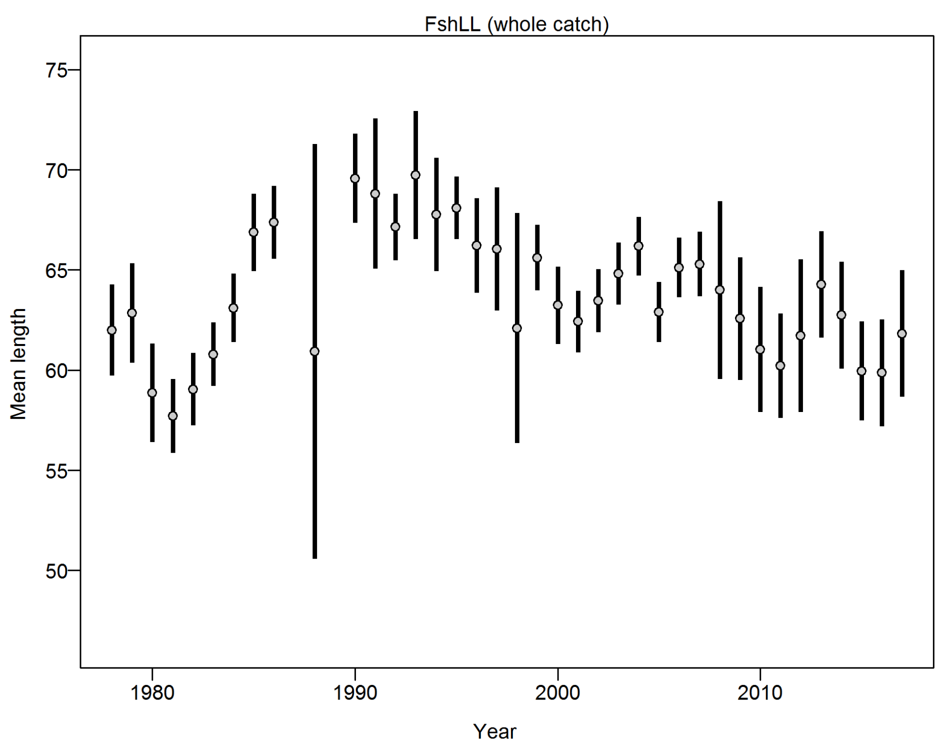


Figure 2.13 Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

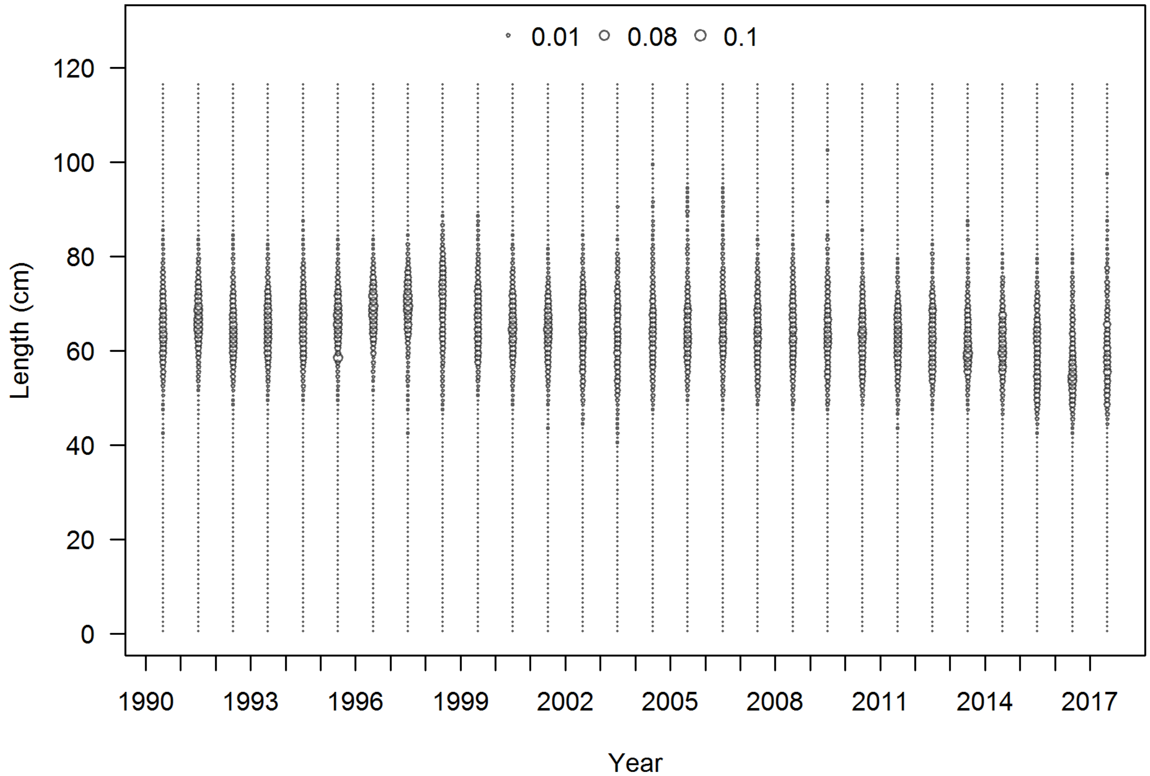


Figure 2.14 Pacific cod length composition by annual proportion from the Gulf of Alaska pot fishery (max=0.08).

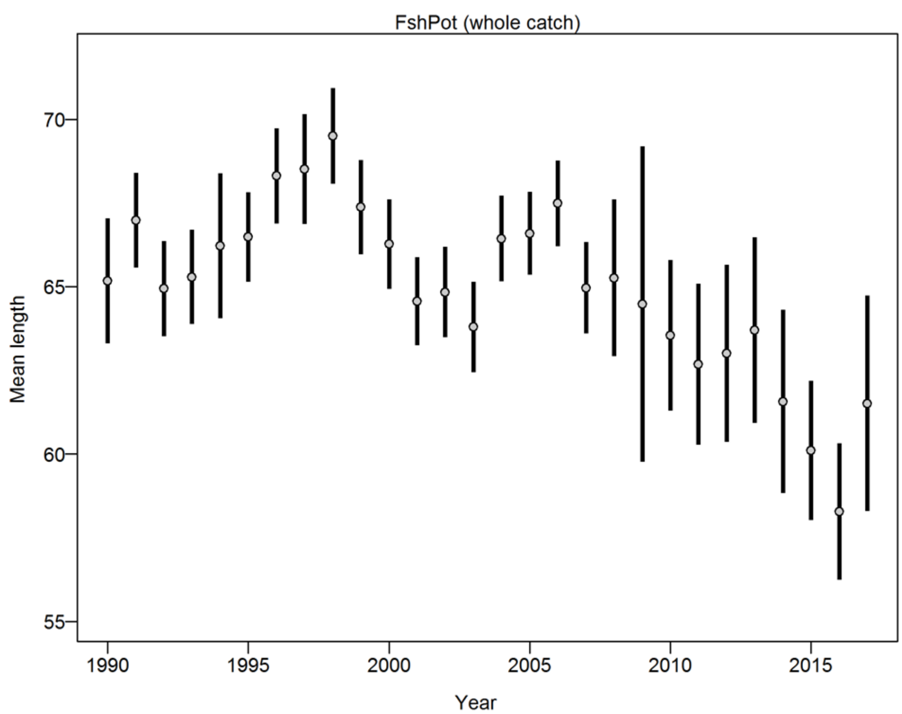


Figure 2.15 Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

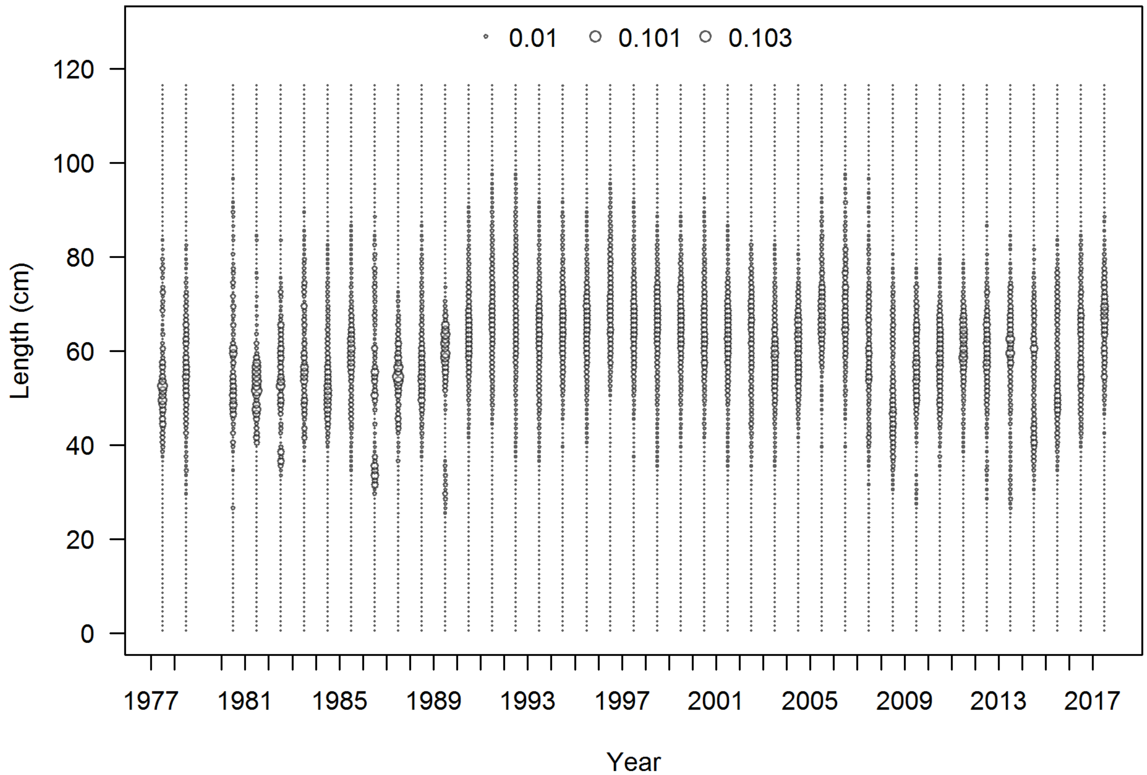


Figure 2.16 Pacific cod length composition by annual proportion from the Gulf of Alaska trawl fishery (max=0.1).

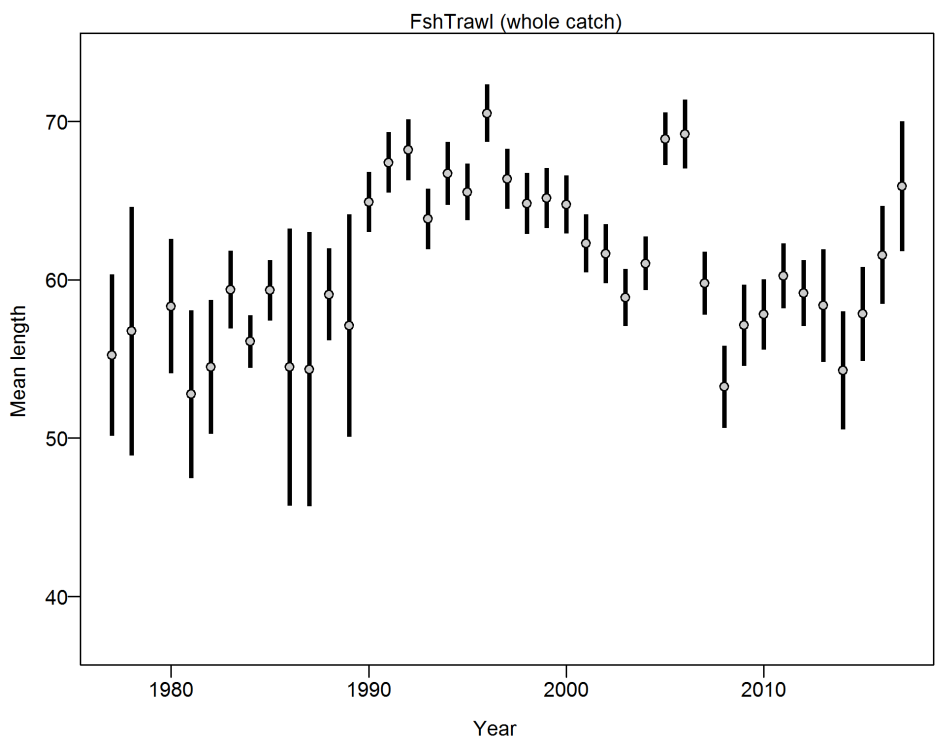


Figure 2.17 Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

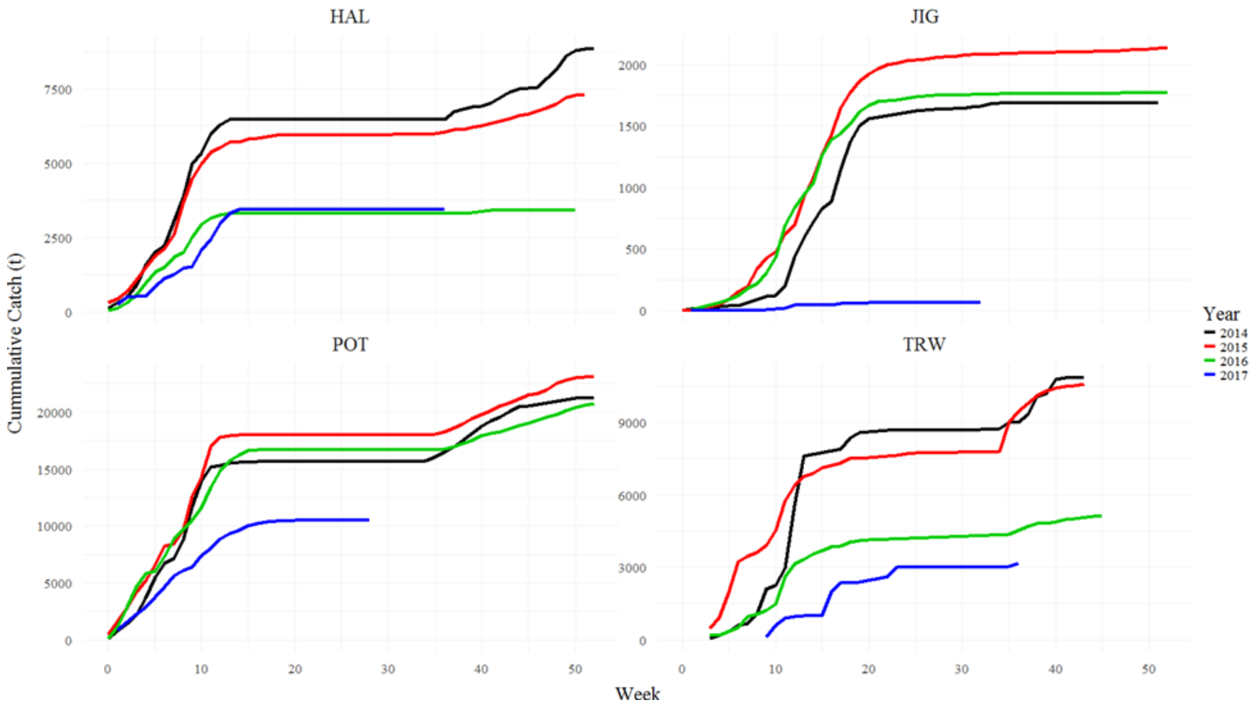


Figure 2.18 Cumulative catch by week of the year and gear for 2014-2017 in the Central regulatory area. 2017 data are through October 2, 2017.

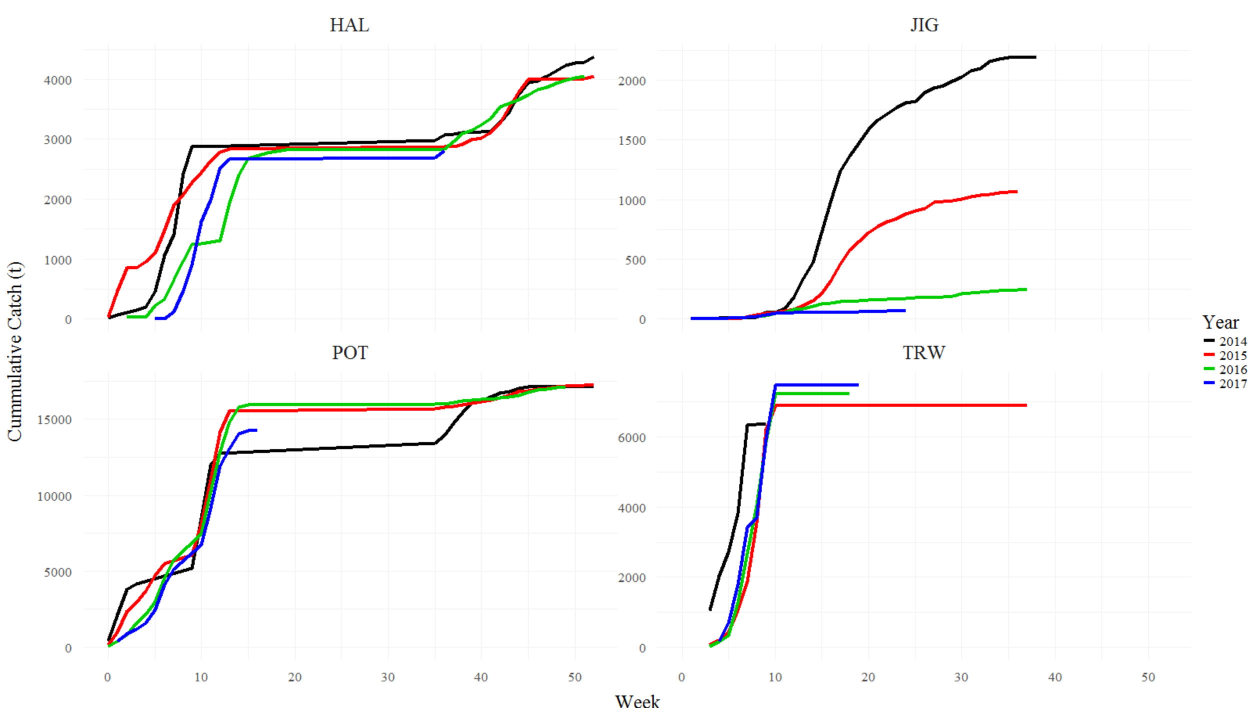


Figure 2.19 Cumulative catch by week of the year and gear for 2014-2017 in the Western regulatory area. The 2017 data are through October 2, 2017.

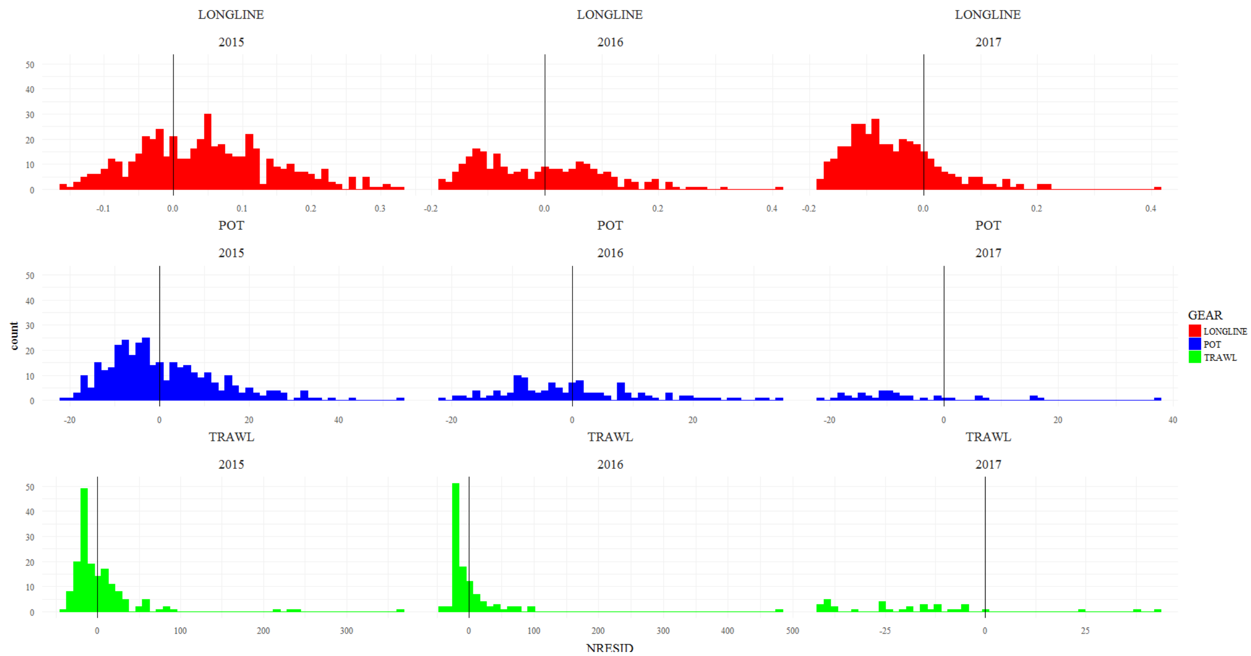


Figure 2.20 Central regulatory area distribution in CPUE by number from the 2015-2017 average for January-August directed cod fishery in longline (top; catch per hook), pot (middle; catch per pot), and trawl (bottom; catch per minute) fisheries.

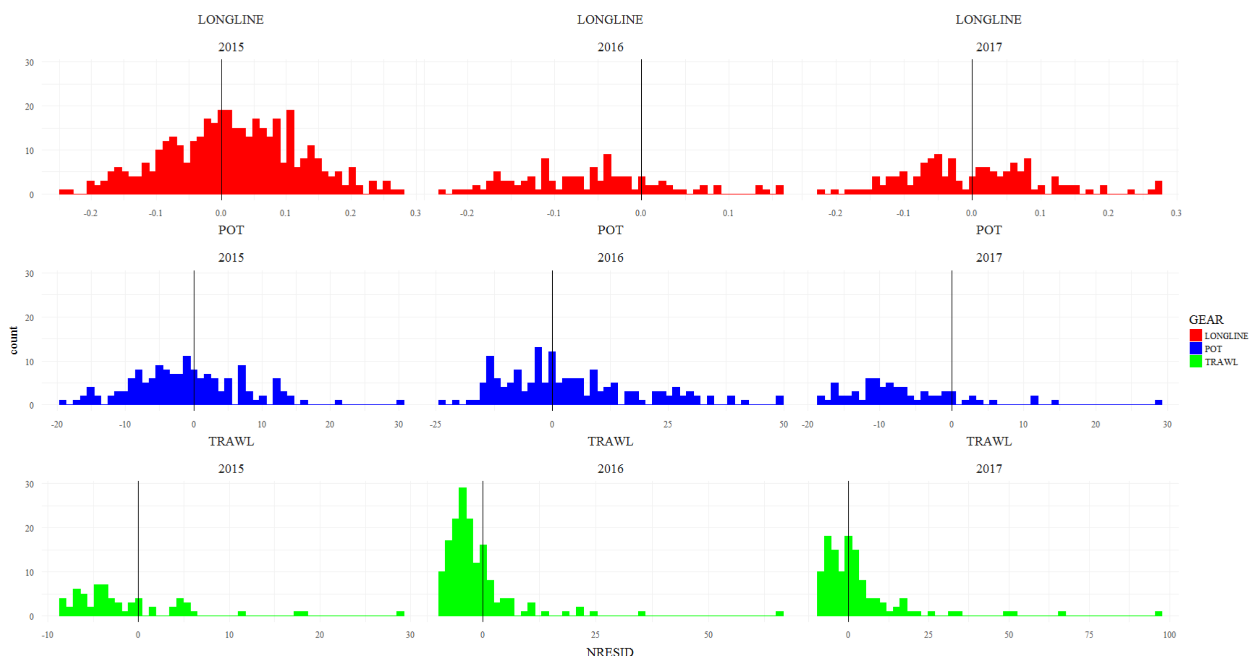


Figure 2.21 Western regulatory area distribution in CPUE by number from the 2015-2017 average for January-August directed cod fishery in longline (top; catch per hook), pot (middle; catch per pot), and trawl (bottom; catch per minute) fisheries.

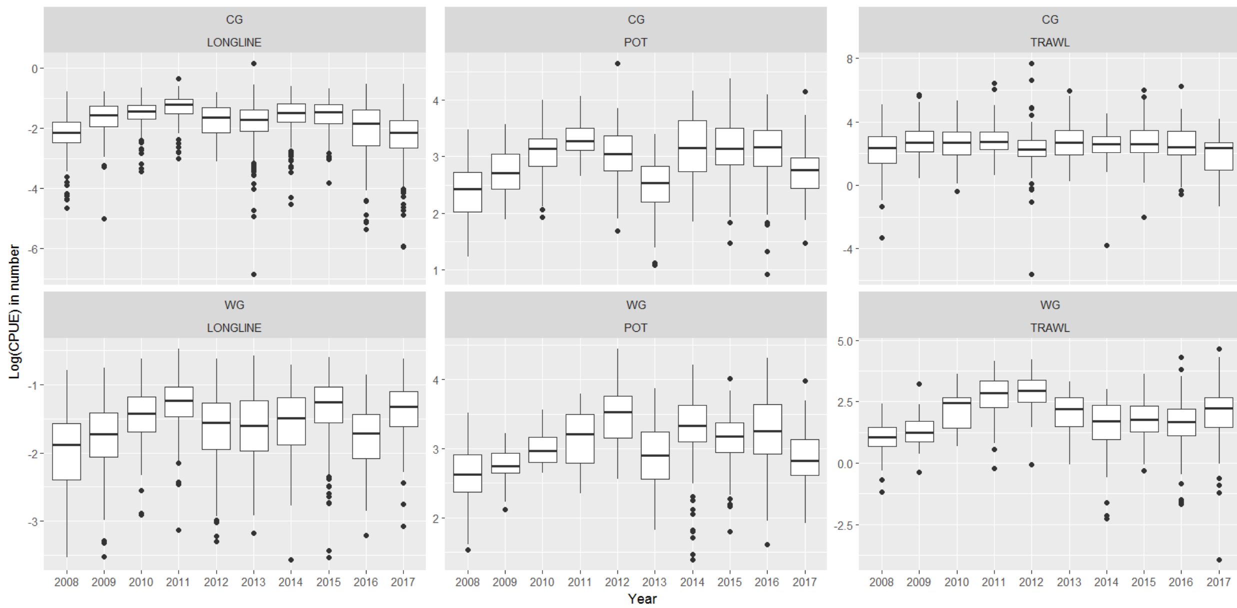


Figure 2.22 Boxplot of CPUE by number from the 2008-2017 directed Pacific cod fishery in longline (left; catch per hook), pot (middle; catch per pot), and trawl (right; catch per minute) fisheries for January-April for the Central (top) and Western (bottom) regulatory areas. Note that the data in these figures are not controlled for vessel or gear differences within a gear type across time, but shows the raw CPUE data distribution.

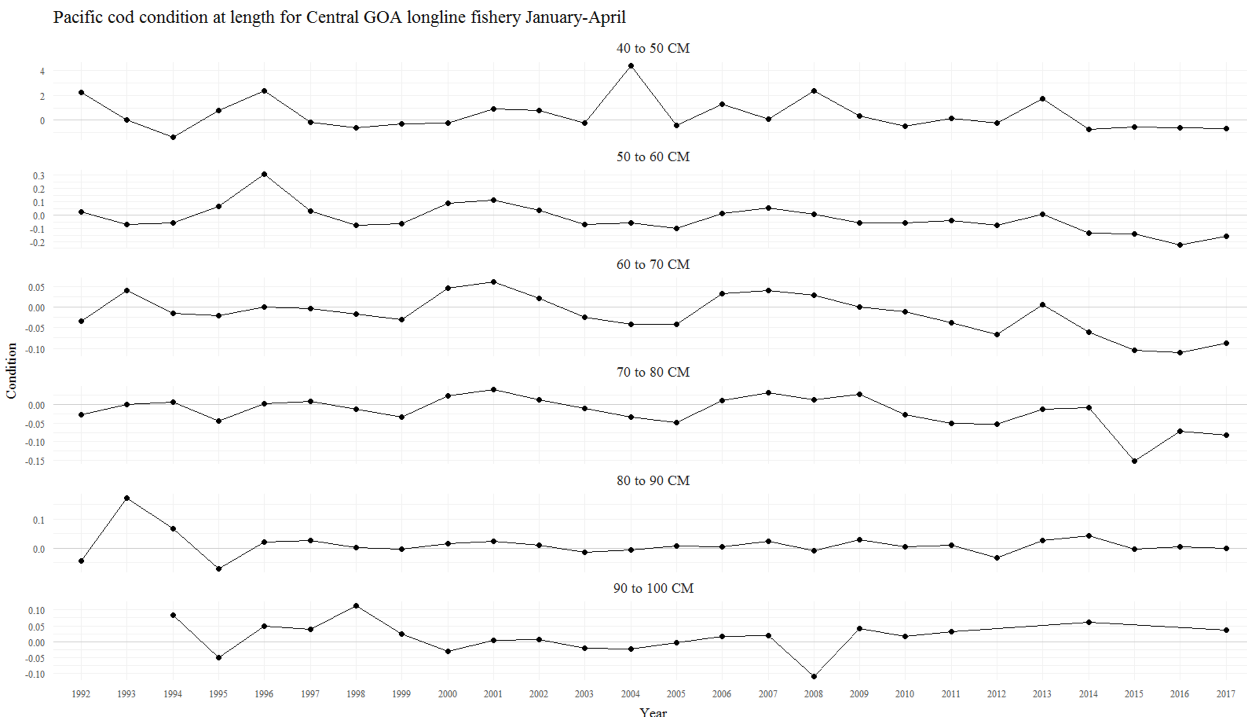


Figure 2.23 Condition of Pacific cod by length category and year in the Central GOA for the longline A-season fisheries (January-April).

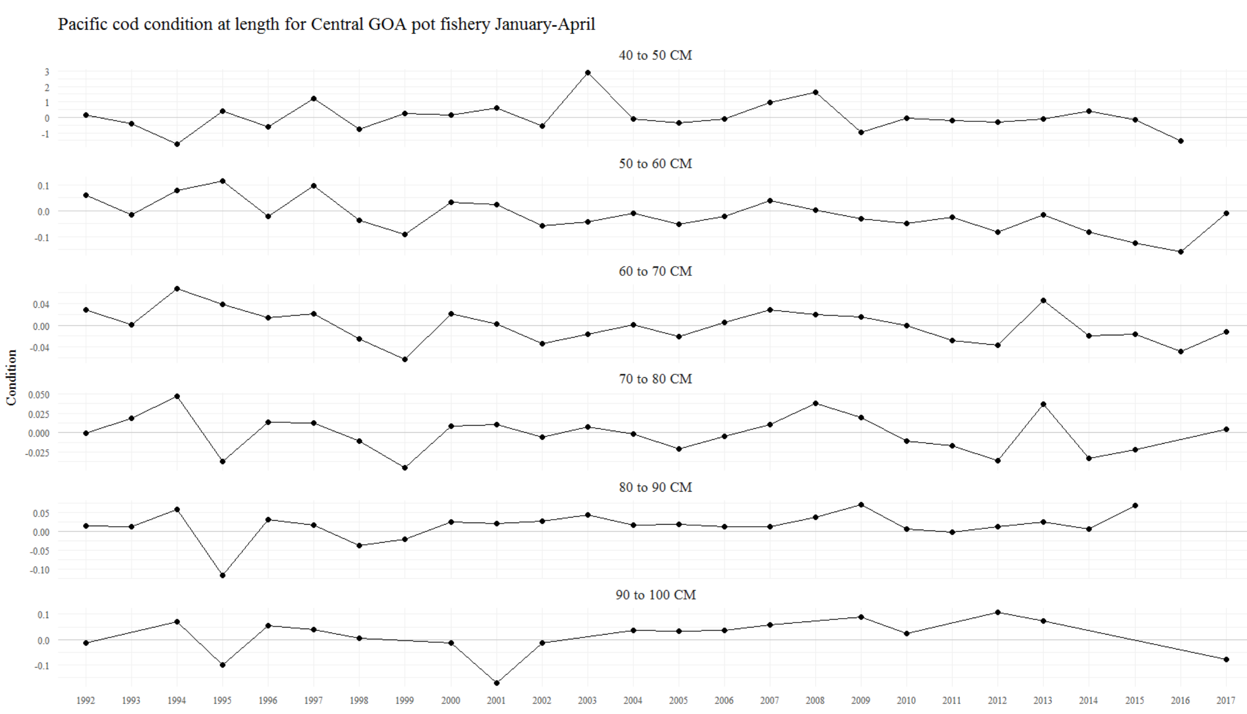


Figure 2.24 Condition of Pacific cod by length category and year in the Central GOA for the pot A-season fisheries (January-April).

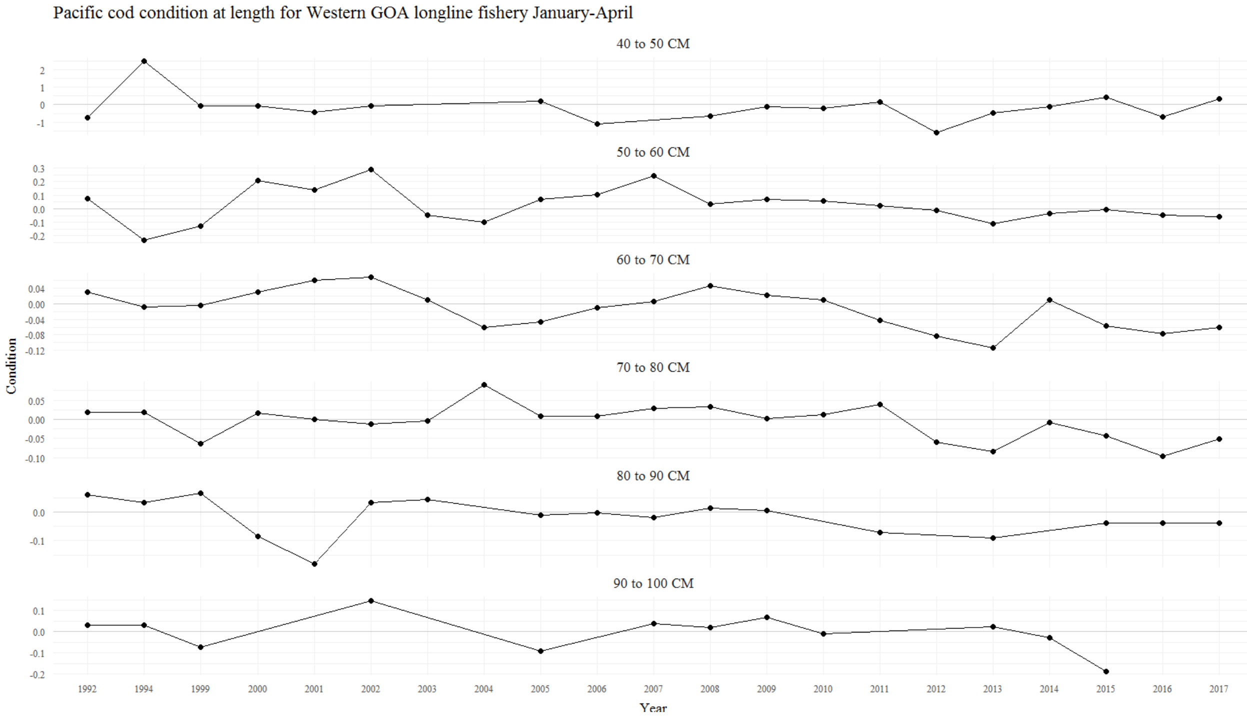


Figure 2.25 Condition of Pacific cod by length category and year in the Western GOA for the longline A-season fisheries (January-April).

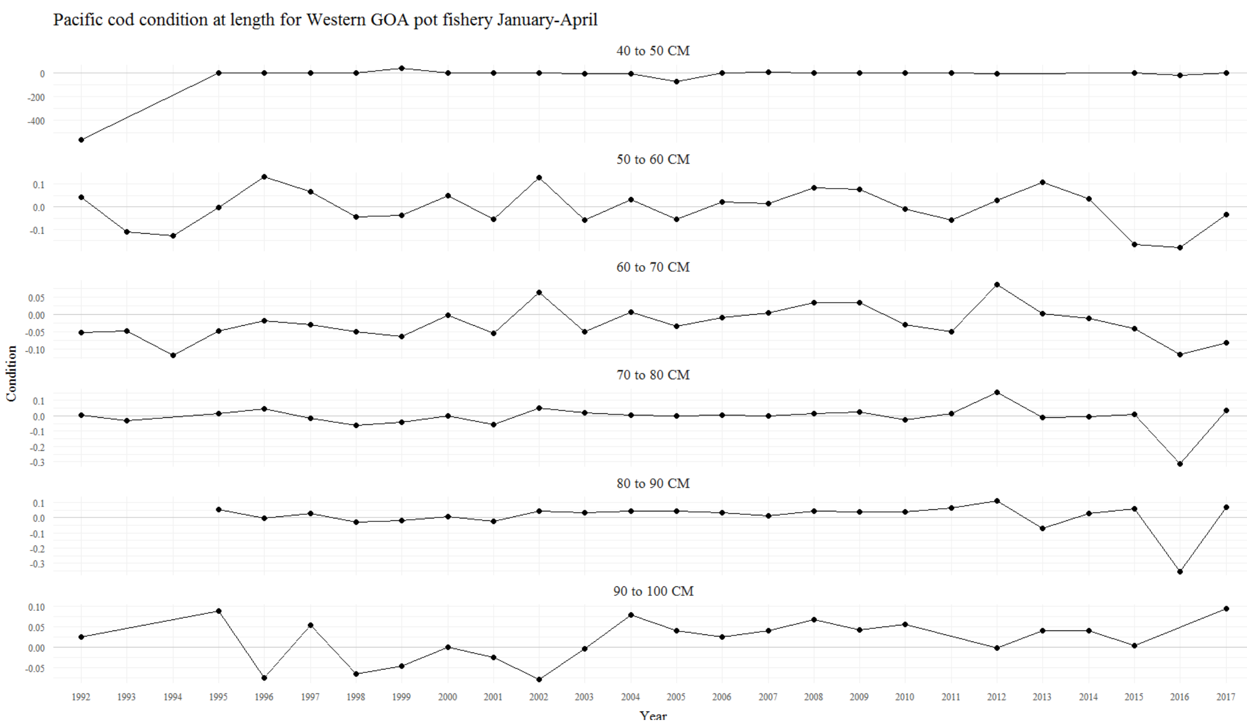


Figure 2.26 Condition of Pacific cod by length category and year in the Western GOA for pot A-season fisheries (January-April).

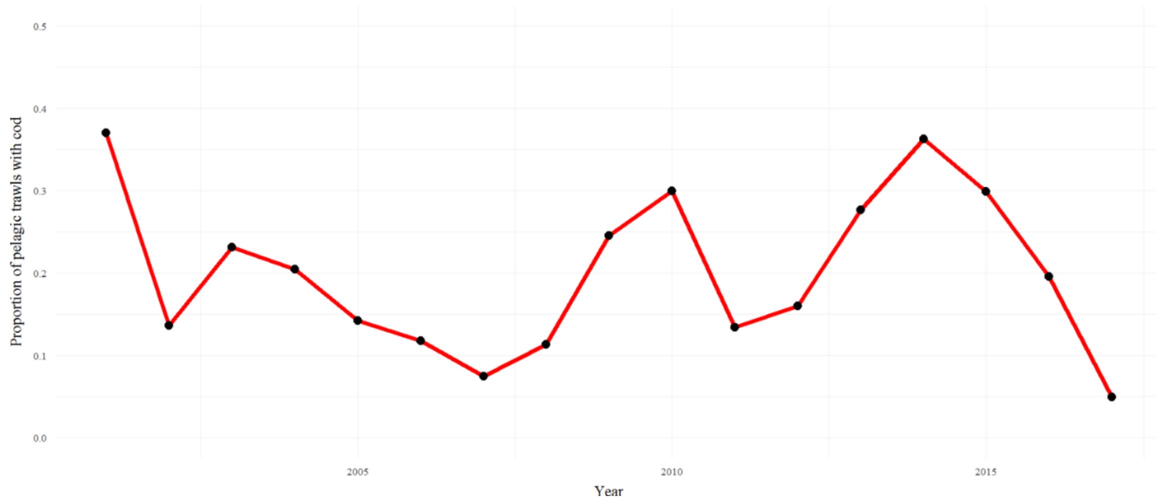


Figure 2.27 Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present.

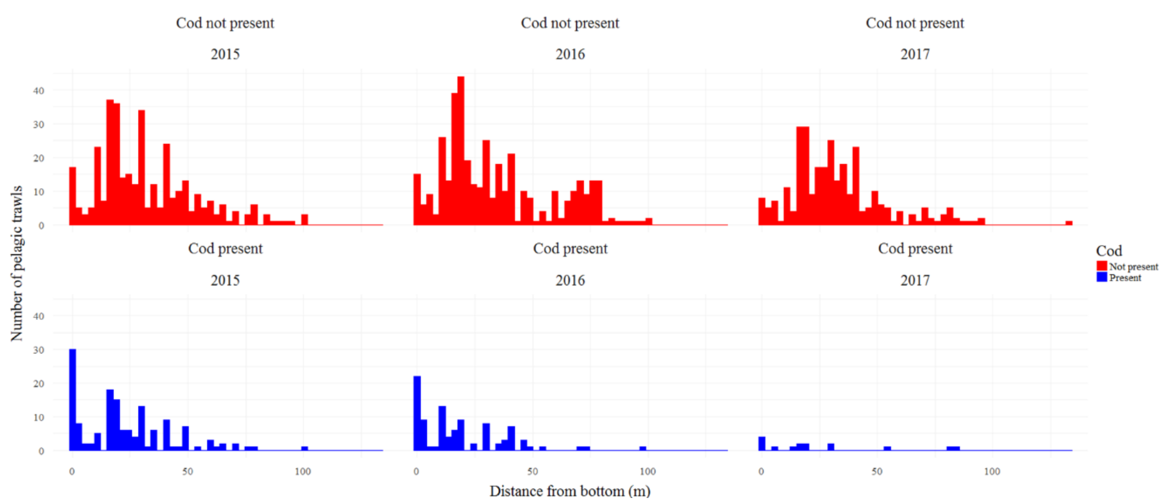


Figure 2.28 –Histogram of observed trawl hauls distance from the bottom with and without cod present (bottom).

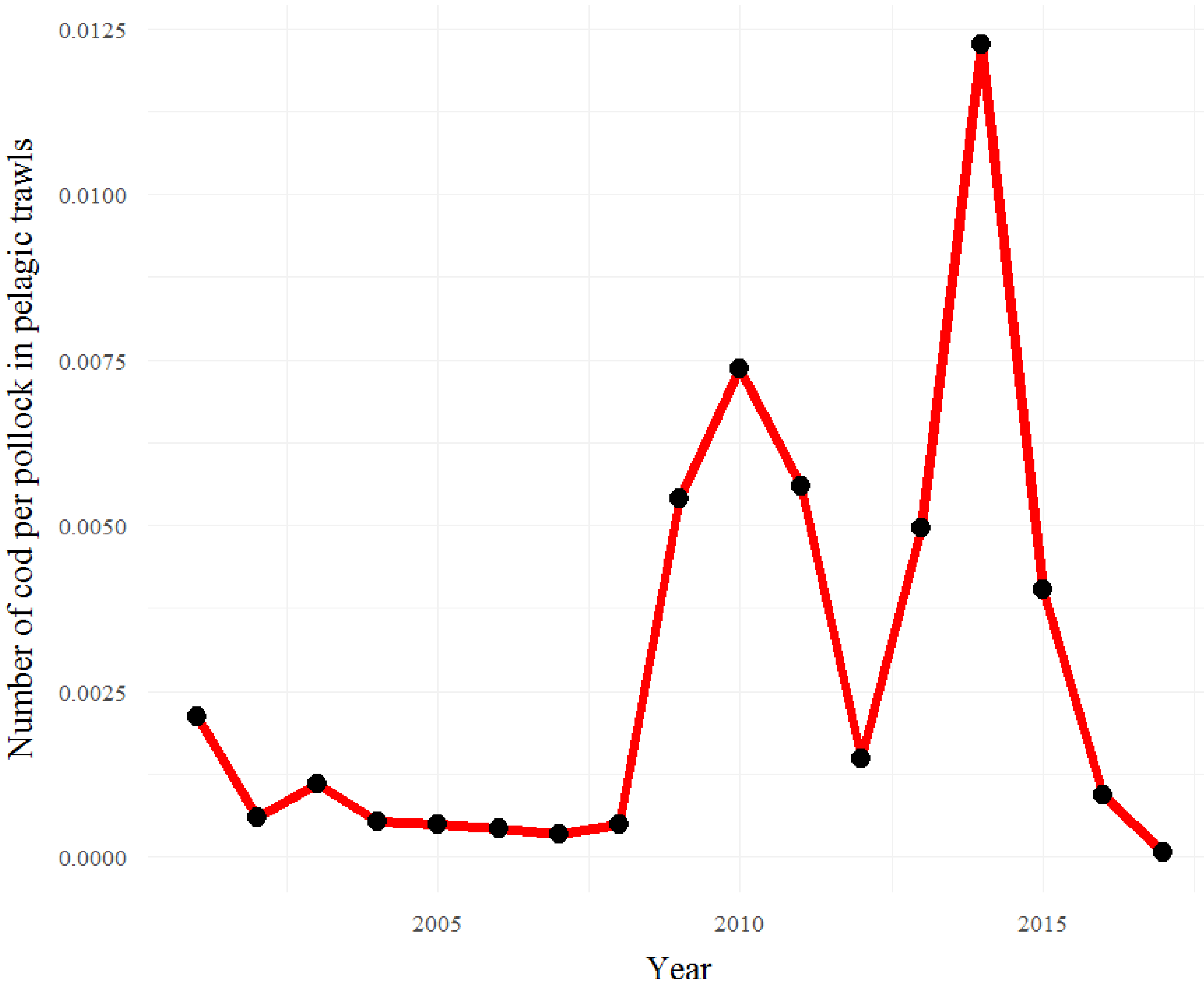


Figure 2.29 Number of cod per pollock from pelagic trawls in the A Season (January-April) walleye pollock fishery.

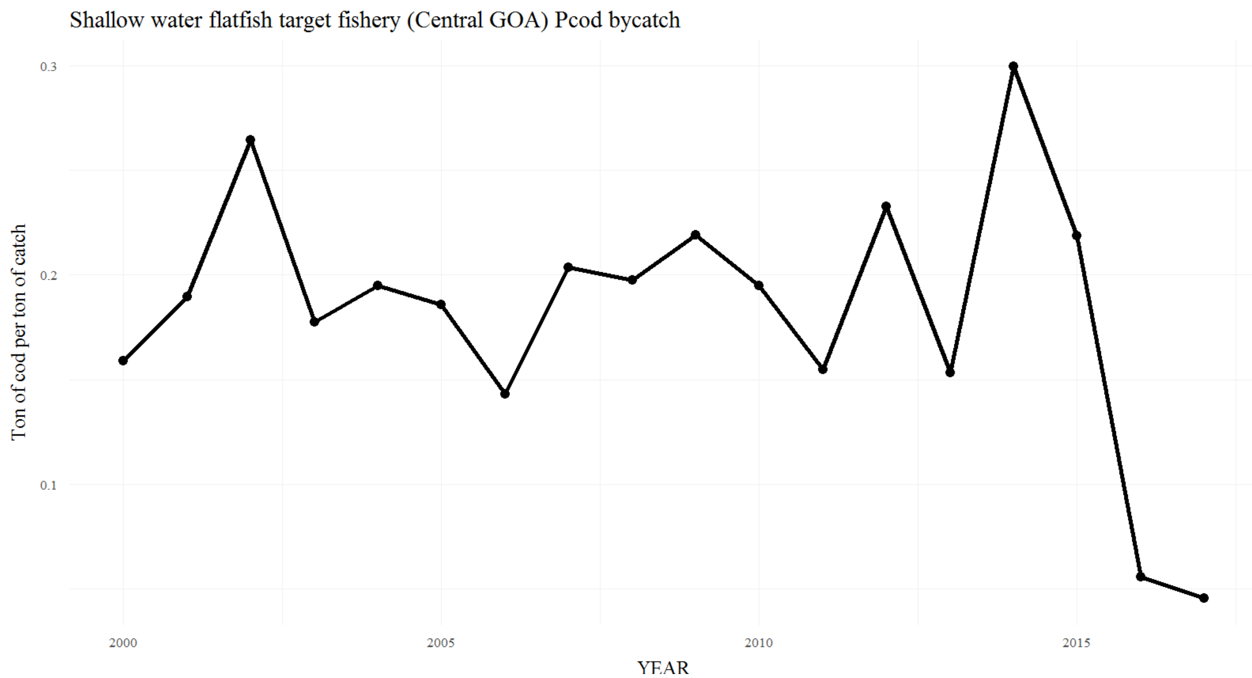


Figure 2.30 Tons of Pacific cod per ton of catch from the A season (January-April) bottom trawl shallow water flatfish fishery.

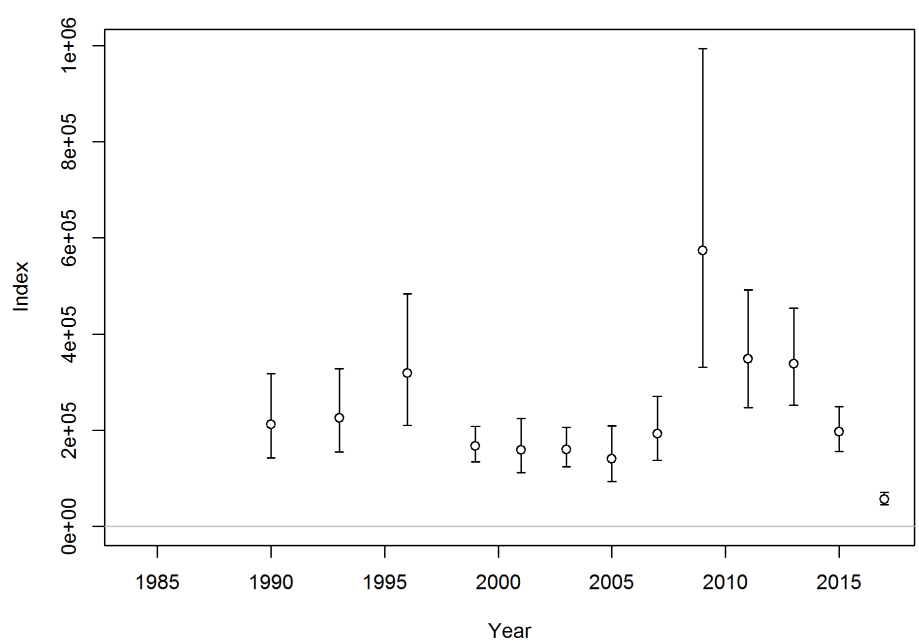


Figure 2.31 GOA bottom trawl survey abundance (numbers) estimate.

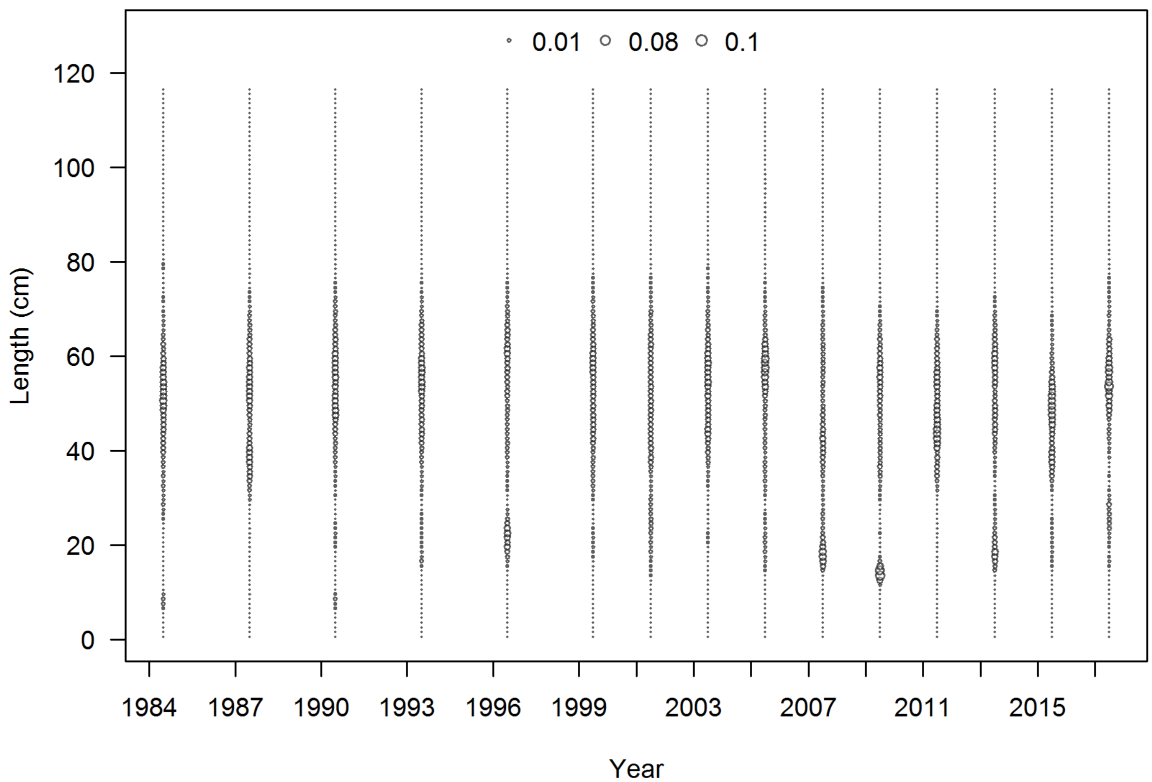


Figure 2.32 GOA bottom trawl survey Pacific cod population numbers at length estimates (max =0.07).

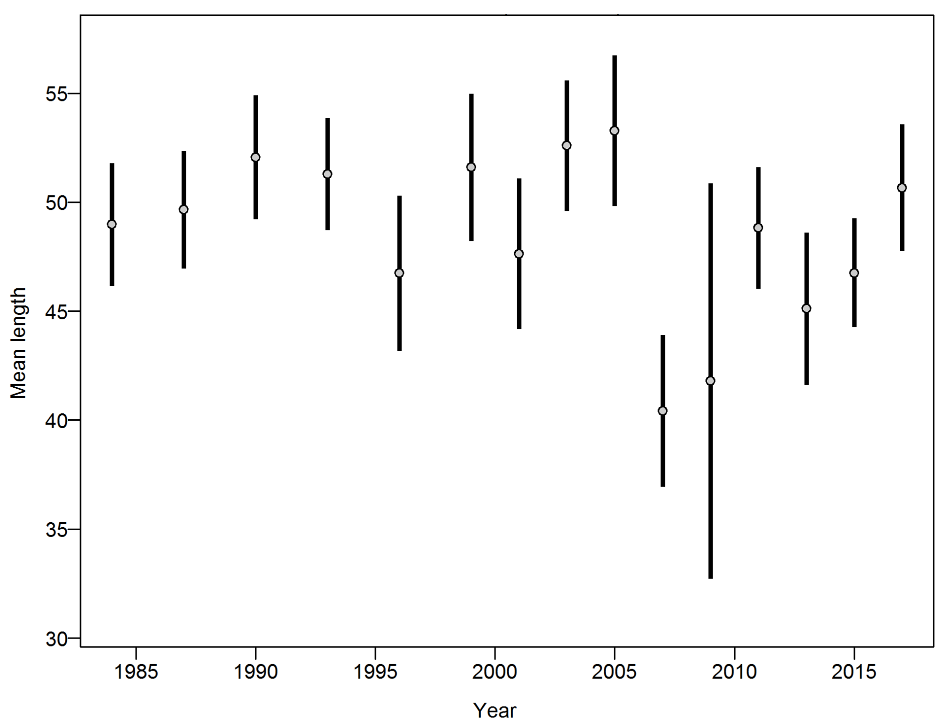


Figure 2.33 Mean length (cm) of Pacific cod in the GOA bottom trawl survey.

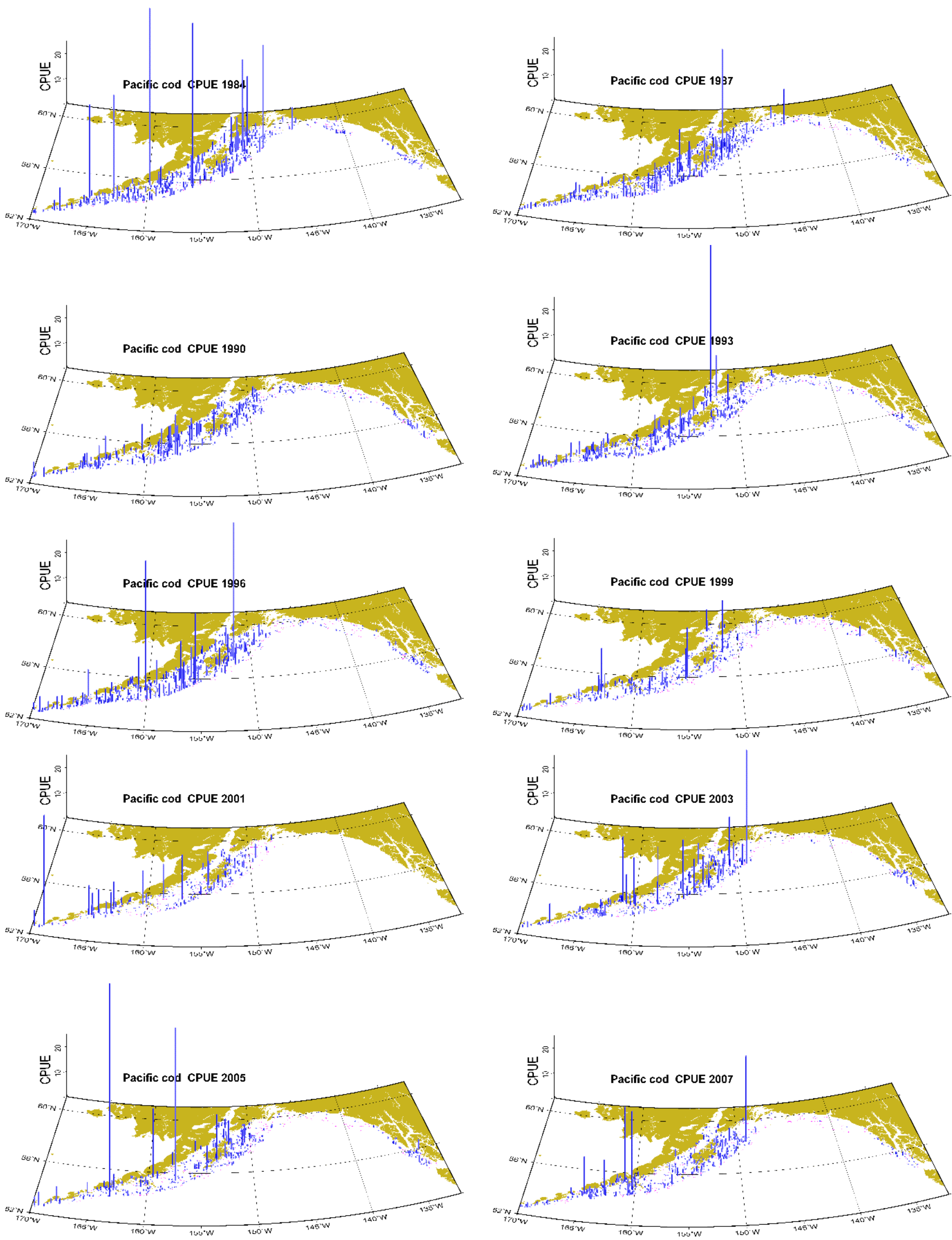


Figure 2.34 Distribution of AFSC bottom trawl survey CPUE of Pacific cod.

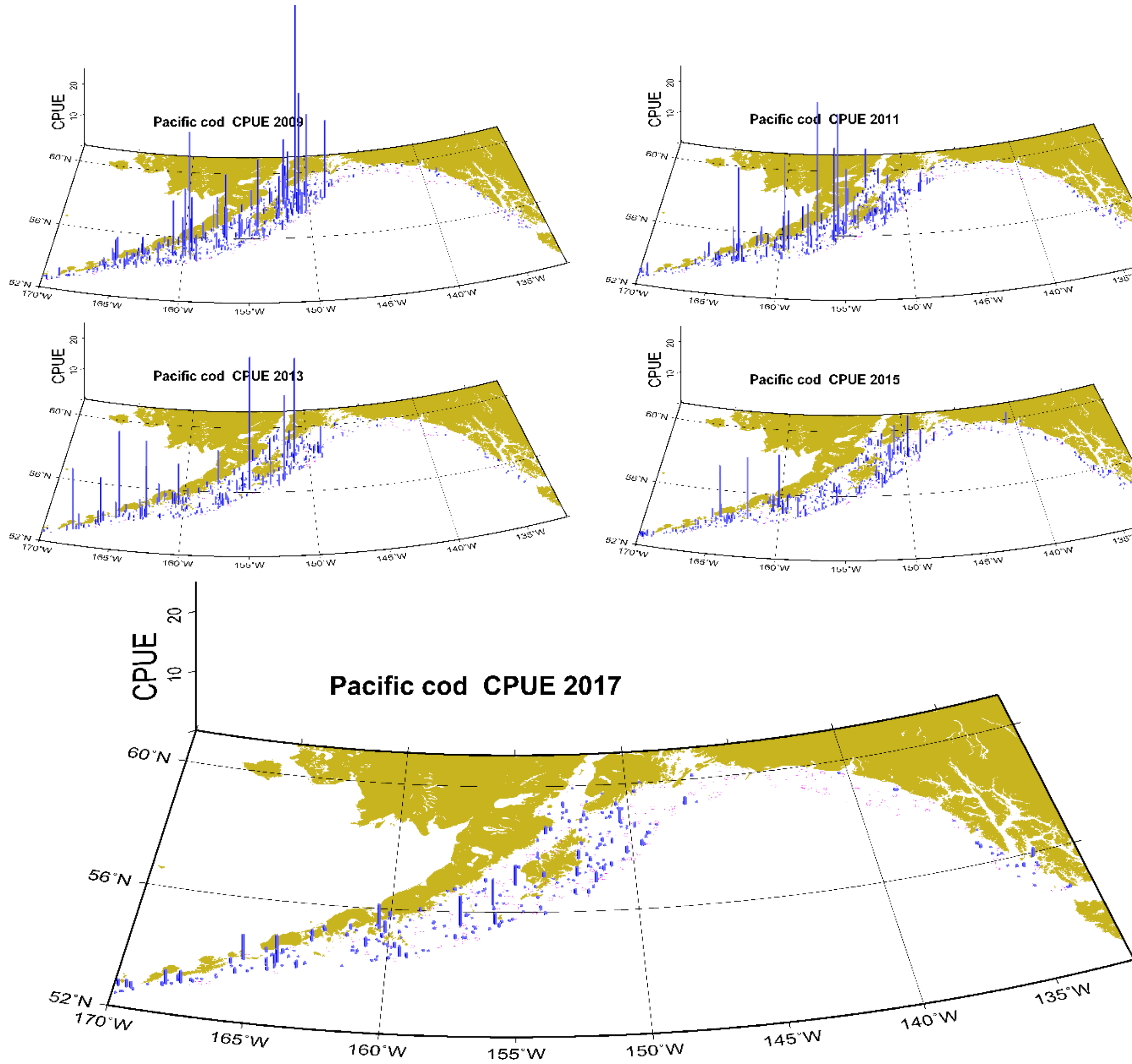


Figure 2.37 Cont. Distribution of AFSC bottom trawl survey CPUE of Pacific cod.

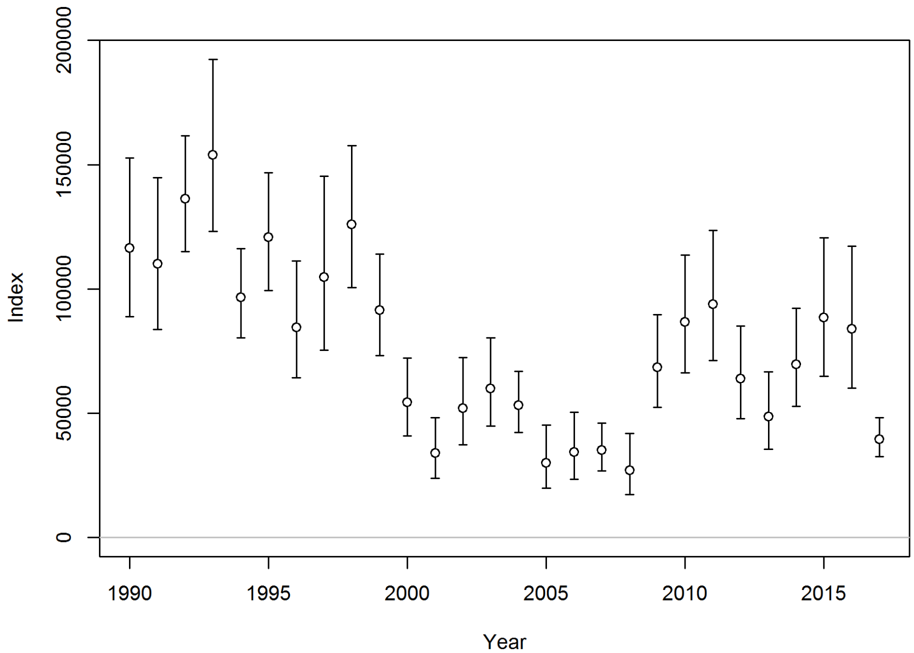


Figure 2.35 AFSC sablefish longline survey Pacific cod relative population numbers (RPN) time series.

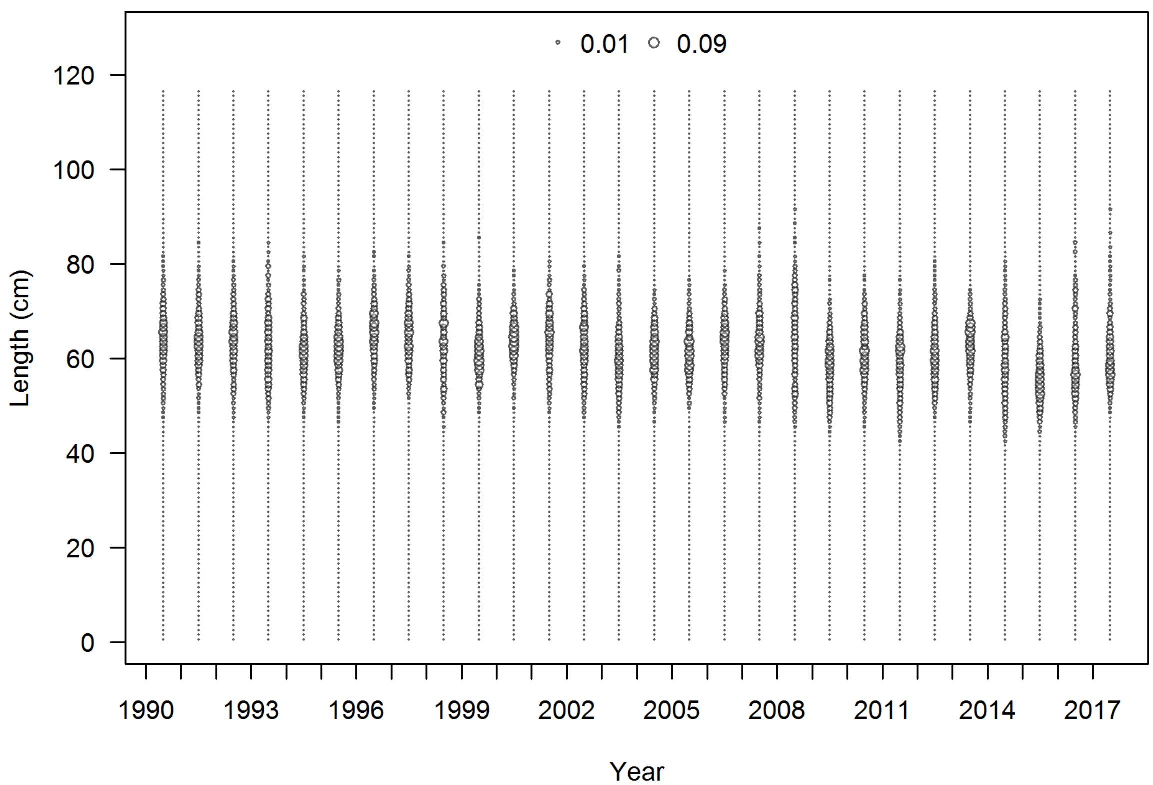


Figure 2.36 AFSC sablefish longline survey Pacific cod size composition (max=0.09).

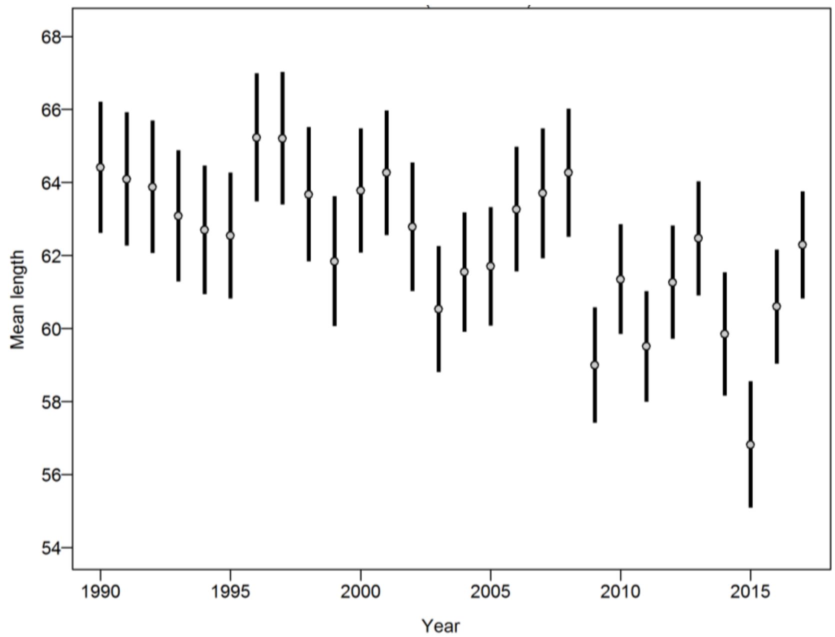
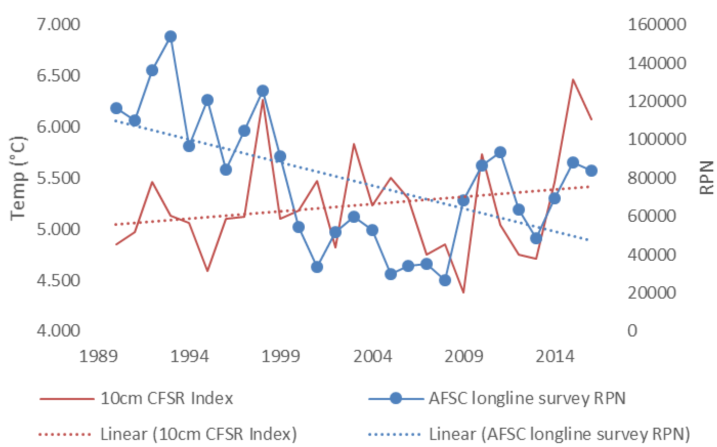


Figure 2.37 Mean length (cm) of Pacific cod from the AFSC sablefish longline survey.



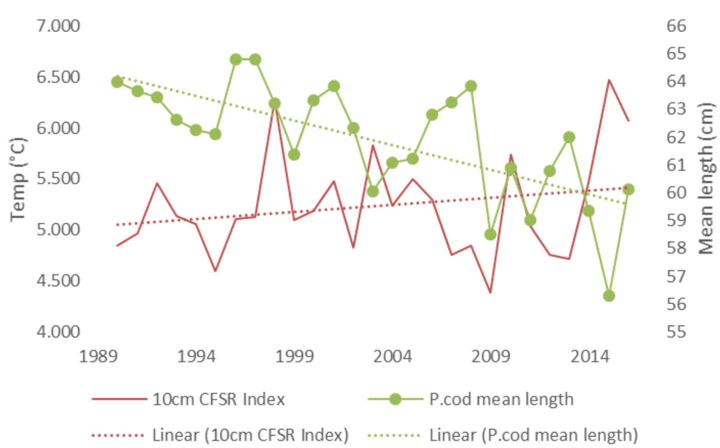


Figure 2.38 AFSC longline survey Pacific cod RPN (top) and mean length (bottom) in comparison with the 10CM CFSR bottom temperature index.

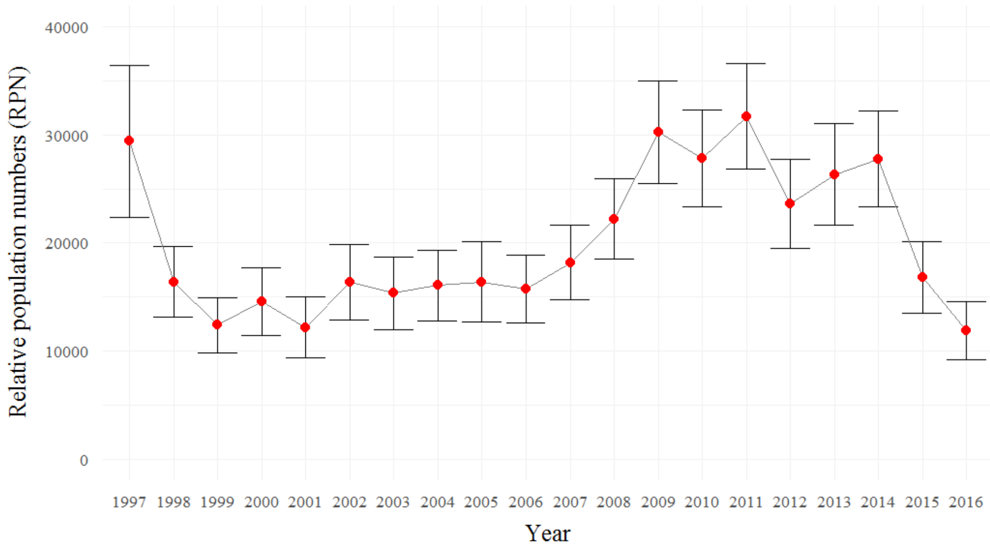


Figure 2.39 IPHC halibut longline survey Pacific cod RPN time series.

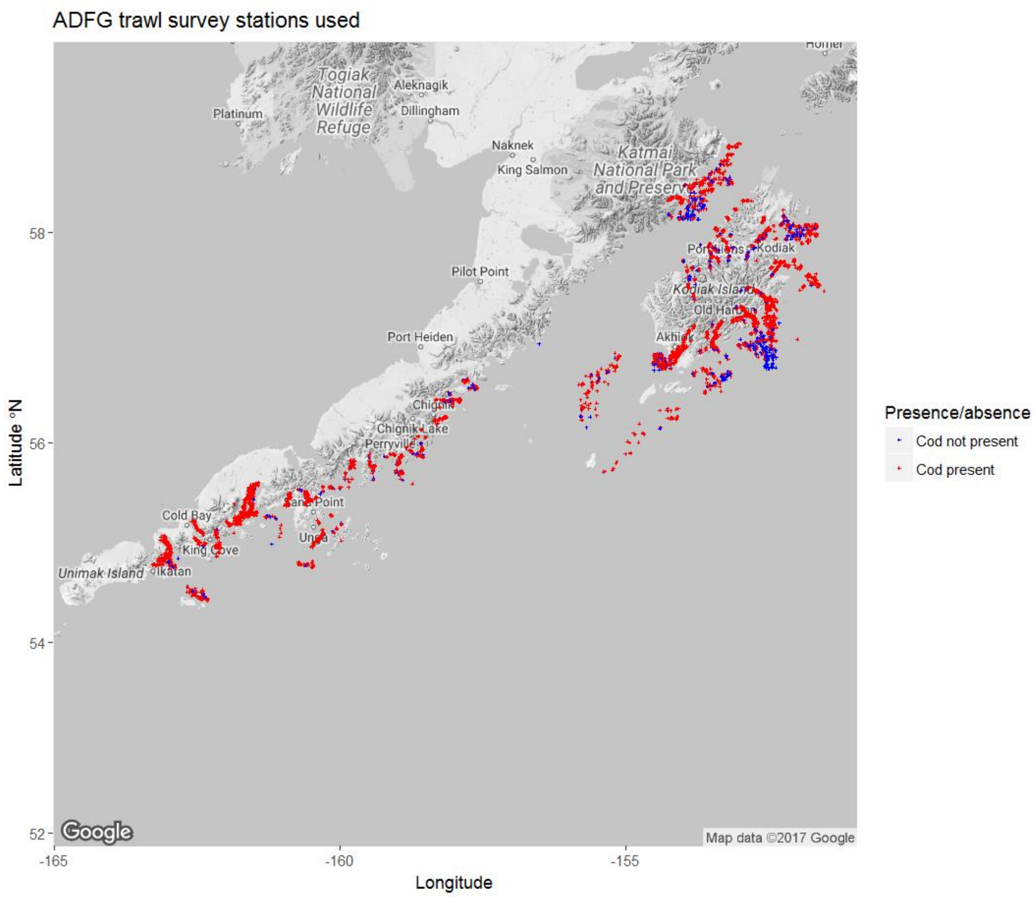


Figure 2.40 ADFG bottom trawl survey stations for 1988-2017 with Pacific cod presence and absence in red and blue for each station.

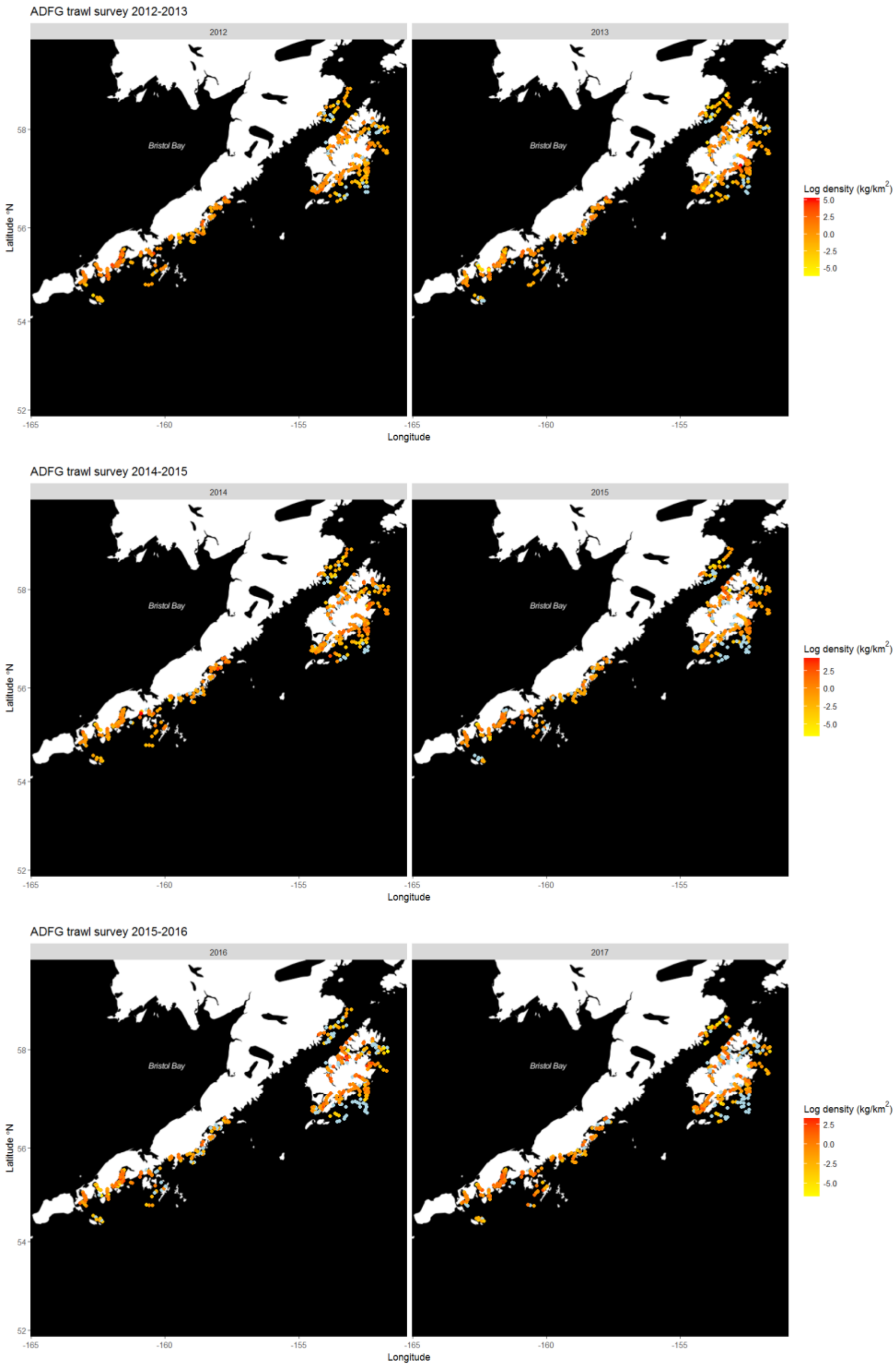


Figure 2.41 ADFG bottom trawl survey stations for 2013-2017 with Pacific cod log density, blue points indicate stations with no Pacific cod.

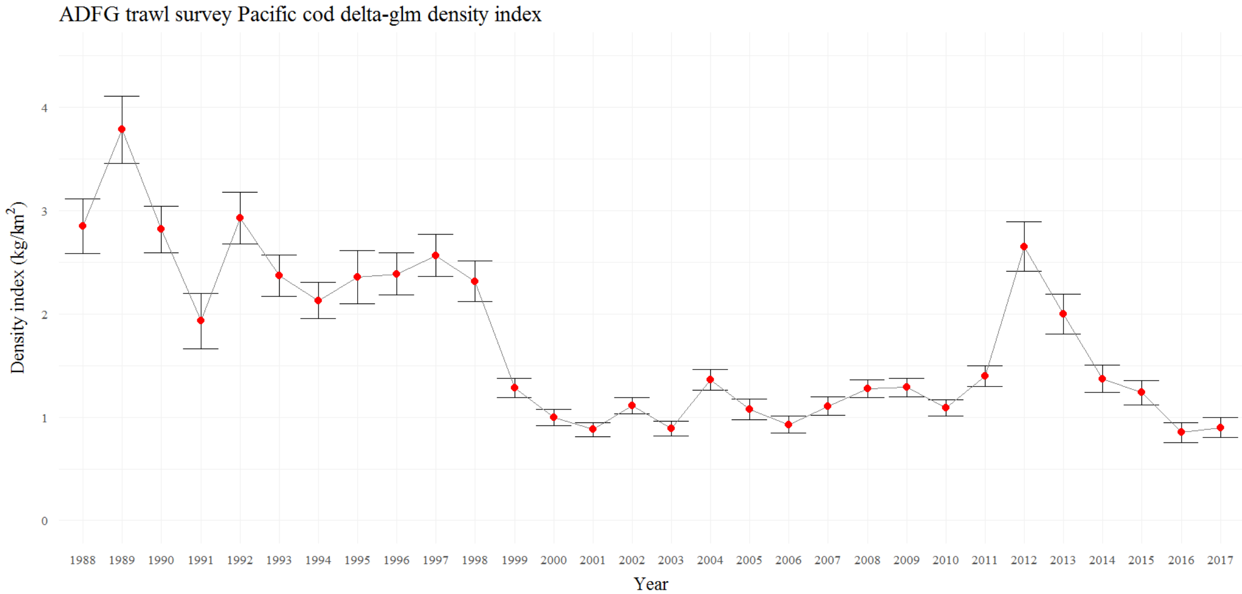


Figure 2.42 ADFG bottom trawl survey delta-glm Pacific cod density index time series.

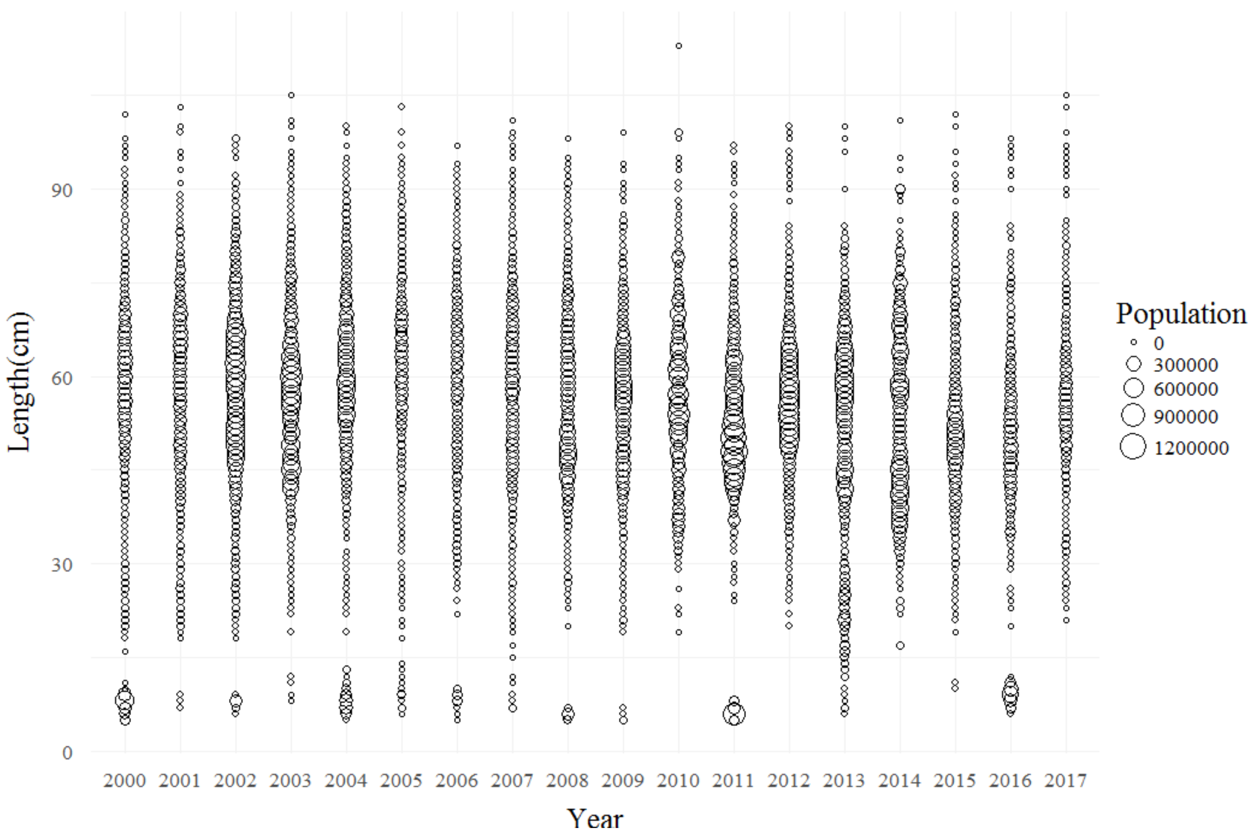


Figure 2.43 ADFG bottom trawl survey Pacific cod population numbers at length estimates.

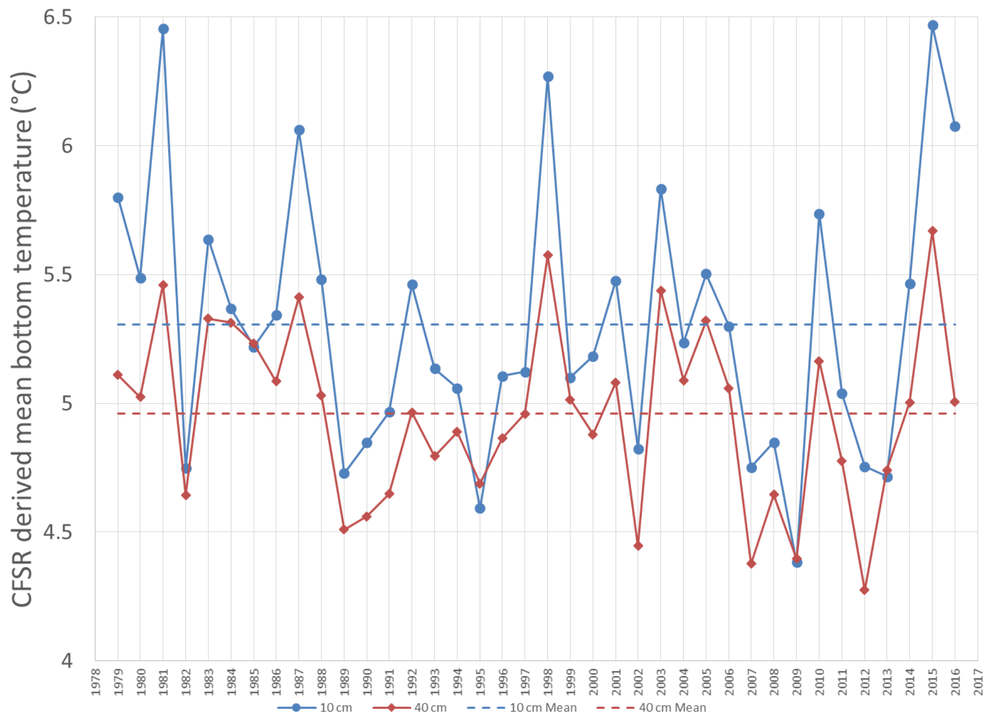


Figure 2.44 Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 10 cm and 40 cm Pacific cod.

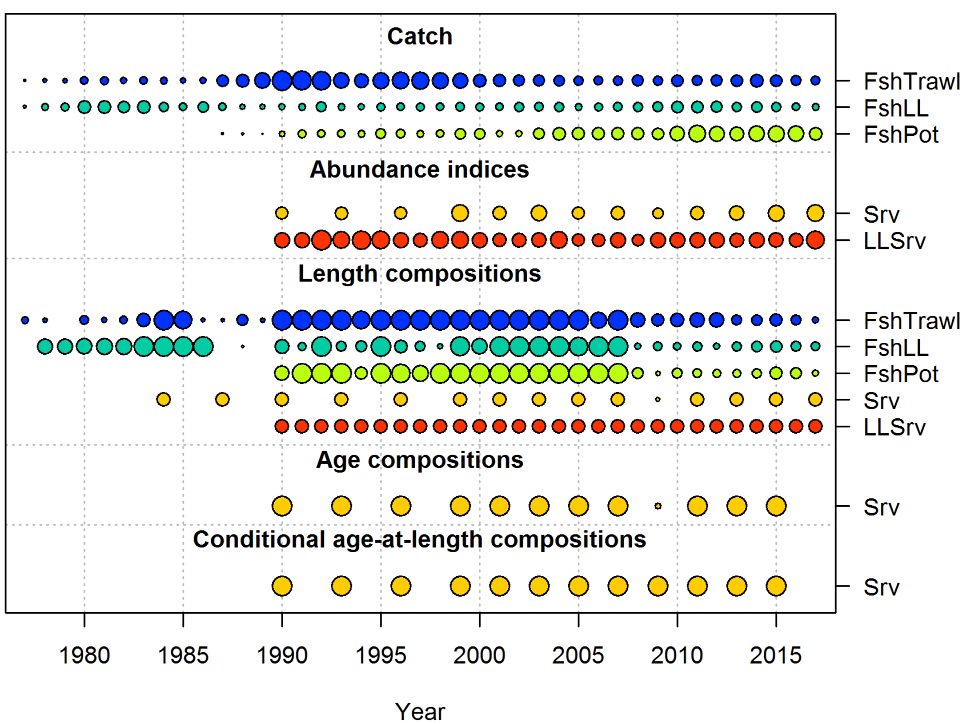


Figure 2.45 Data used in the 2017 models, circle area is relative to initial precision within data type.

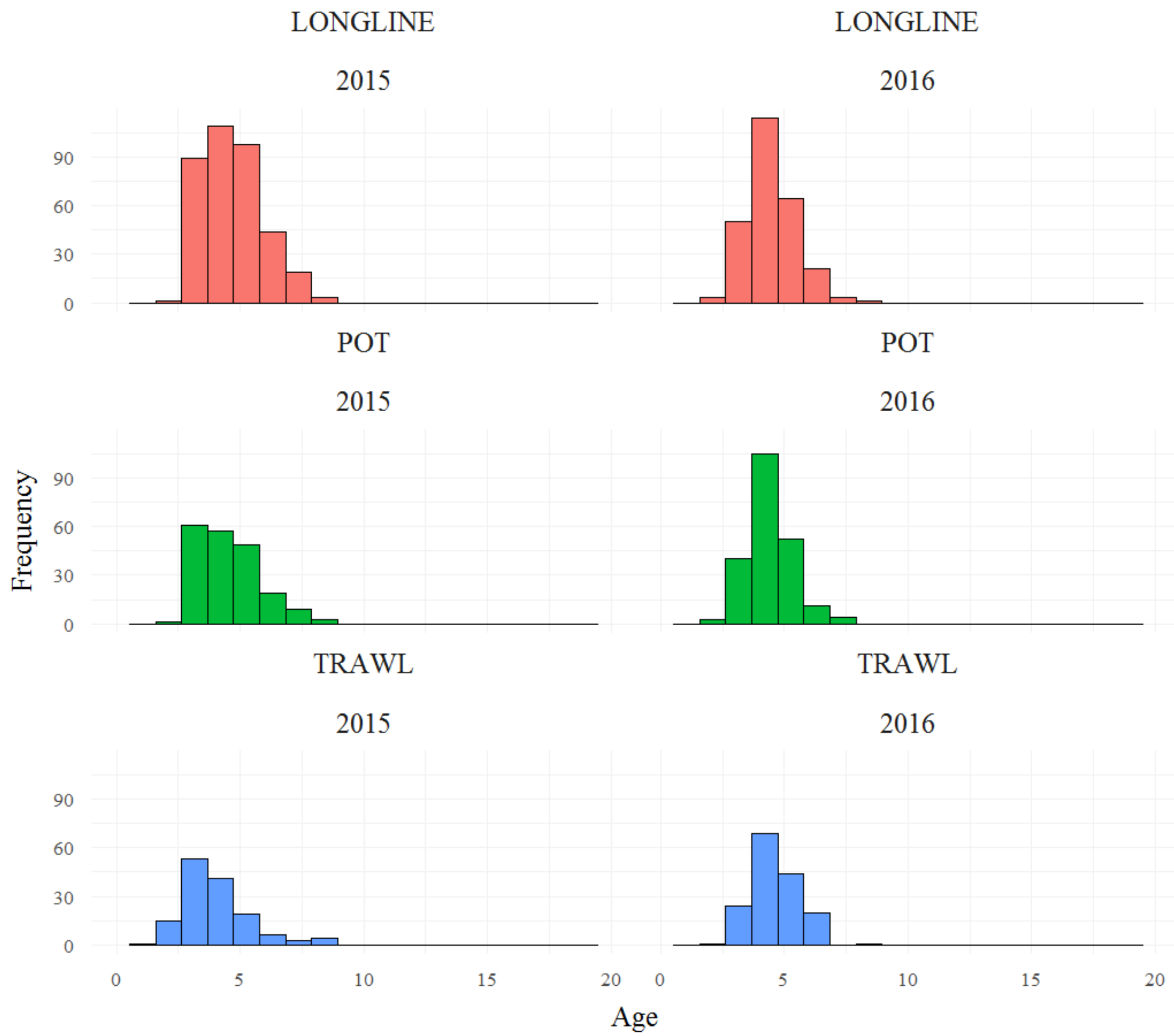


Figure 2.46 Pacific cod age composition data from the Gulf of Alaska fisheries by gear type 2015-2016.

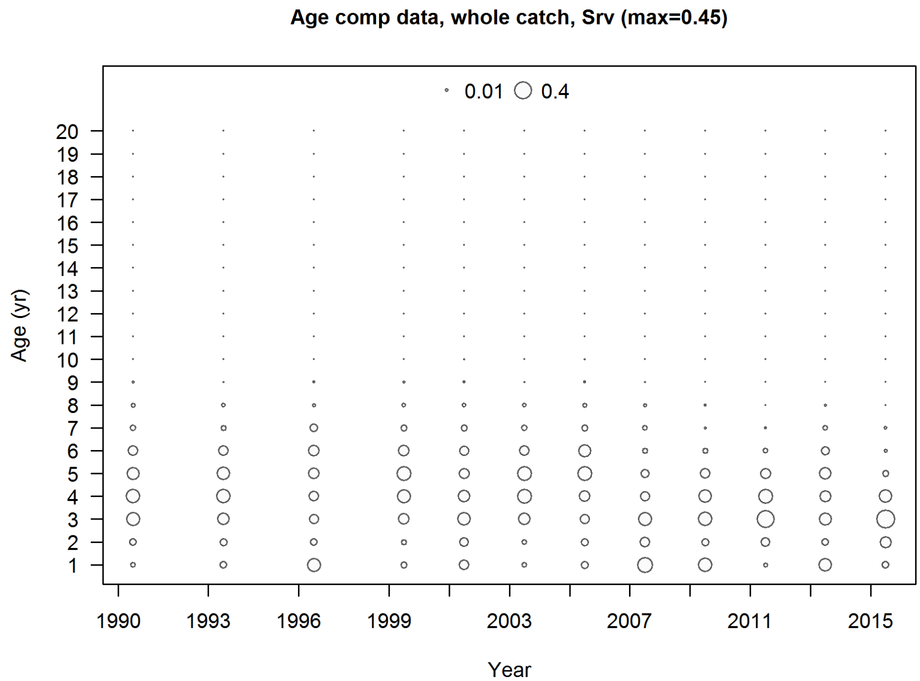


Figure 2.47 Pacific cod age composition data from the Gulf of Alaska bottom trawl survey 1987-2015.

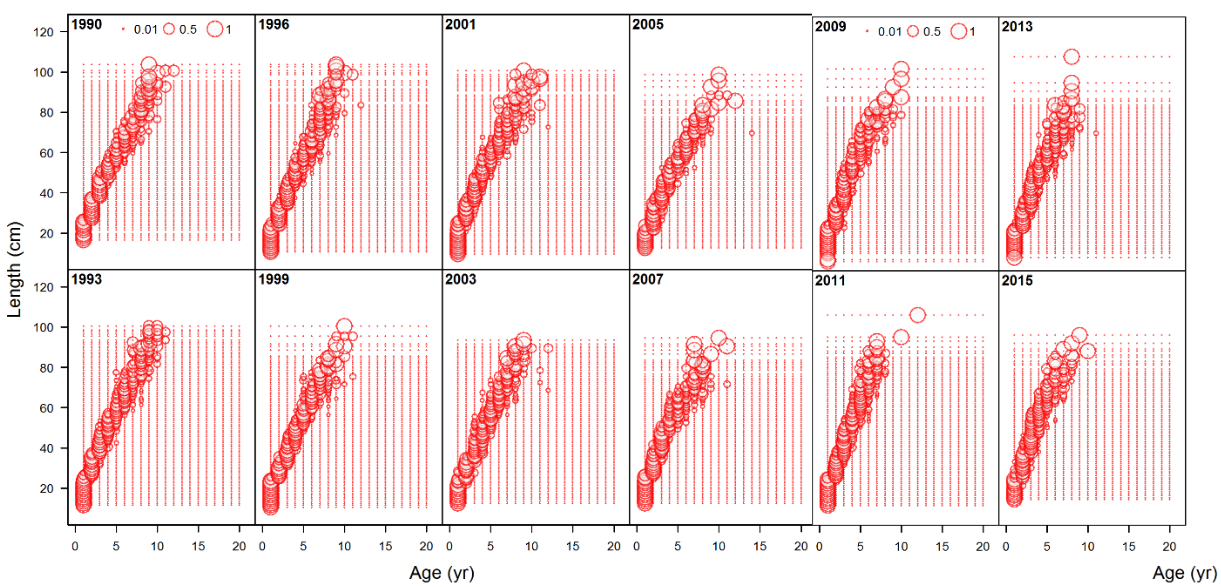


Figure 2.48 Pacific cod conditional length at age from the Gulf of Alaska bottom trawl survey 1987-2015.

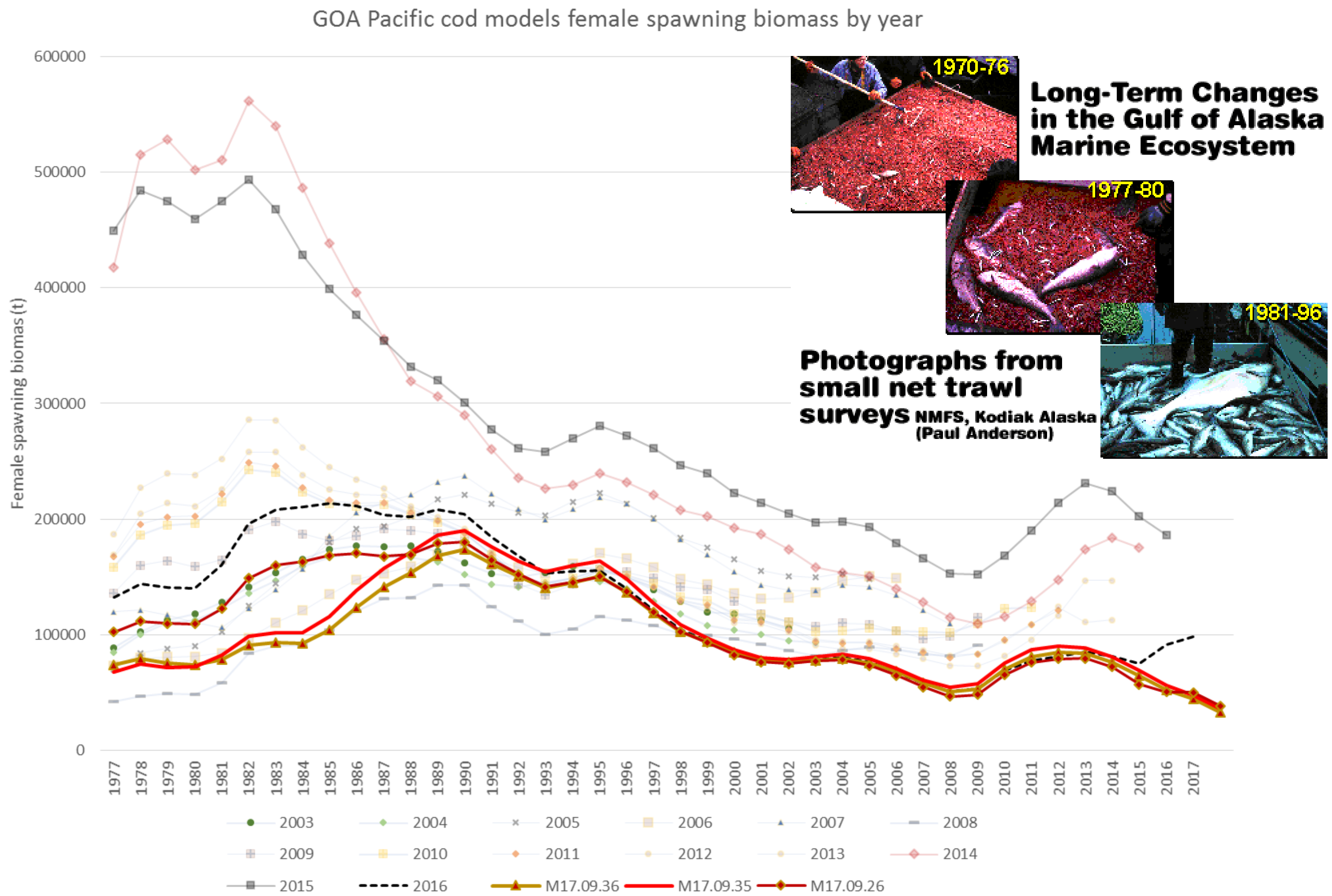


Figure 2.49 1977-2016 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2016 stock assessments with the author's preferred Model 17.09.35, Model 17.09.36, and Model 17.09.26, and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thexxnakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

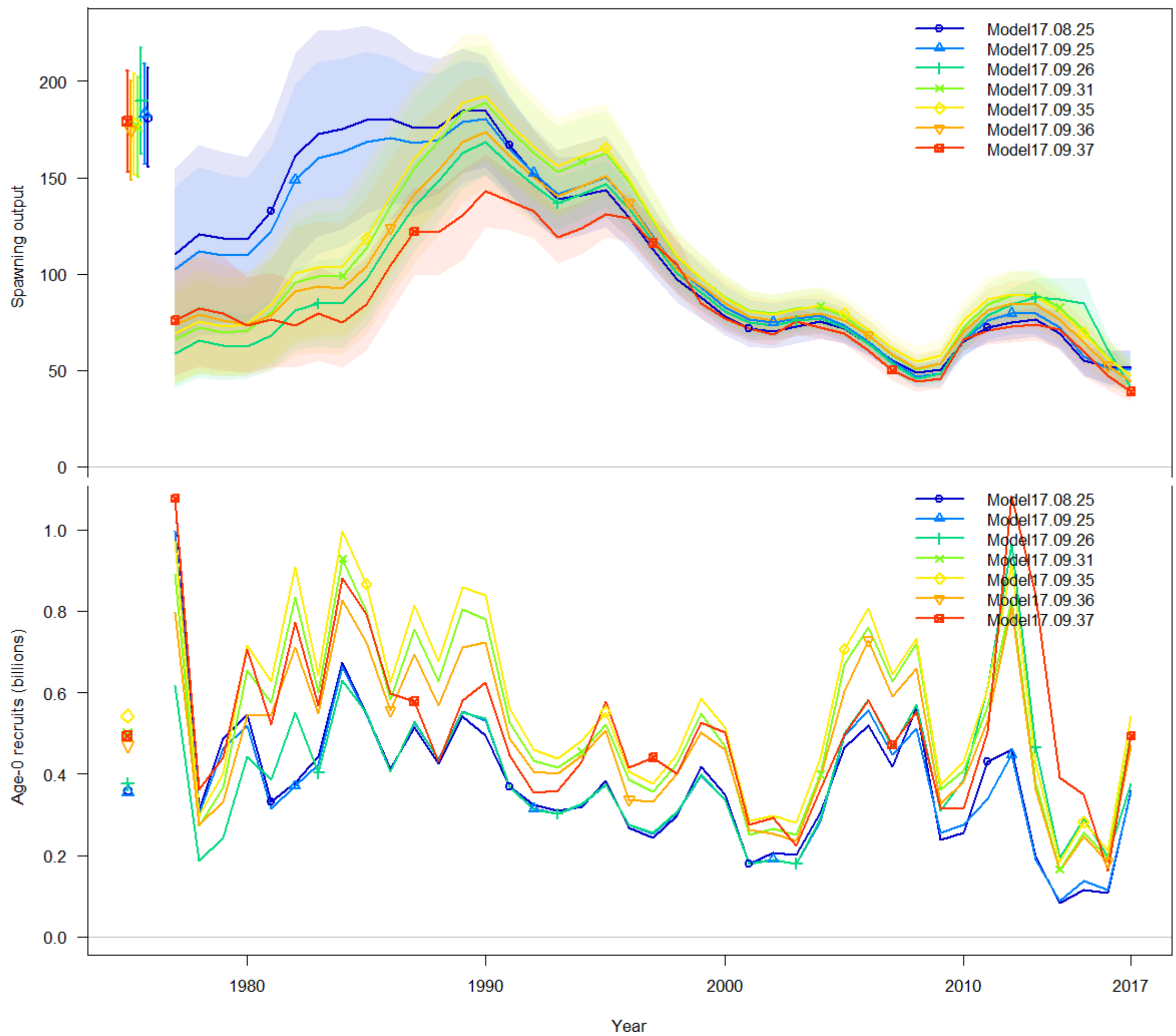


Figure 2.50 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for 2016 reference model with 2017 data (Model 17.08.25) and the proposed alternative 2017 models.

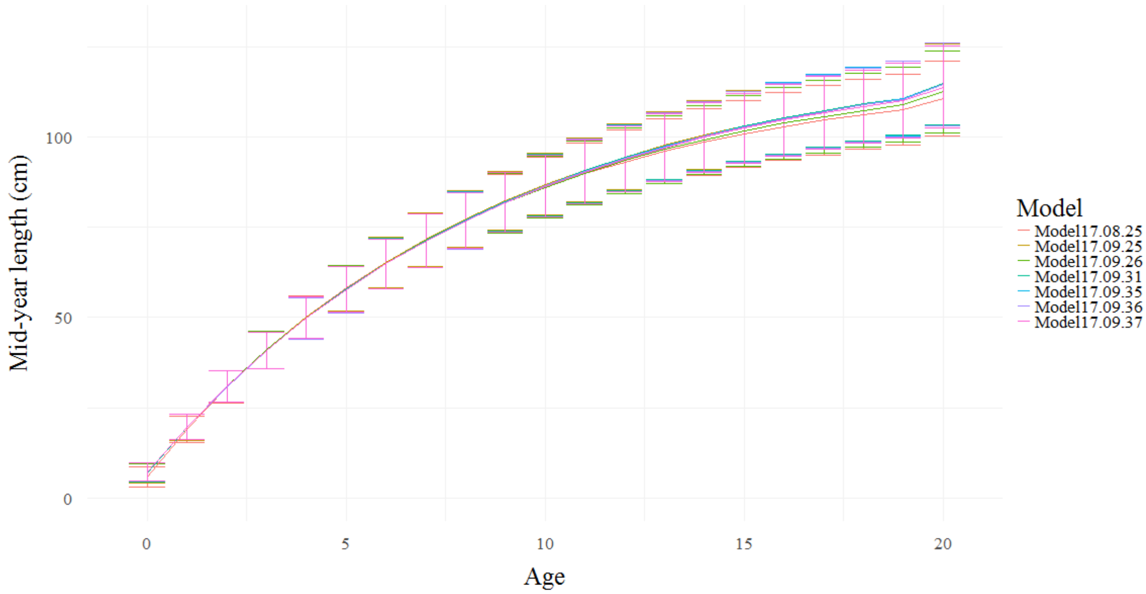


Figure 2.51 Estimates of length at age for 2016 reference model with 2017 data (Model 17.08.25) and the proposed alternative 2017 models showing very little difference among models.

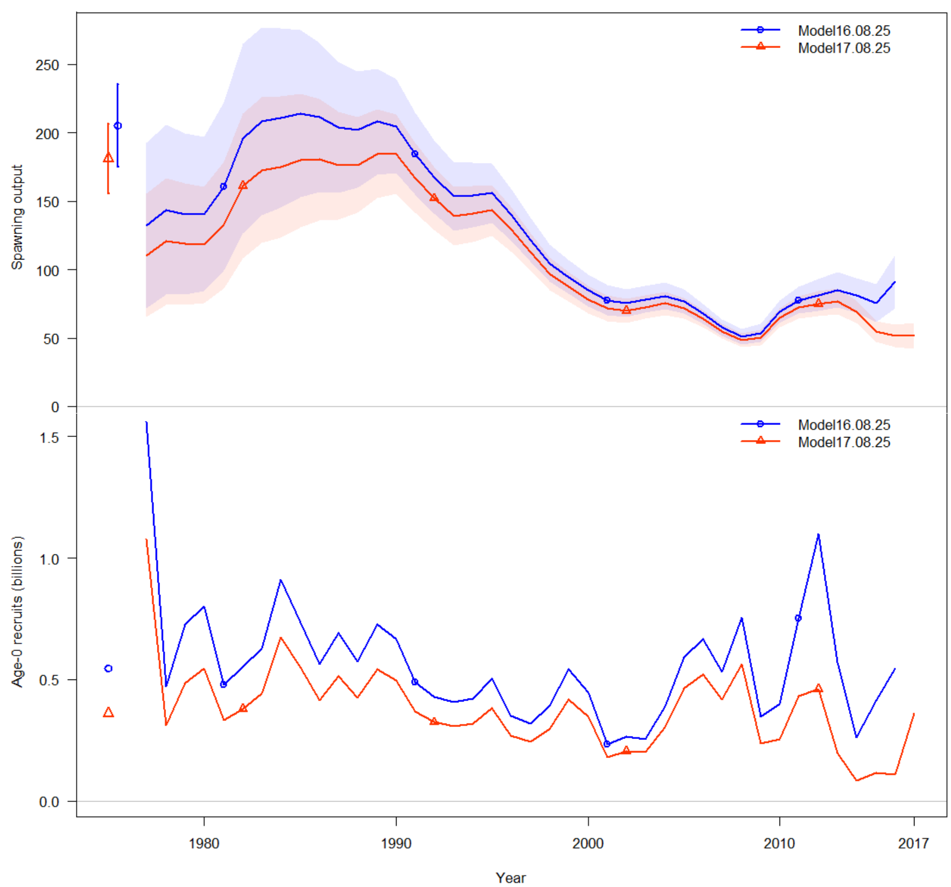


Figure 2.52 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 16.08.25 with and without 2017 data.

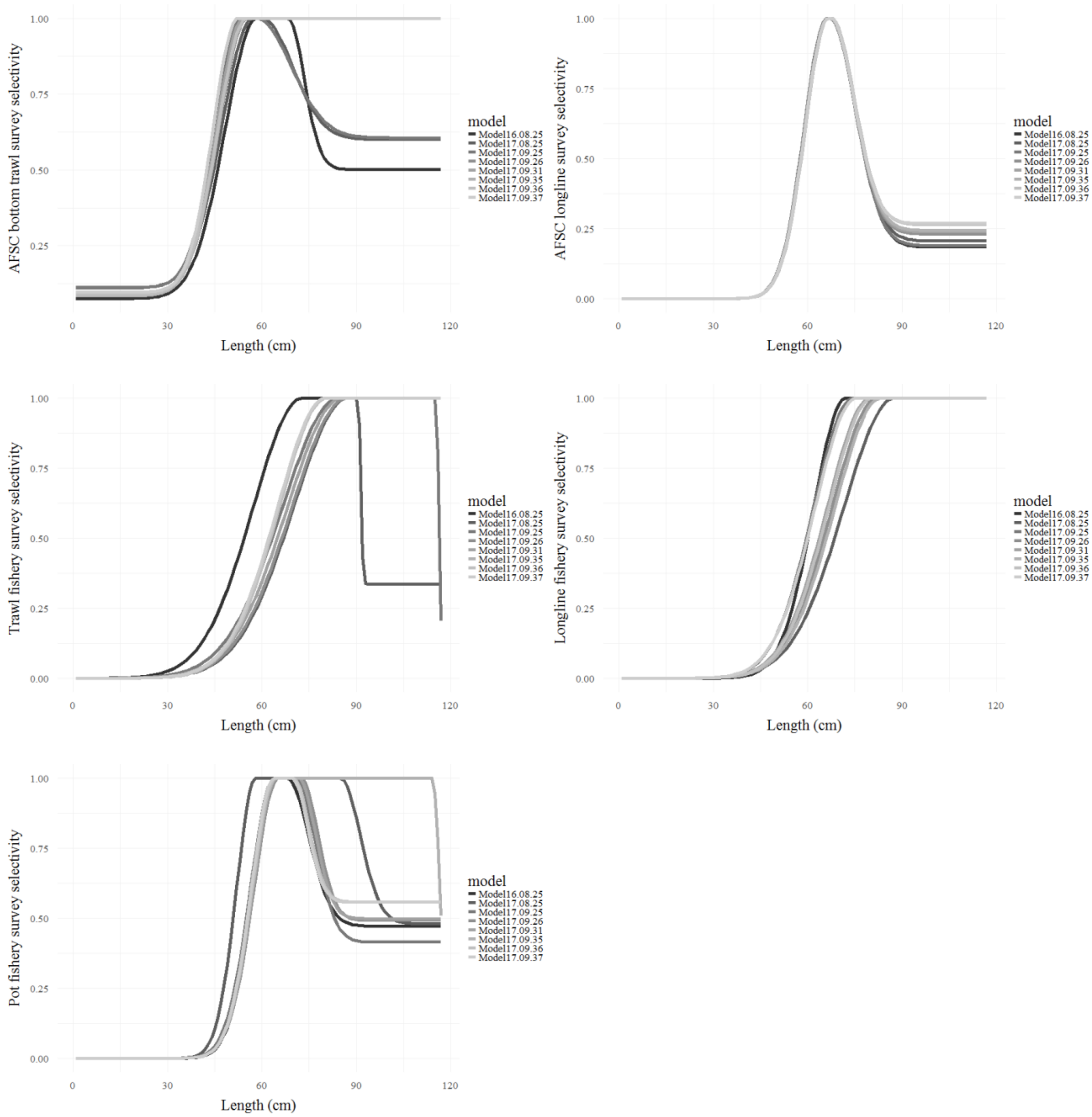


Figure 2.53 –2016 (Model16.08.25) and 2017 (all other models) selectivity for all size composition components.

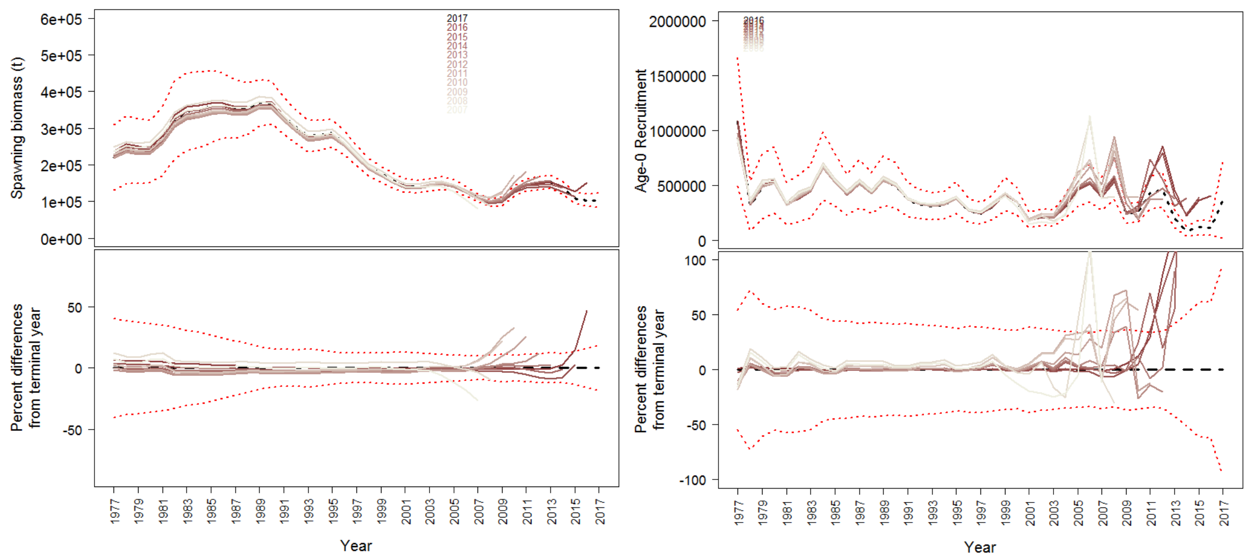


Figure 2.54 Retrospective analysis for Model 17.08.25 for Female spawning biomass (top left) age-0 recruits (top right), and showing Age-0 recruits from Model 17.08.25 and Model 17.08.25 with the 2017 data removed (Model17.08.25 retro -1 year).

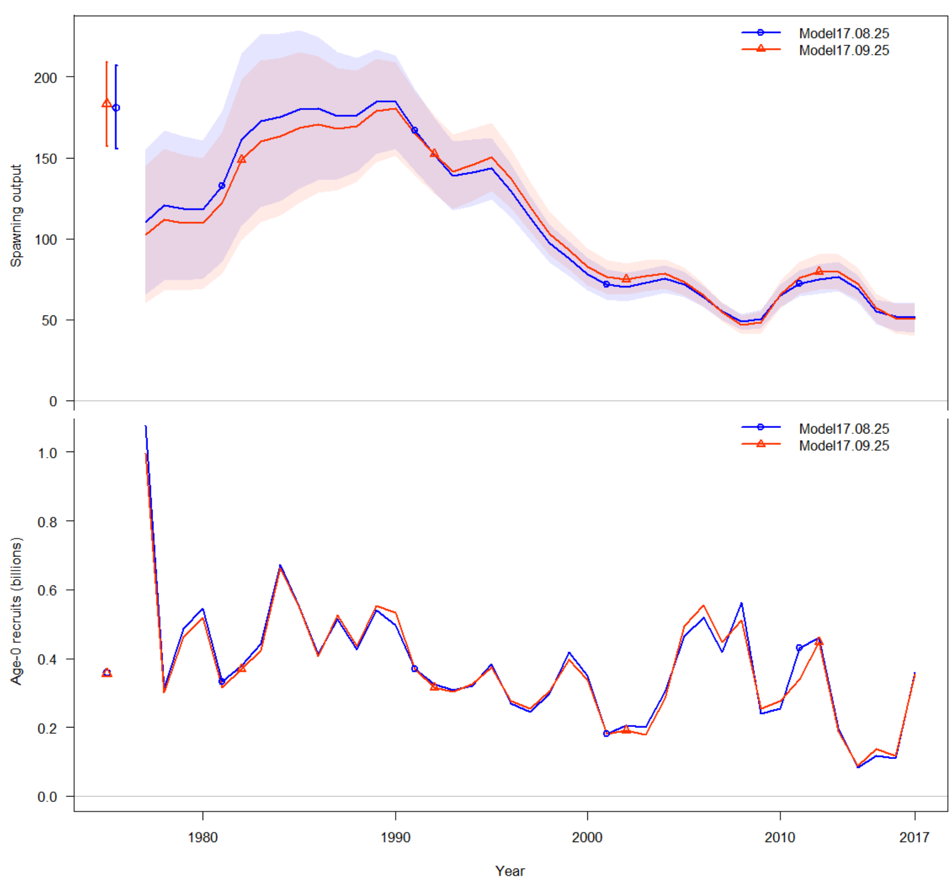


Figure 2.55 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.08.25 and Model 17.09.25.

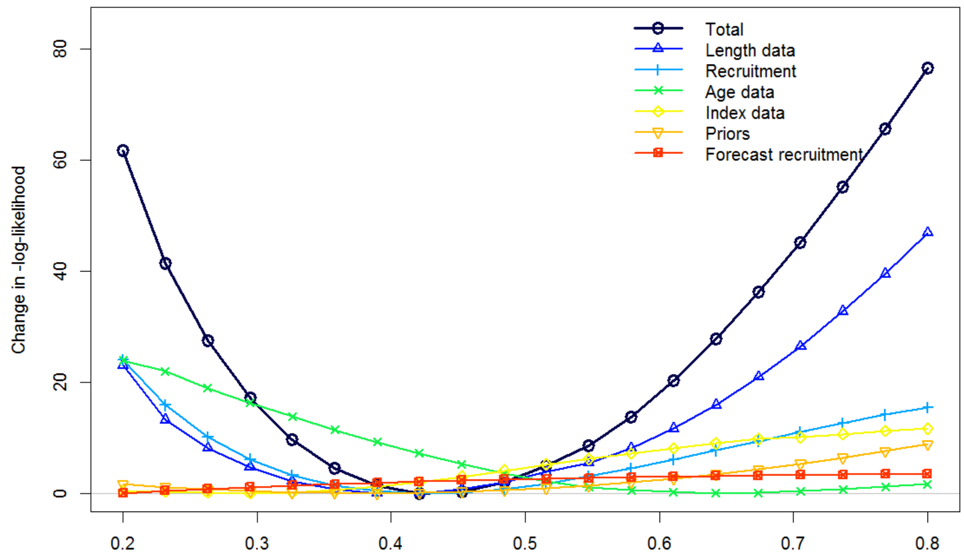


Figure 2.56 Likelihood profile on natural mortality in Model 17.09.25.

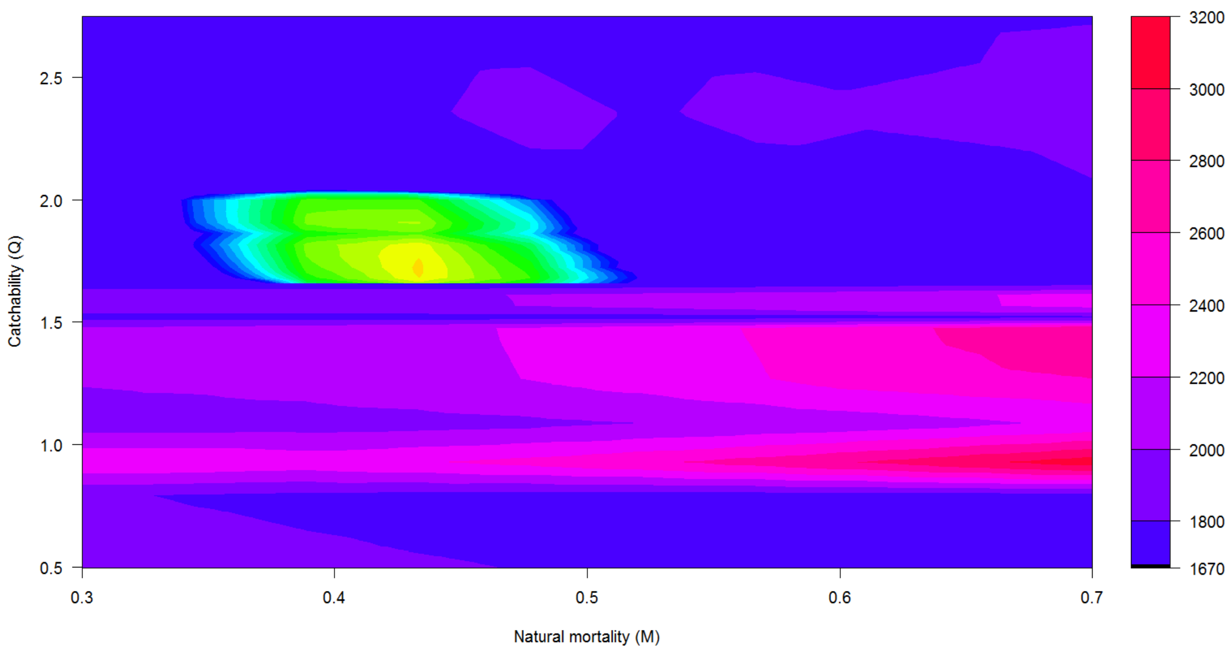


Figure 2.57 Likelihood profile on natural mortality and catchability in Model 17.09.25.

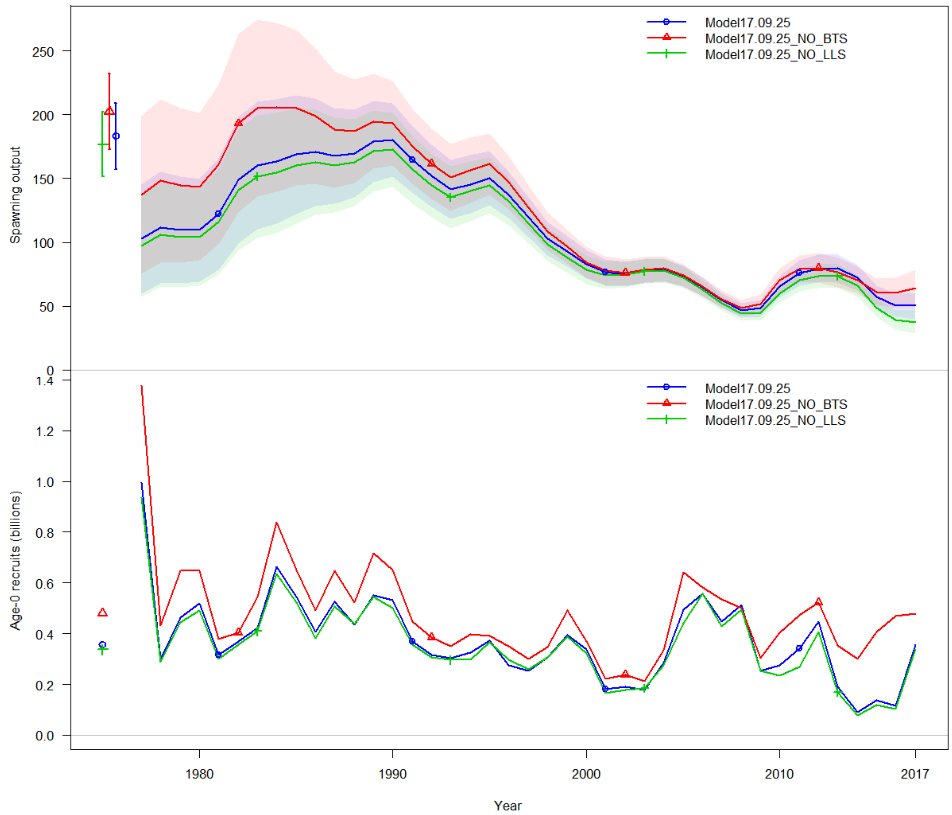


Figure 2.58 Female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) in Model 17.09.25 with both the AFSC longline and bottom trawl surveys and without each of these data series.

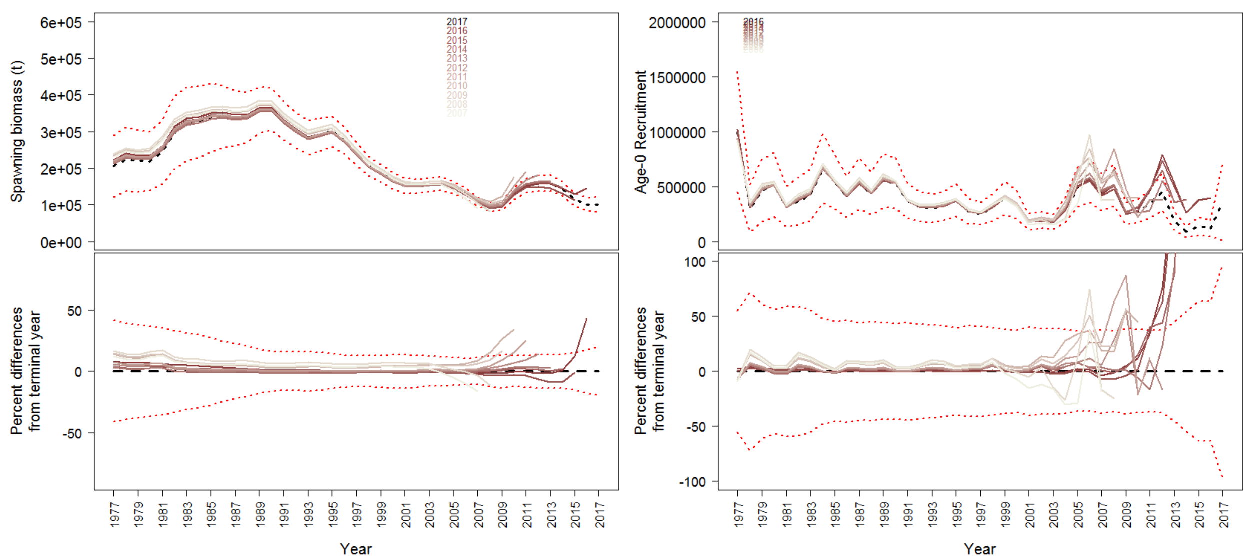


Figure 2.59 Retrospective analysis for Model 17.09.25 for Female spawning biomass (left) age-0 recruits (right).

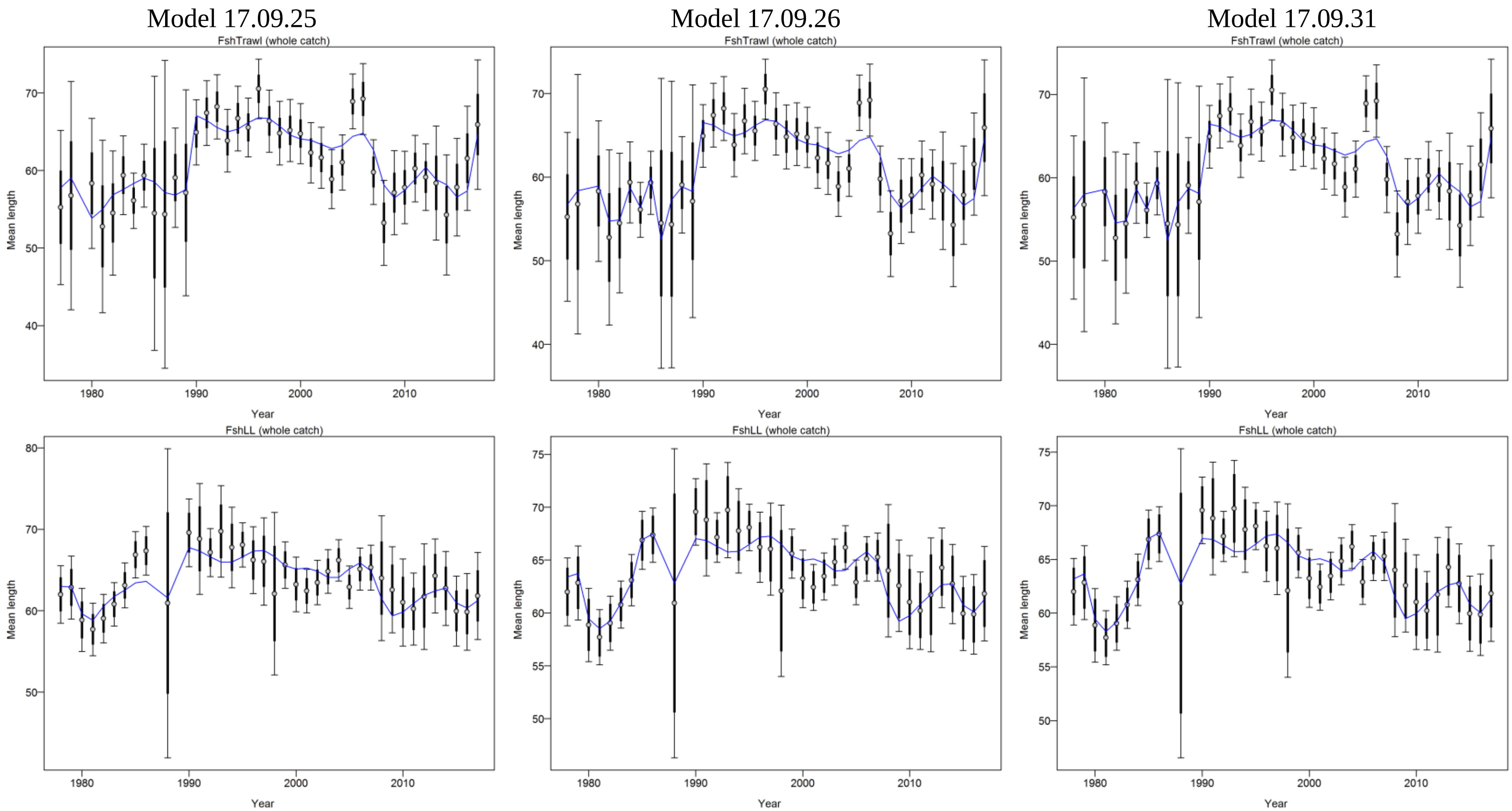


Figure 2.60 Model 17.09.25 (left), Model 17.09.26 (middle), and Model 17.09.31 (right) fits (line) to mean length from the trawl (top) and longline (bottom) fisheries.

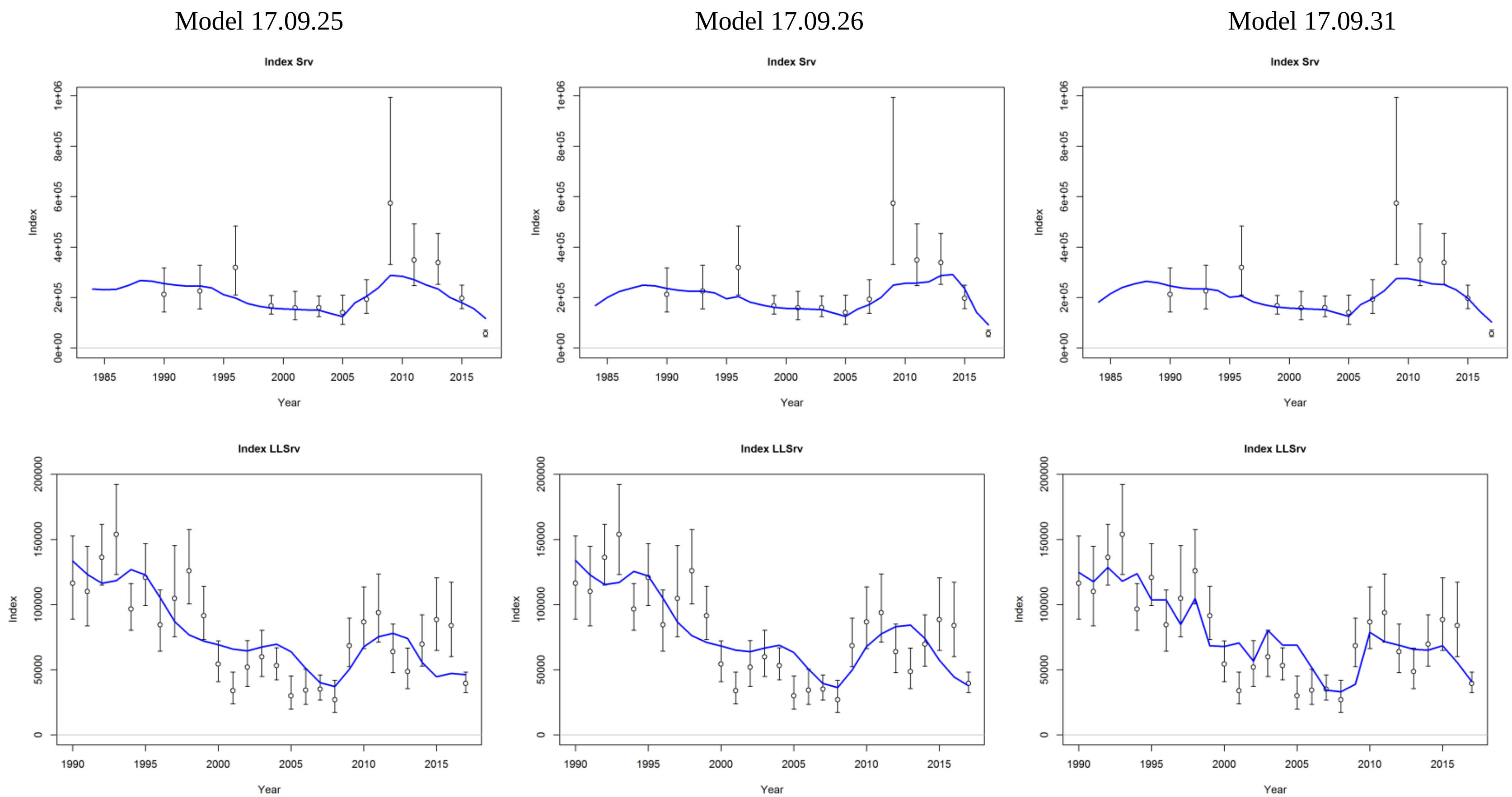


Figure 2.61 Model 17.09.25 (left), Model 17.09.26 (middle), and Model 17.09.31 (right) fits (line) to mean length from the AFSC bottom trawl (top) and AFSC longline (bottom) surveys.

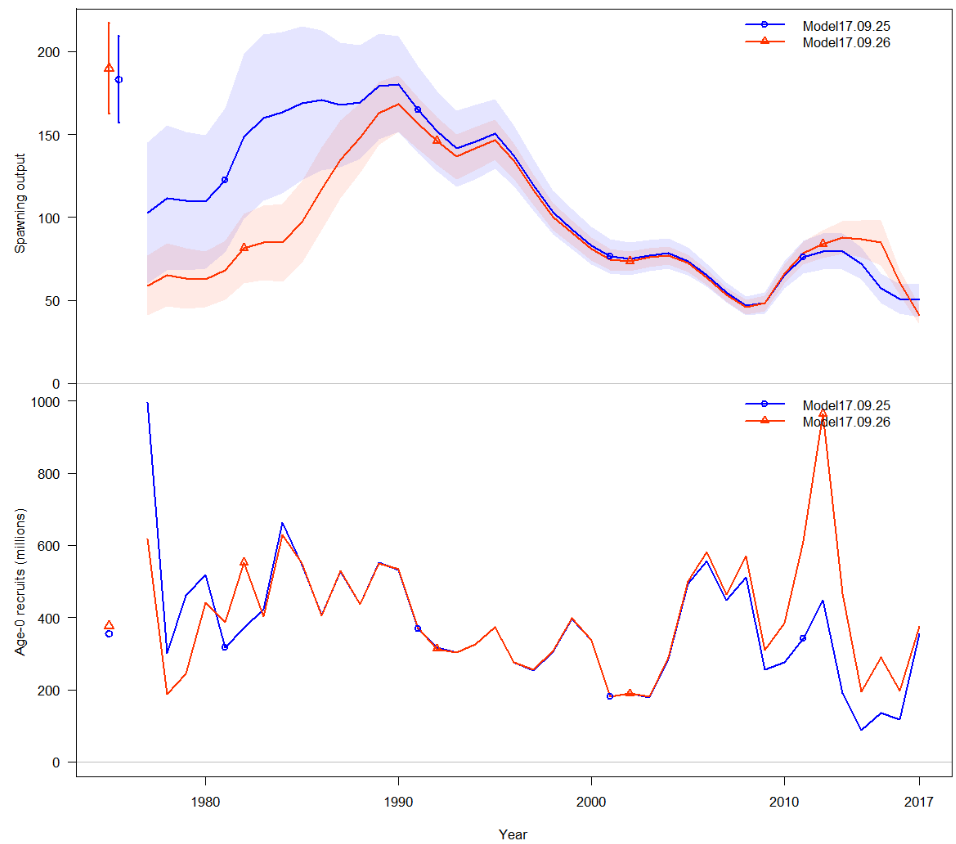


Figure 2.62 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09.25 and Model 17.09.26.

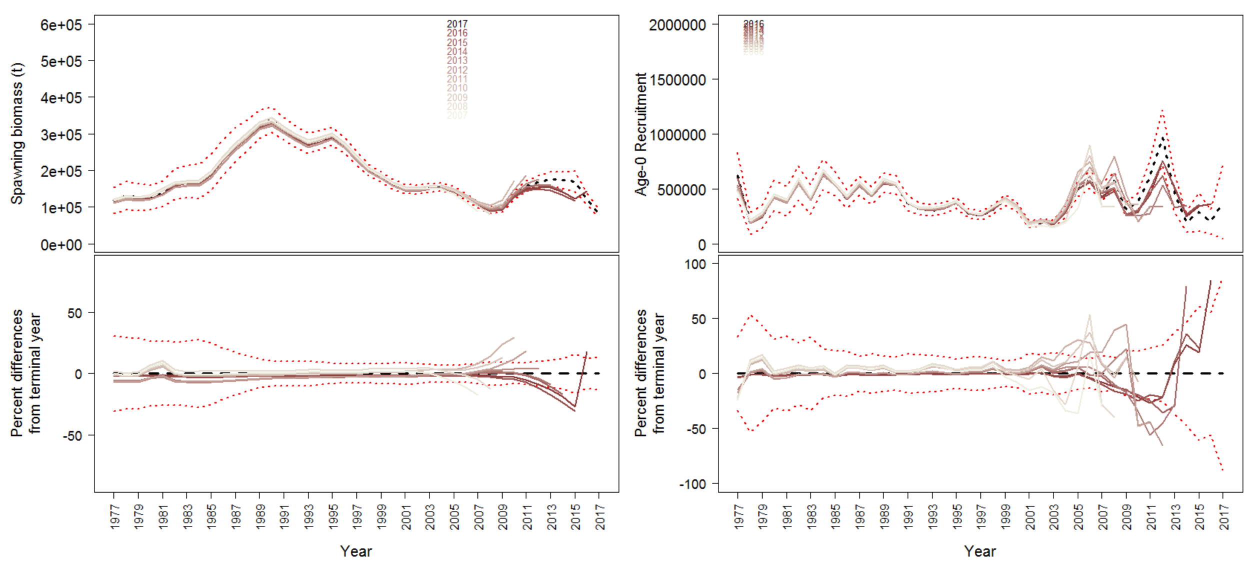


Figure 2.63 Retrospective analysis for Model 17.09.26 for Female spawning biomass (left) age-0 recruits (right).

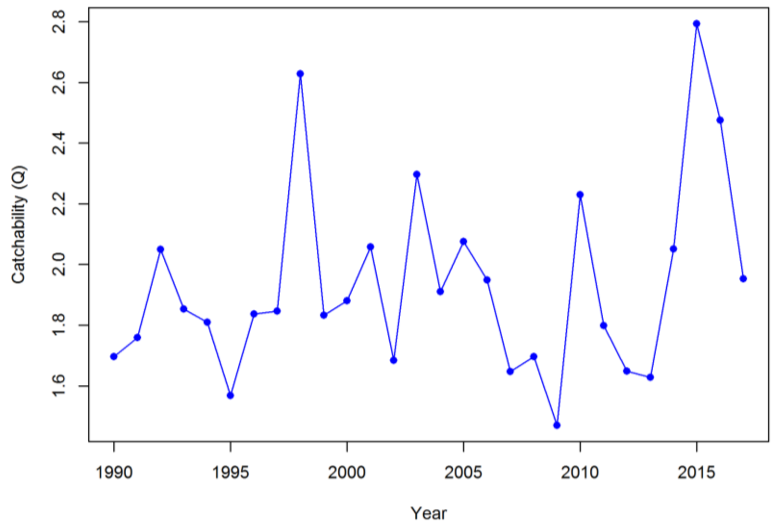


Figure 2.64 Time varying catchability for the AFSC sablefish longline survey in Model 17.09.31 scaled by the 10 cm CFSR bottom temperature index anomaly.

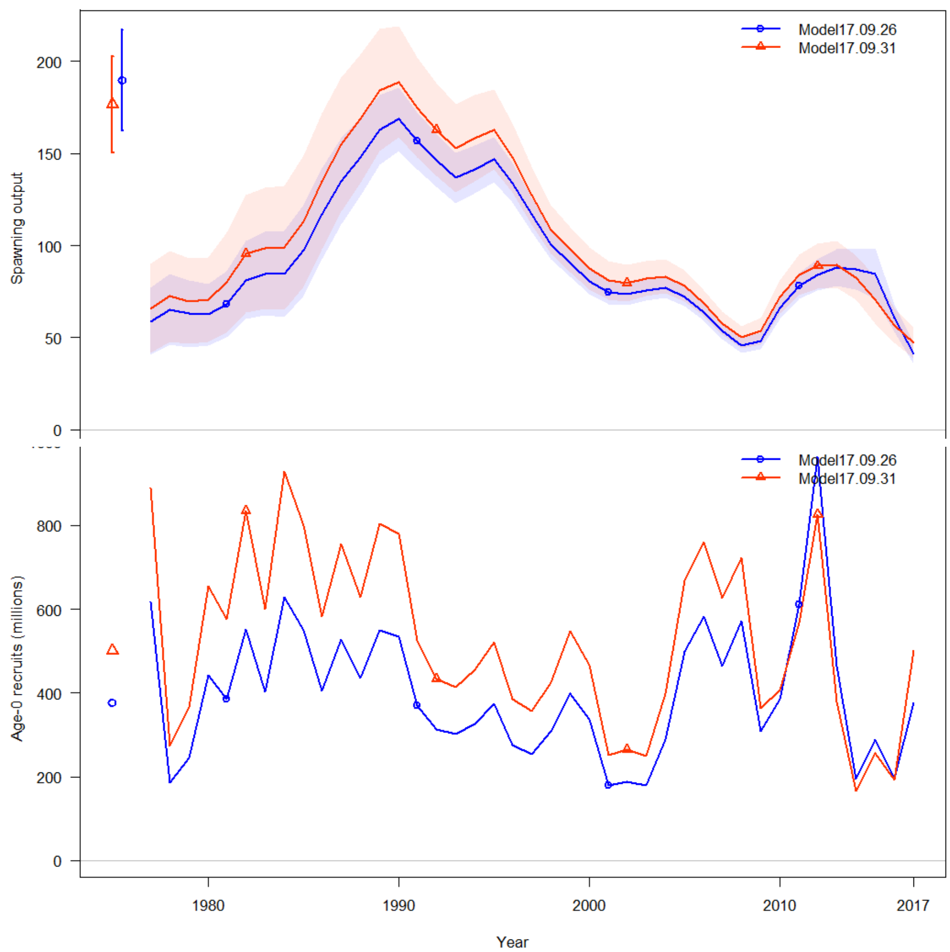


Figure 2.65 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09.26 and Model 17.09.31.

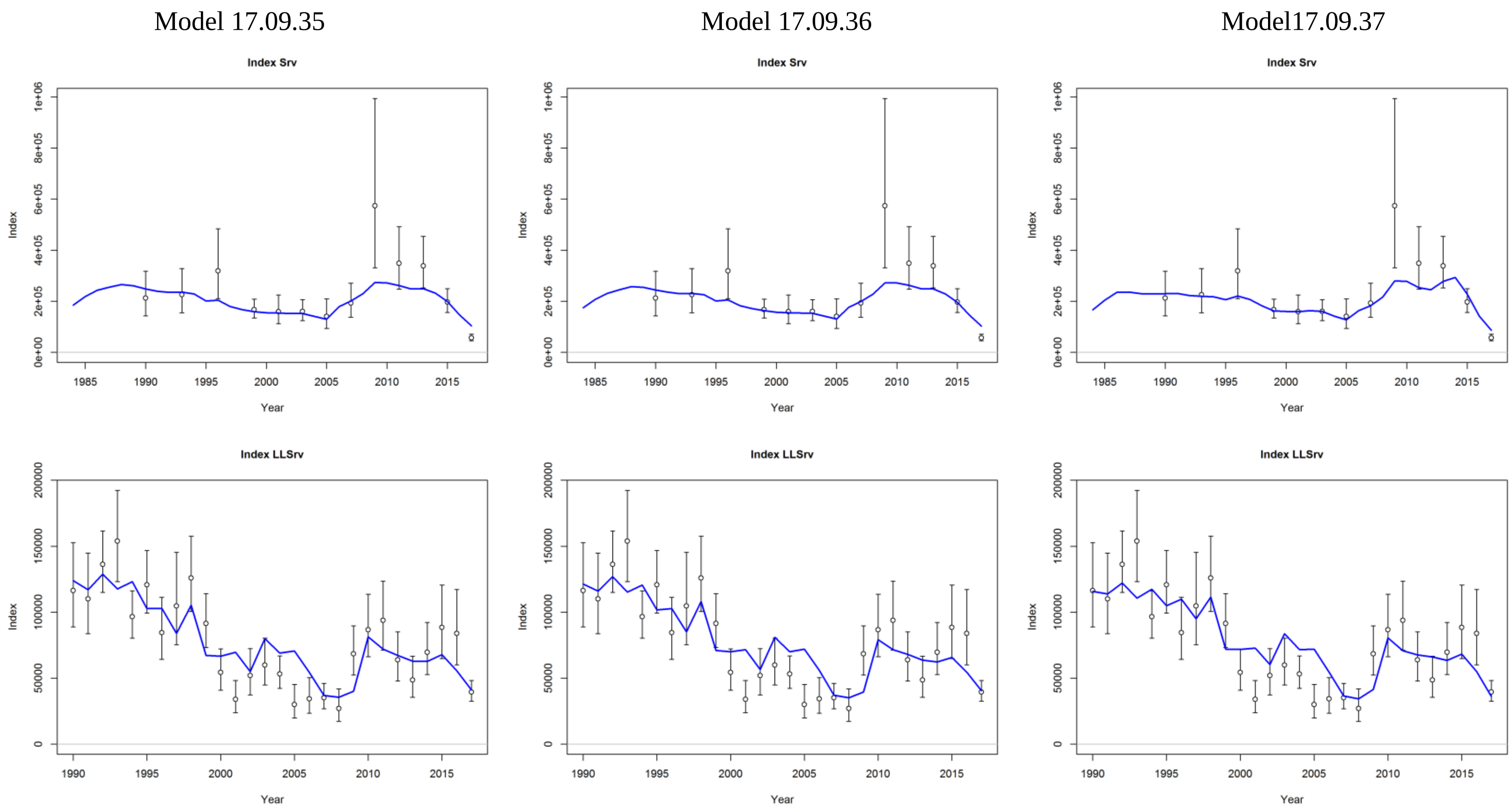


Figure 2.66 Model 17.09.35 (left), Model 17.09.36 (middle) and Model 17.09.37 (right), fits (line) to AFSC bottom trawl index of abundance (top) and AFSC longline RPN index (bottom).

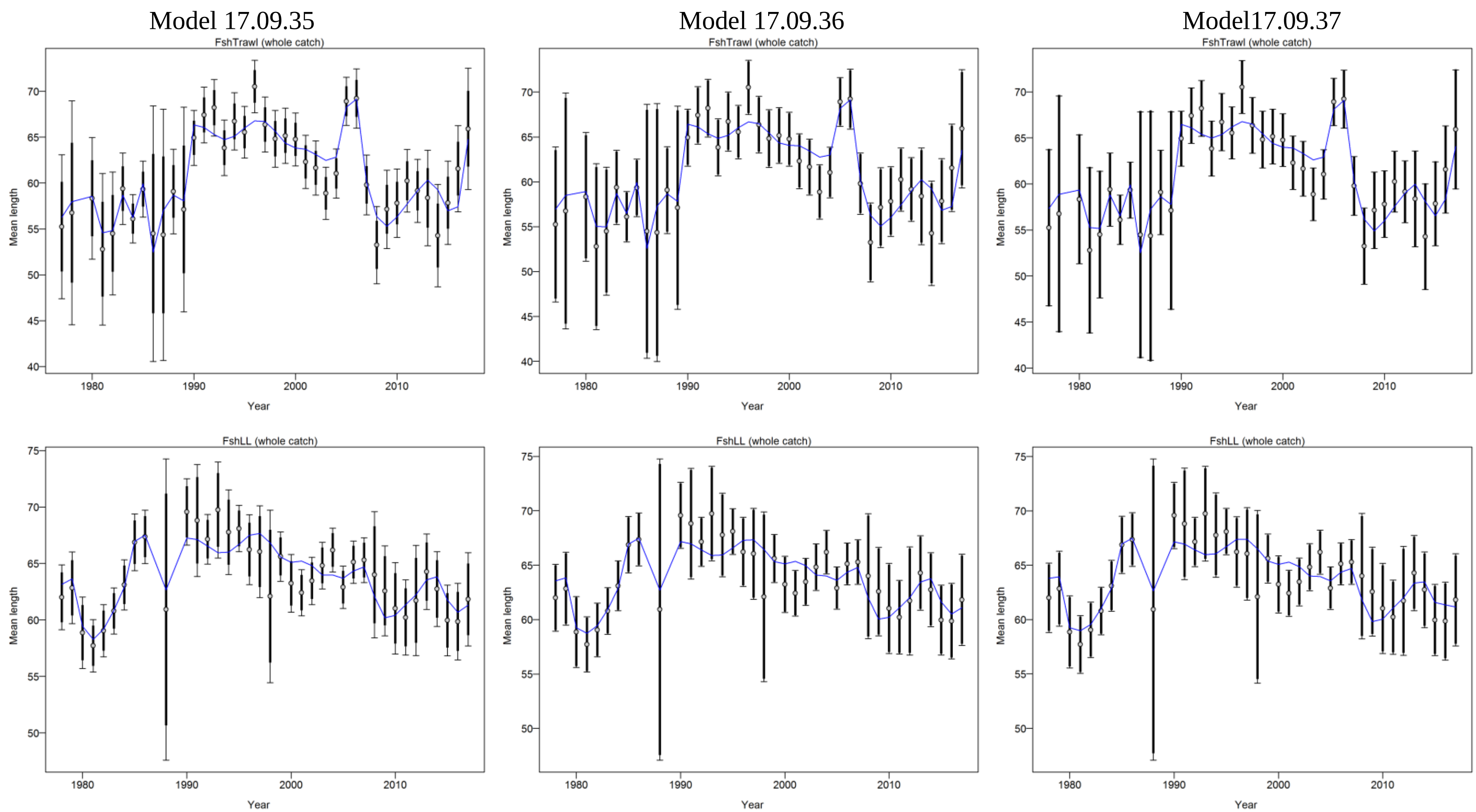


Figure 2.67 Model 17.09.35 (left), Model 17.09.36 (middle), and Model 17.09.37 (right) fits (line) to mean length from the trawl (top) and longline (bottom) fisheries.

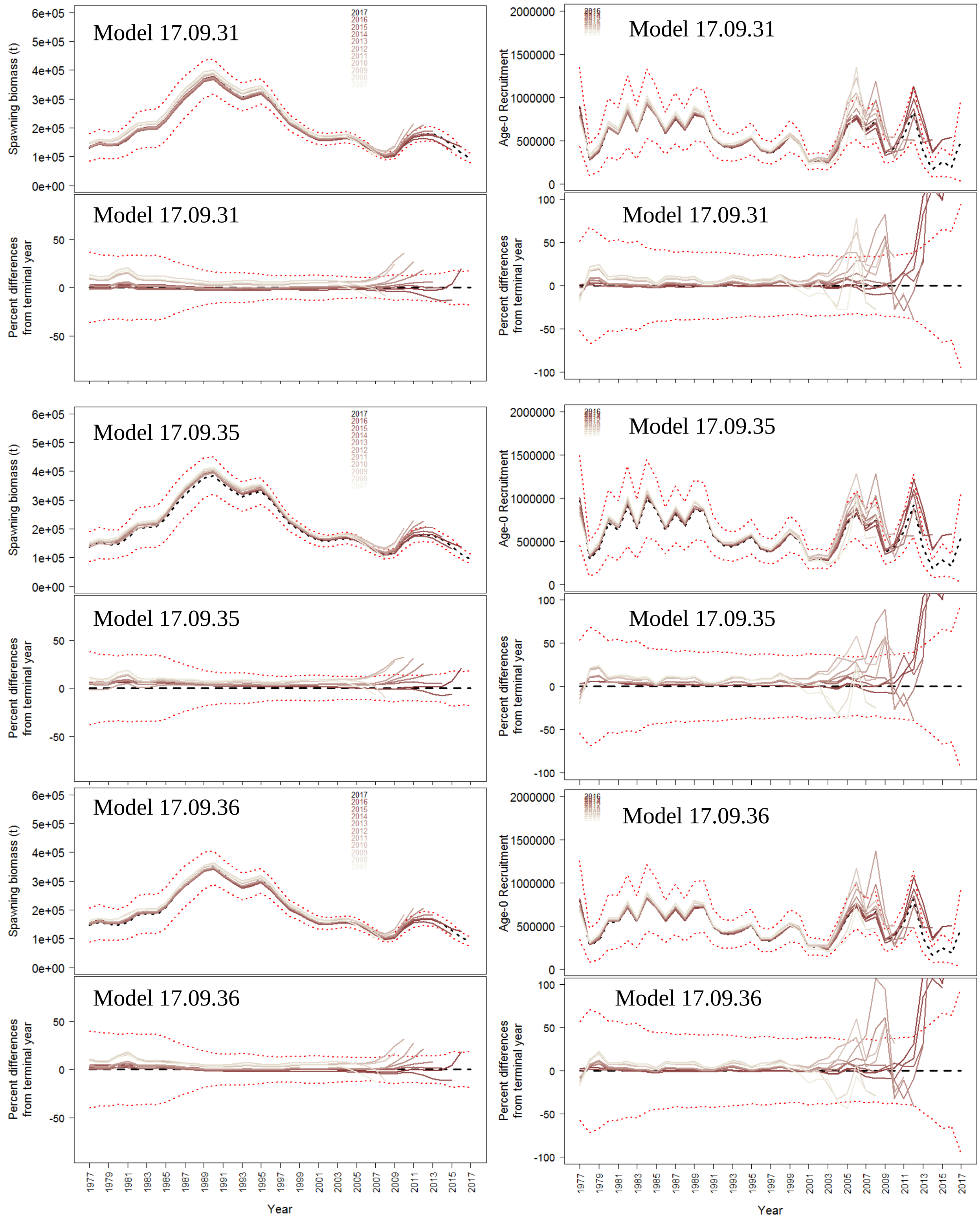


Figure 2.68 Retrospective analysis for Model 17.09.31 (top), Model 17.09.35 (middle), and Model 17.09.36 (bottom) for Female spawning biomass (left) age-0 recruits (right).

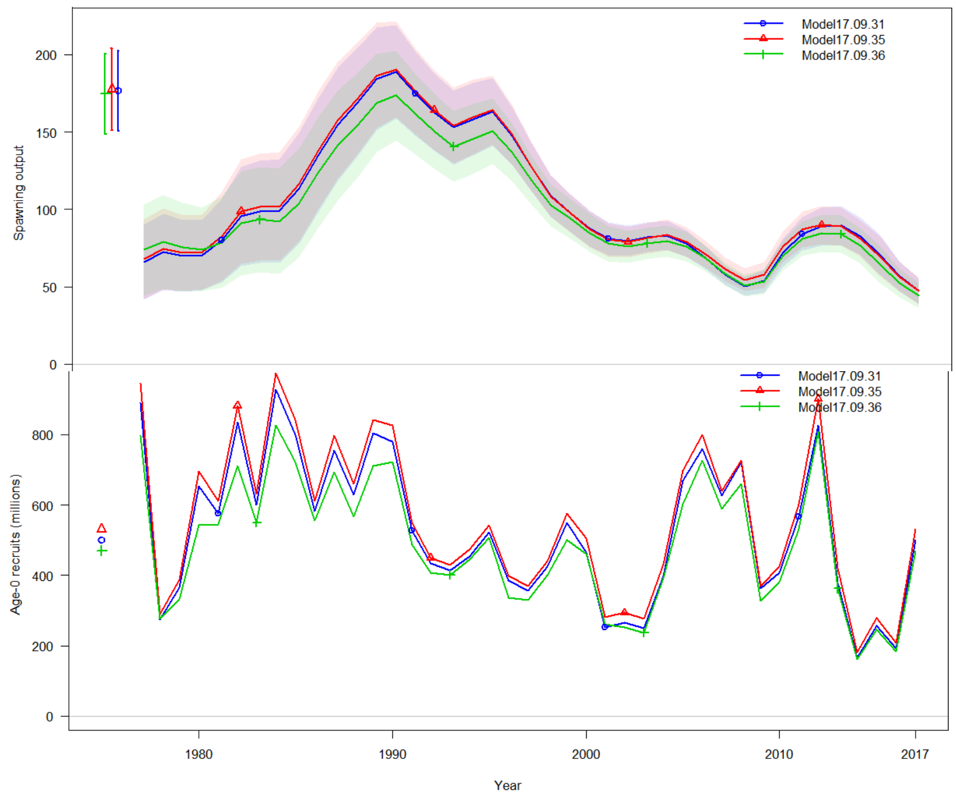


Figure 2.69 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09.31, Model 17.09.35, and Model 17.09.36.

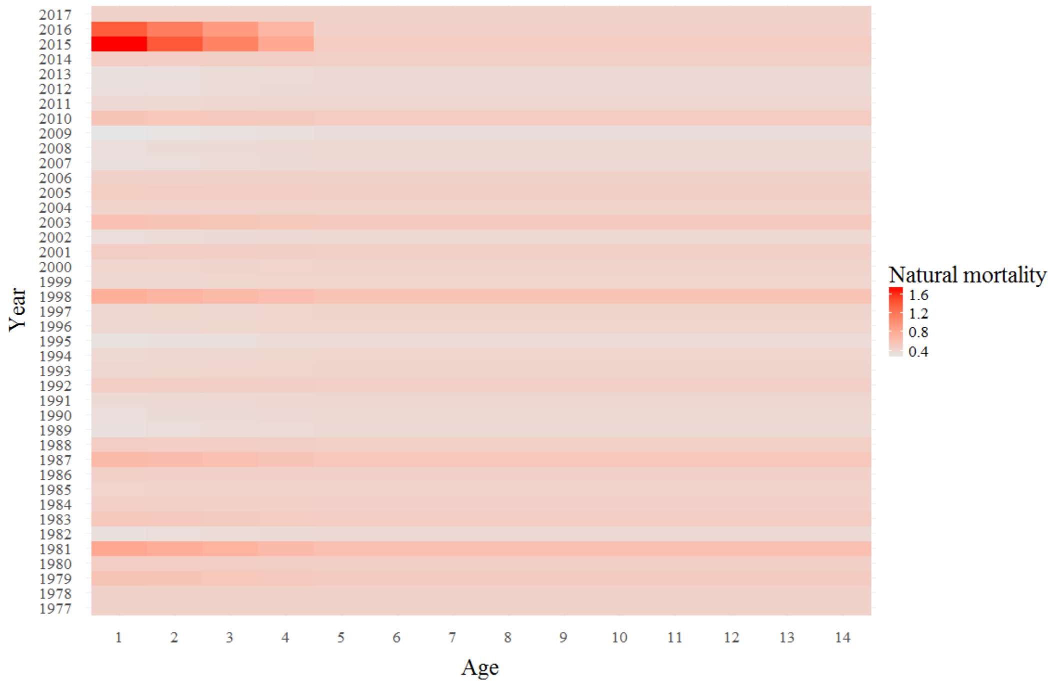


Figure 2.70 Dynamic natural mortality for ages 1-14 for Model 17.09.37 fit. Note that natural mortality for Age-0 was fixed at 0.75 and for ages 15+ is the same as that estimated for age 14.

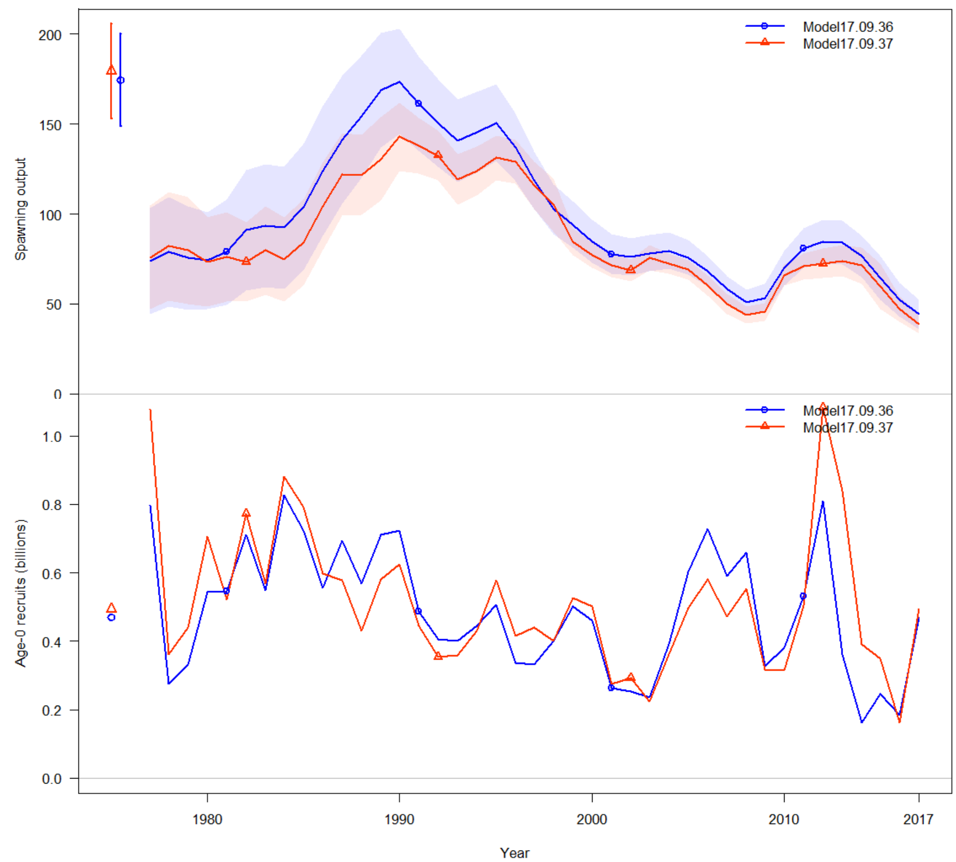


Figure 2.71 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for Model 17.09.36 and Model 17.09.37.

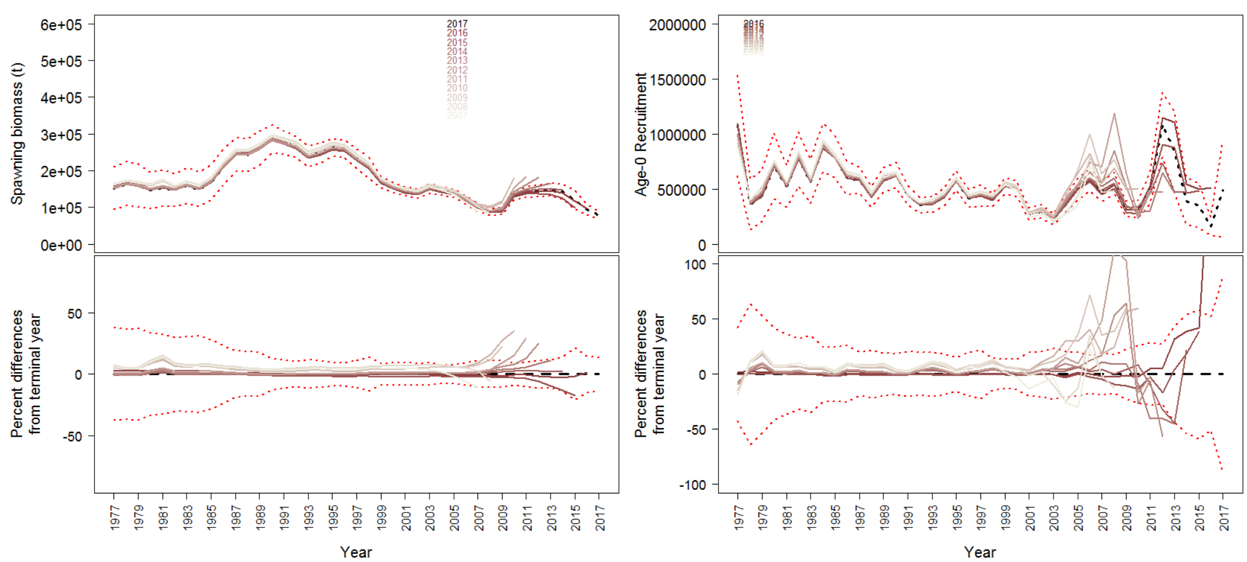


Figure 2.72 Retrospective analysis for Model 17.09.37 for Female spawning biomass (left) age-0 recruits (right).

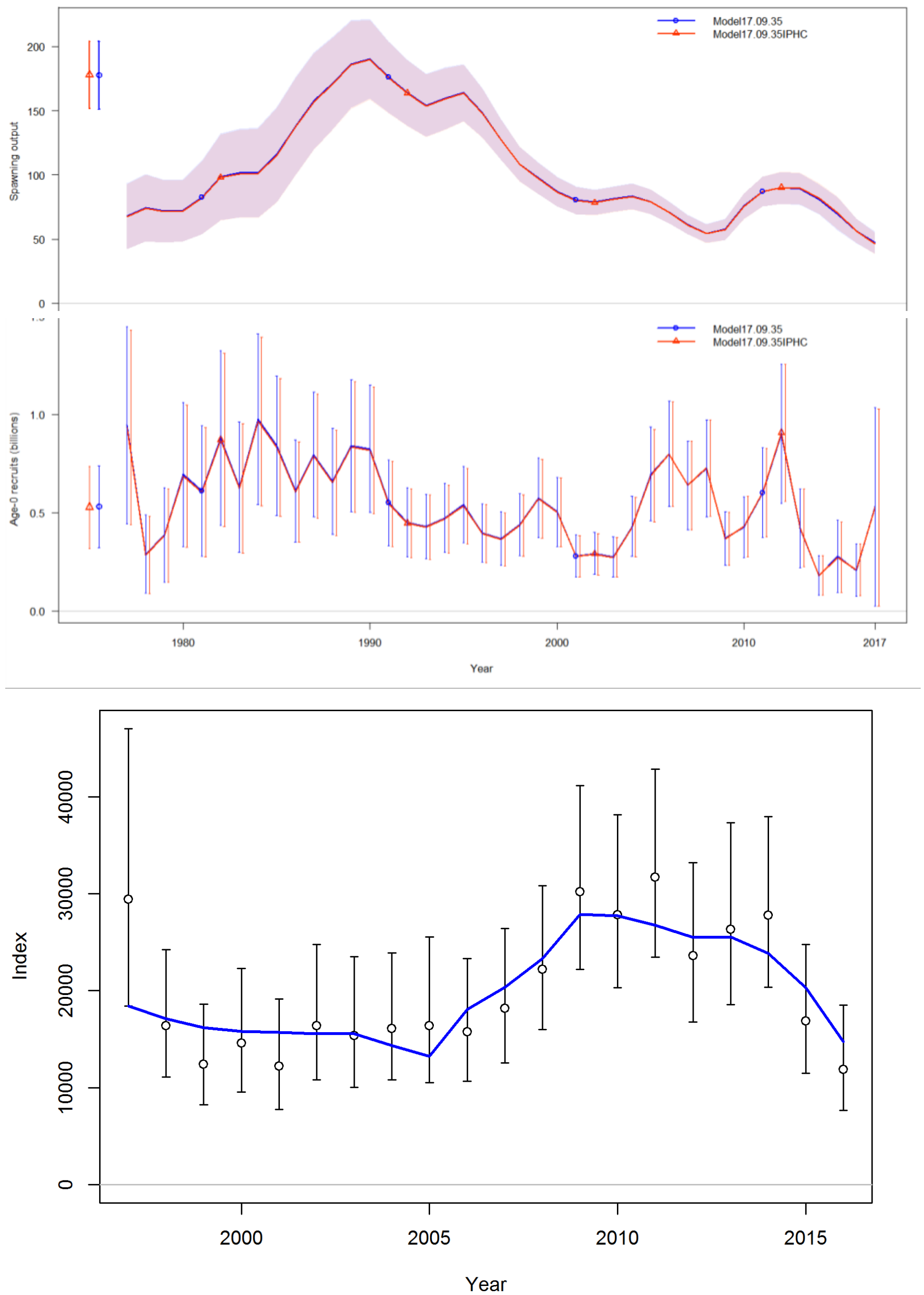


Figure 2.73 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; middle) for Model 17.09.35 with and without the IPHC longline index fit (bottom) in the model.

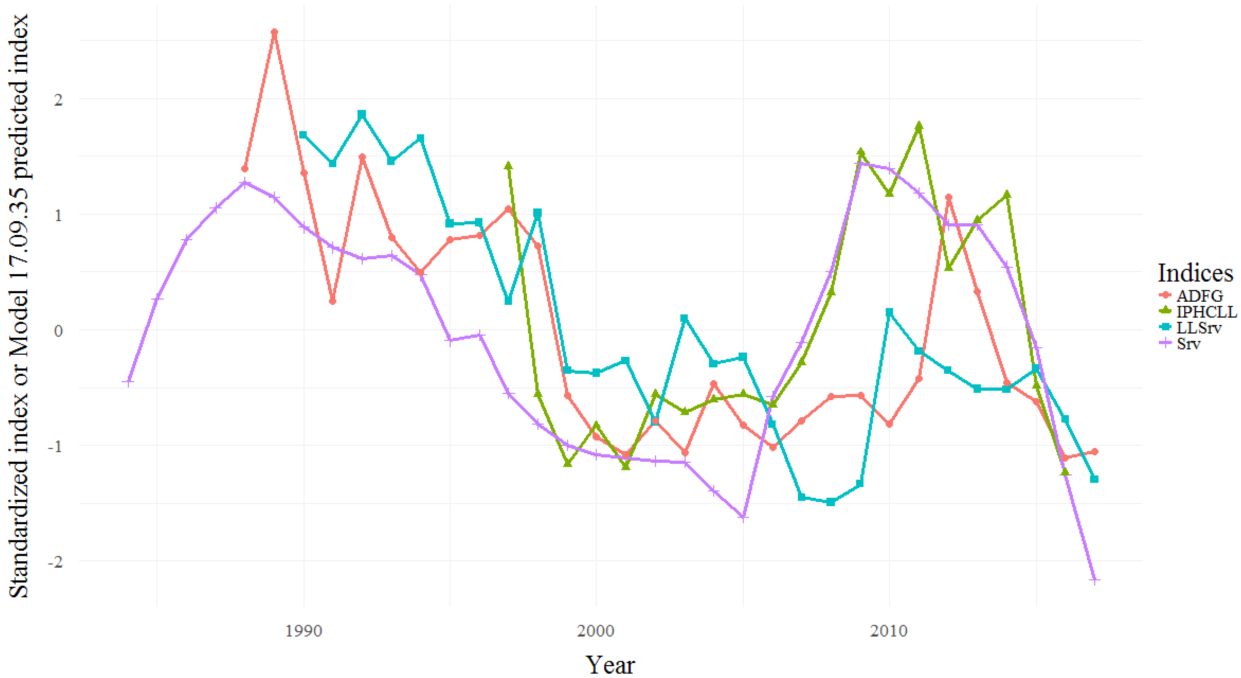


Figure 2.74 Standardized indices for the ADFG trawl survey (ADFG) and IPHC longline survey (IPHCLL) and Model 17.09.35 predicted index values for the AFSC longline (LLSrv) and bottom trawl (Srv) surveys.

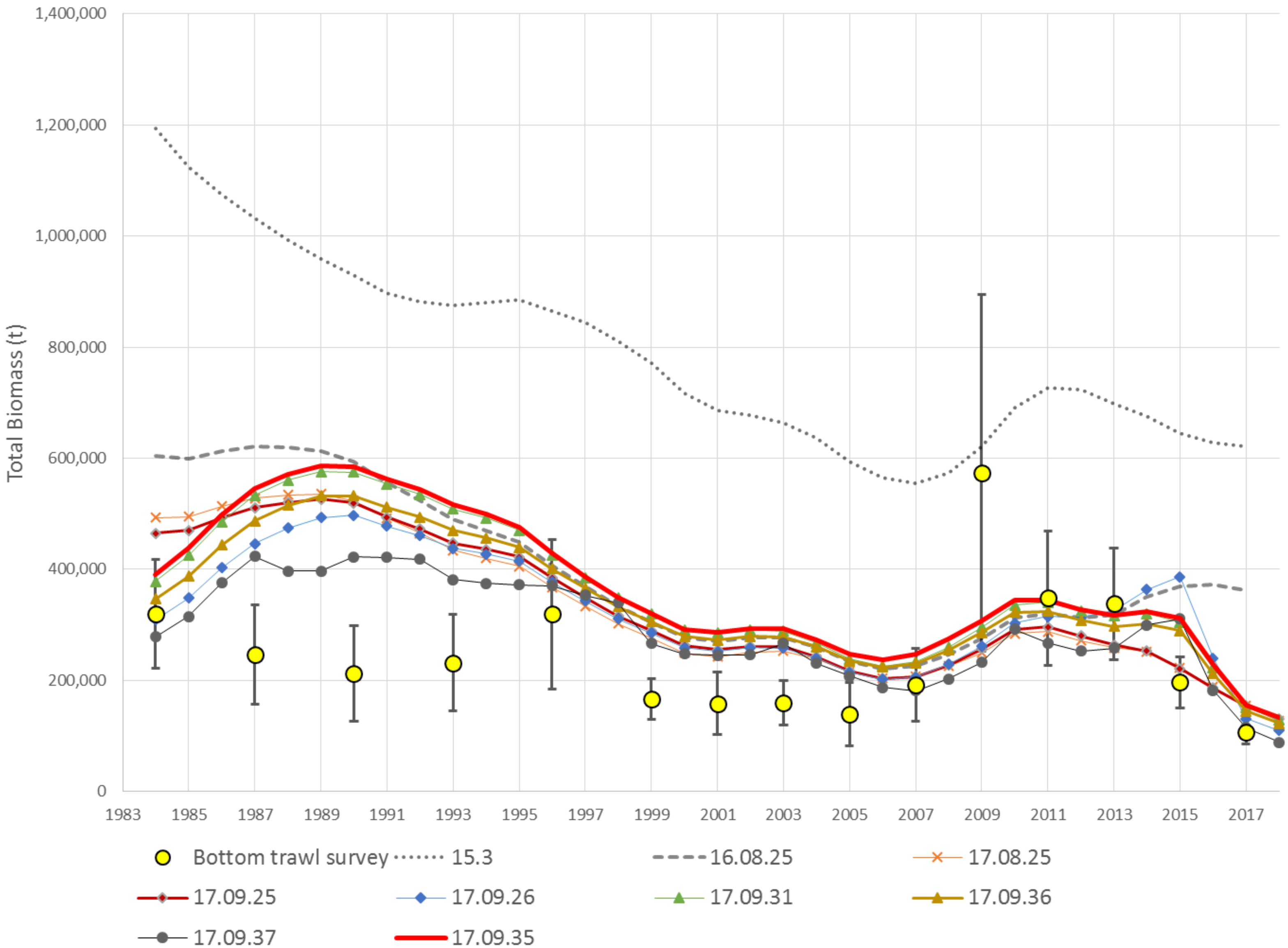


Figure 2.75 Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

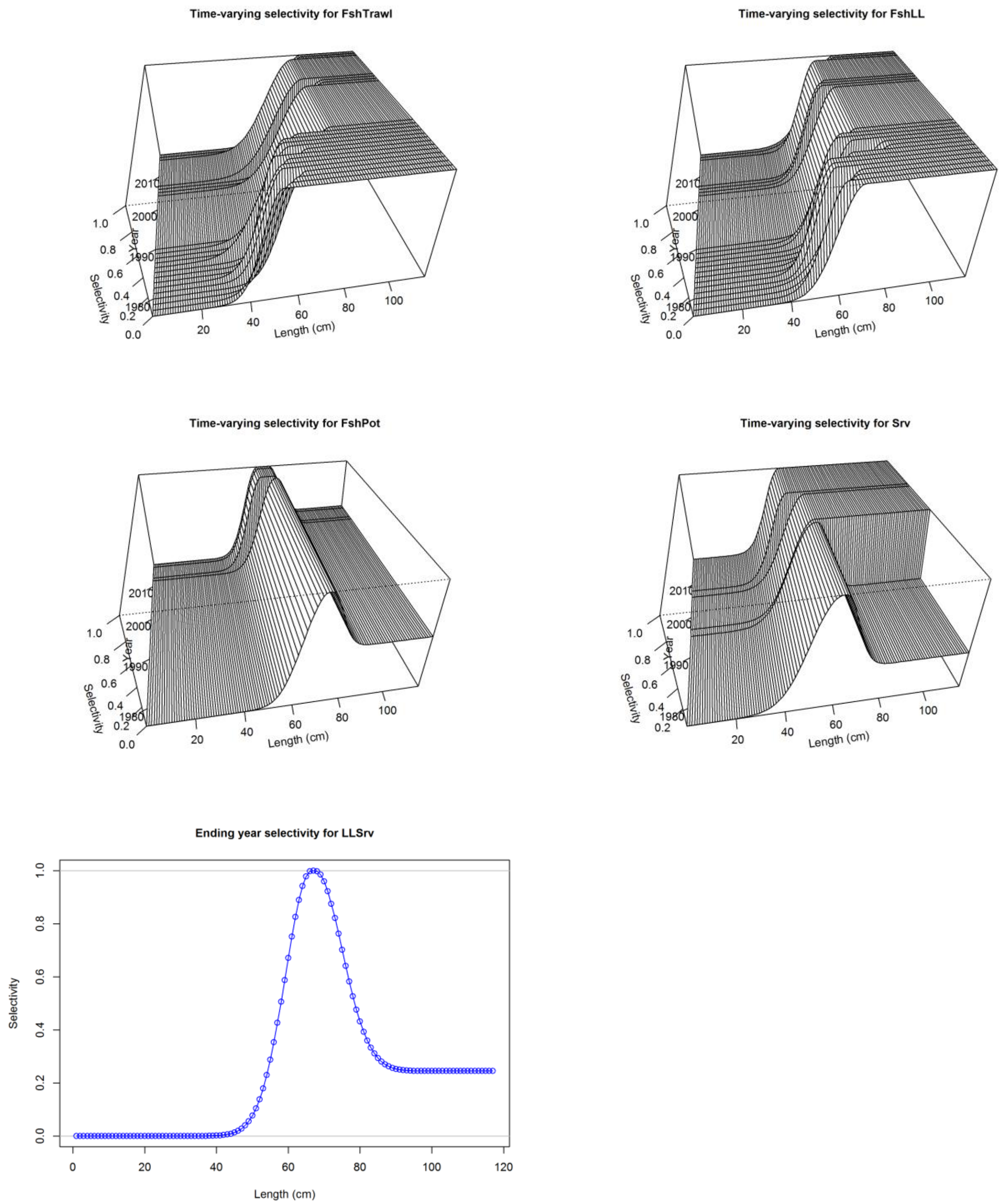


Figure 2.76 Selectivity curves for Model 17.09.35 Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and Auke Bay longline survey (LLSrv) length composition data.

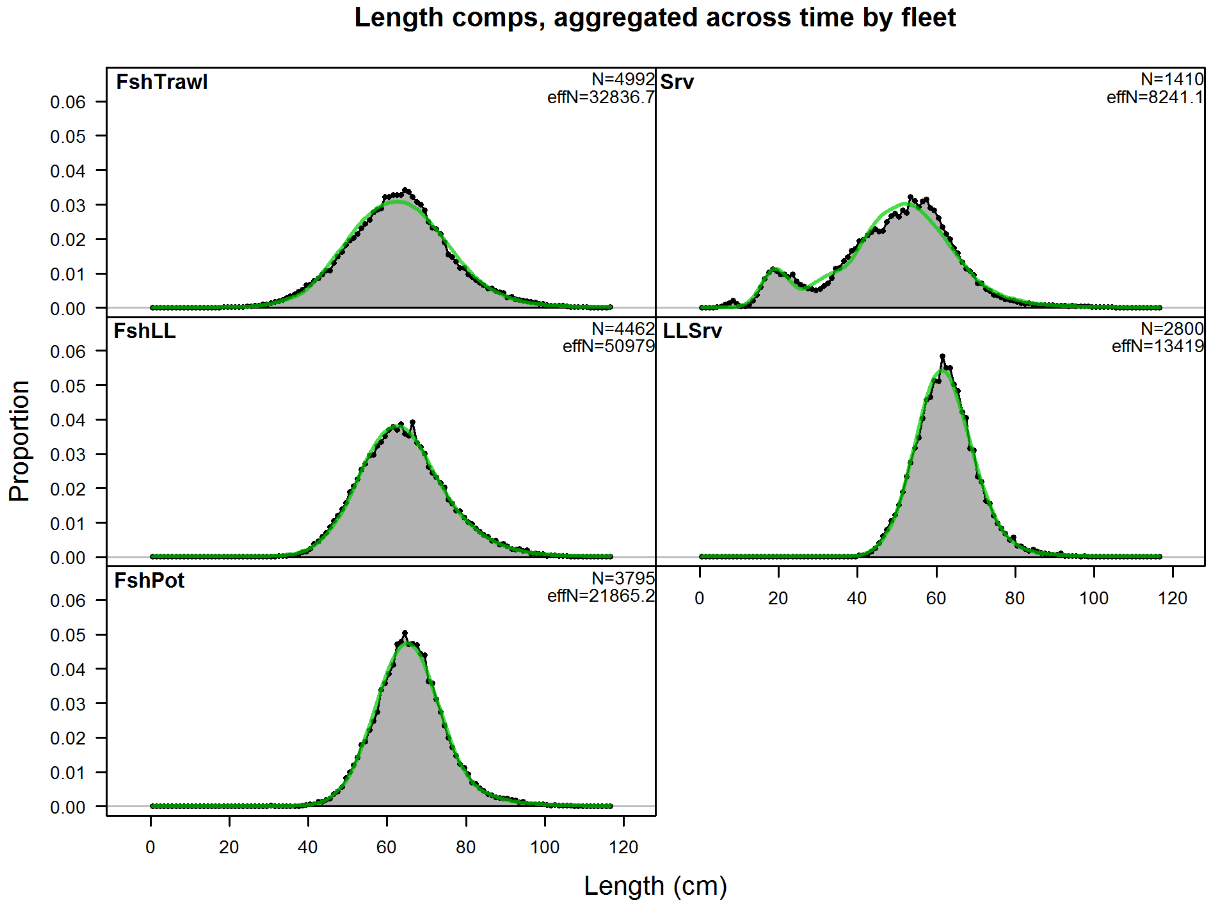


Figure 2.77 Overall Model 17.09.35 fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and Auke Bay longline survey (LLSrv) length composition data.

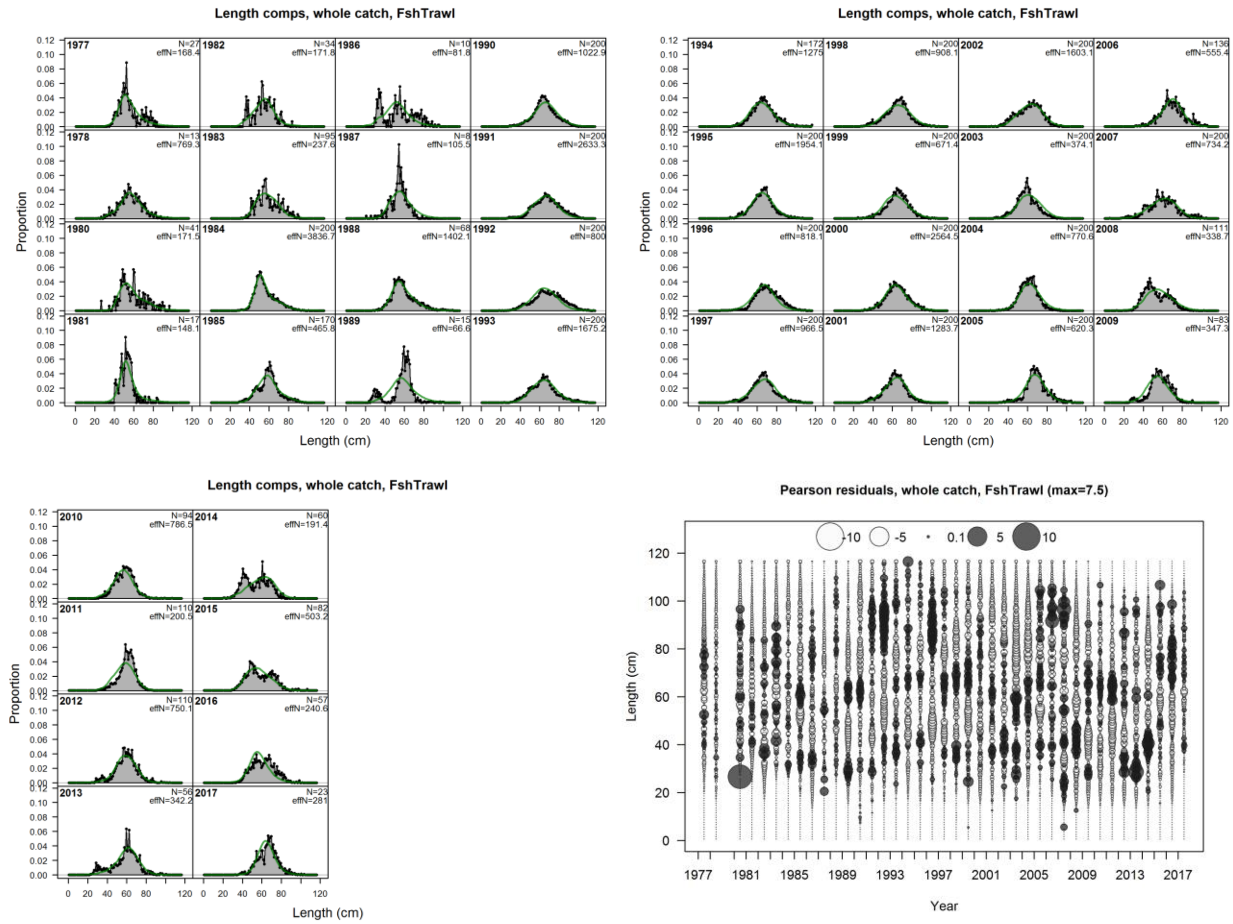


Figure 2.78 Trawl fishery length composition and Model 17.09.35 fit (top and left) and Pearson residuals (right bottom).

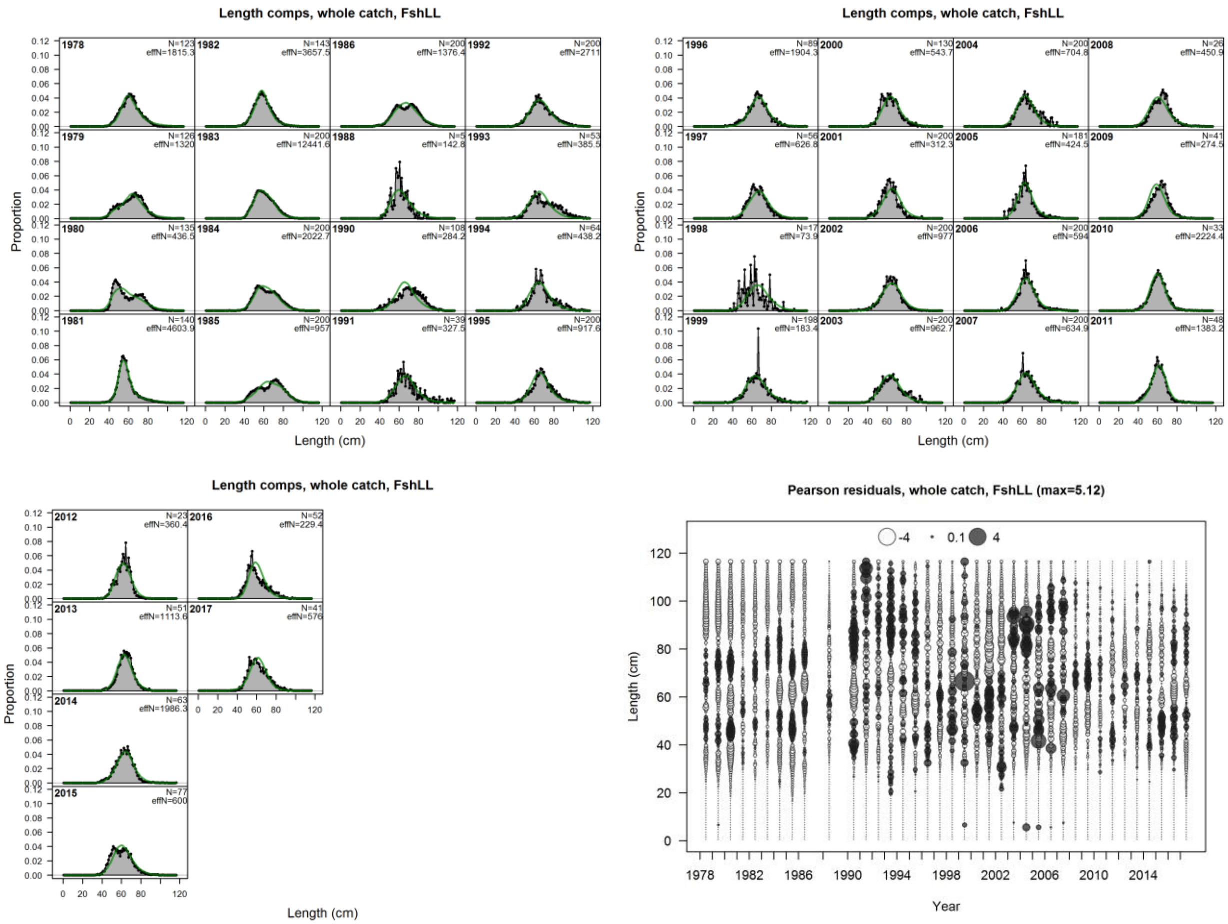


Figure 2.79 Longline fishery length composition and Model 17.09.35 fit (top and left) and Pearson residuals (max = 5.12; right bottom).

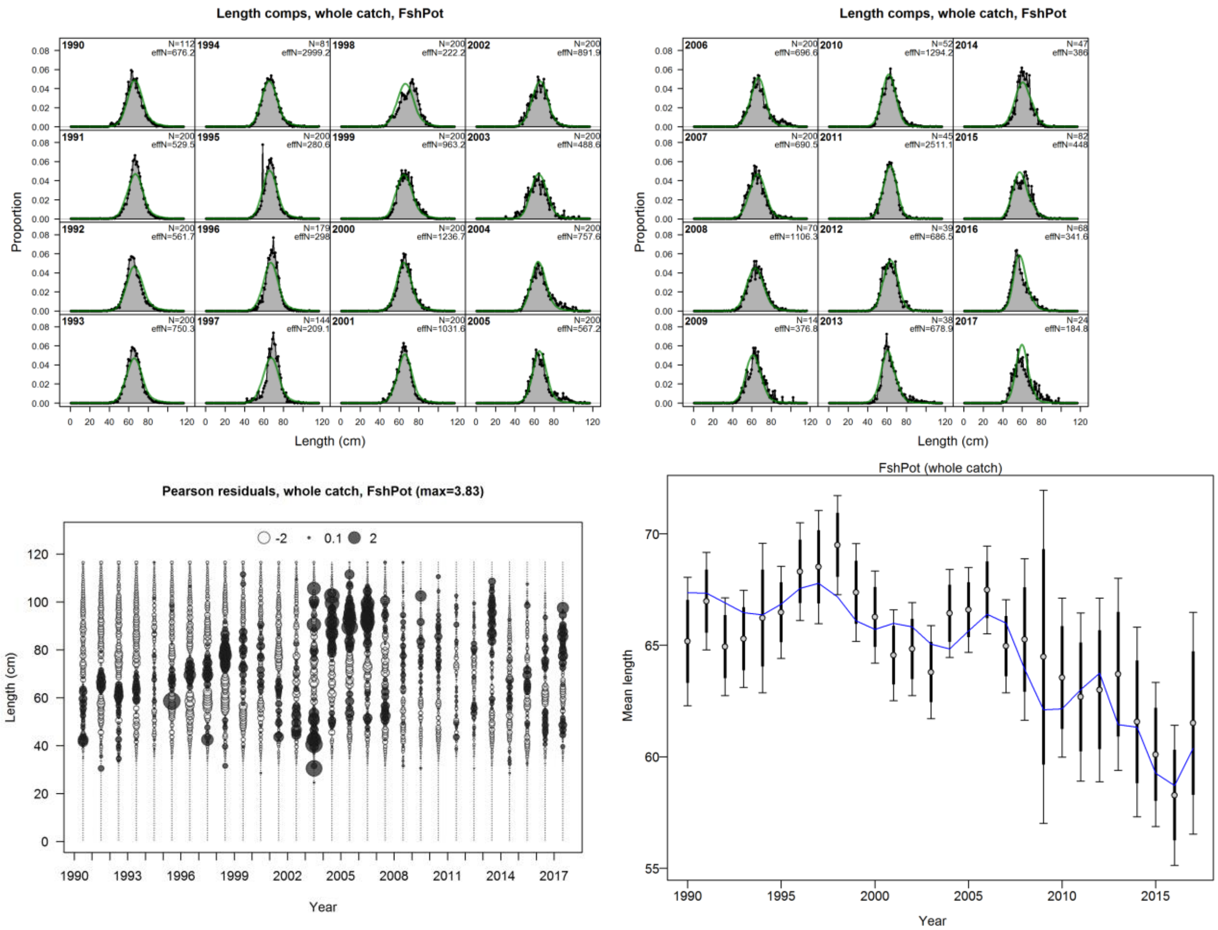


Figure 2.80 Pot fishery length composition and Model 17.09.35 fit (top), and Pearson residuals (max=3.83; bottom).

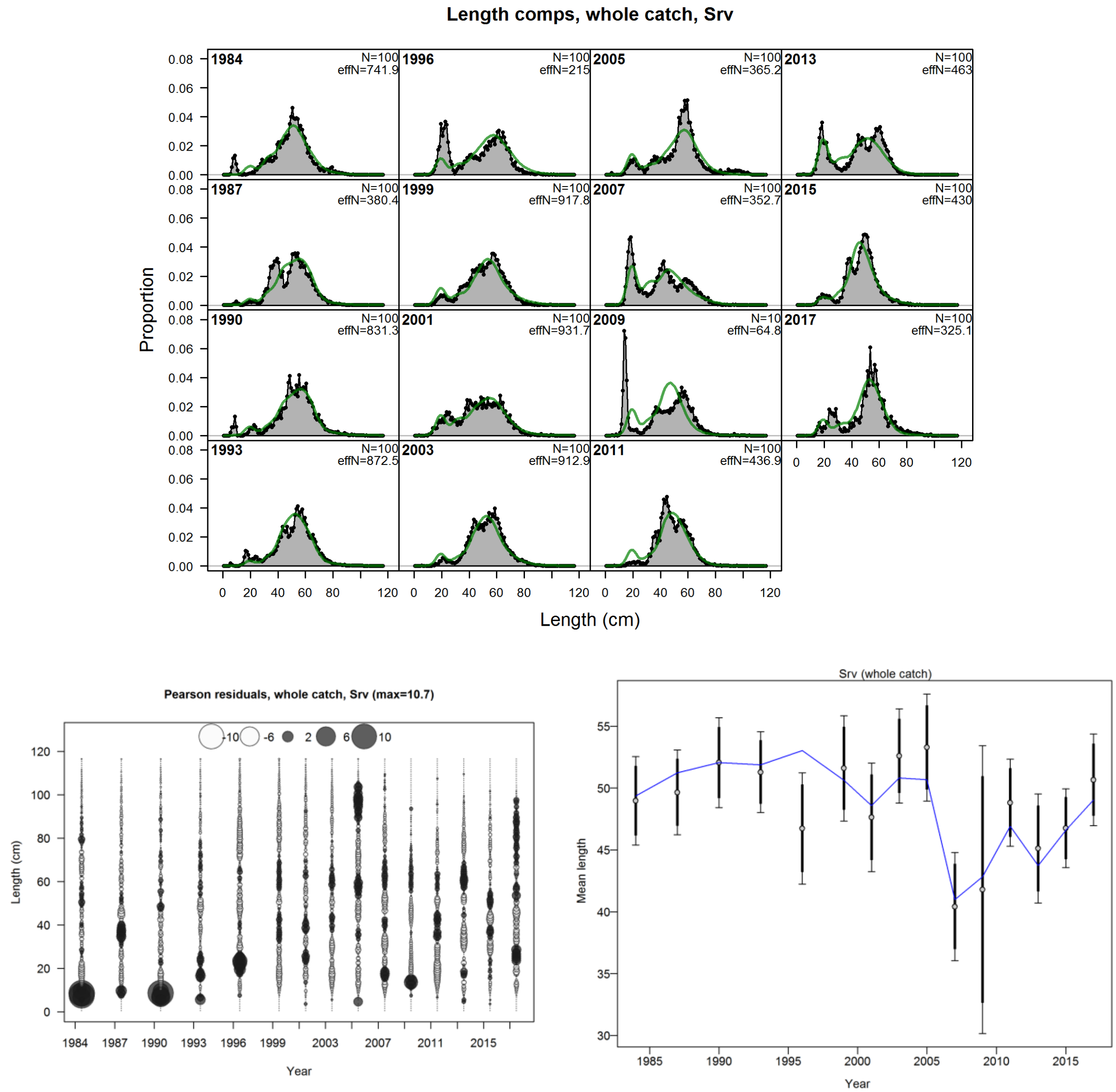


Figure 2.81 NMFS bottom trawl survey length composition and Model 17.09.35 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

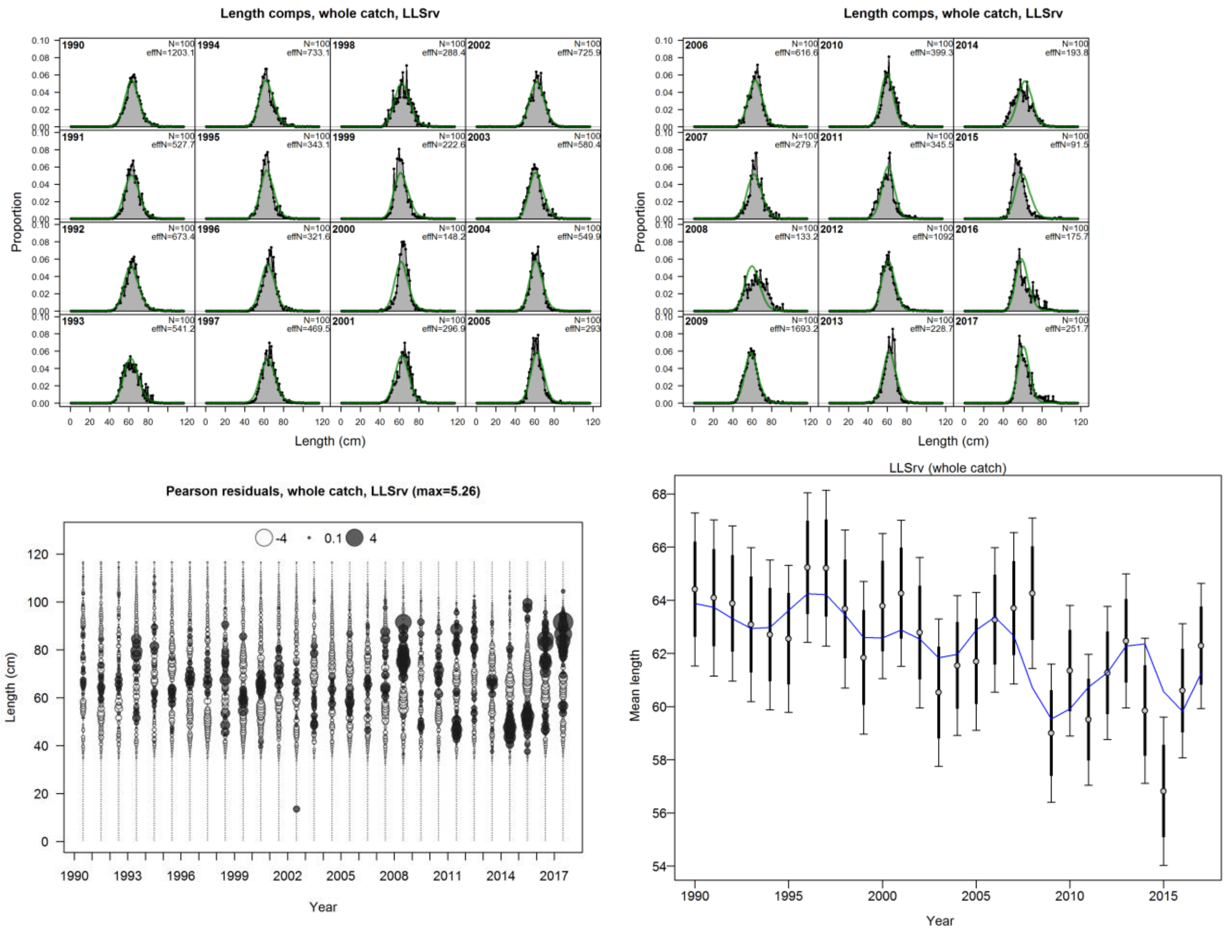


Figure 2.82 Auke Bay longline survey length composition and Model 17.09.35 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

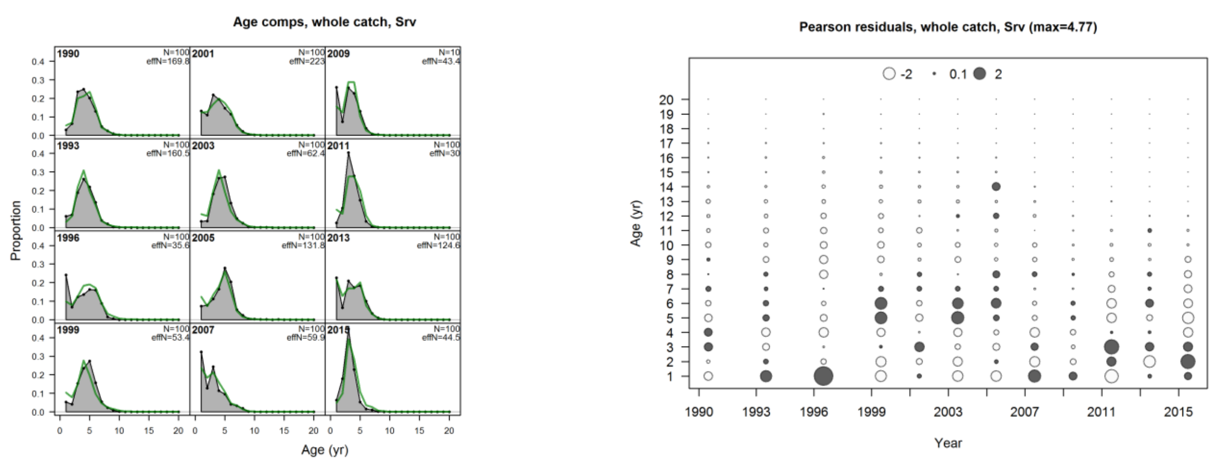


Figure 2.83 NMFS bottom trawl survey (Srv) age composition and Model 17.09.35 fit (left) and Pearson's residuals (right).

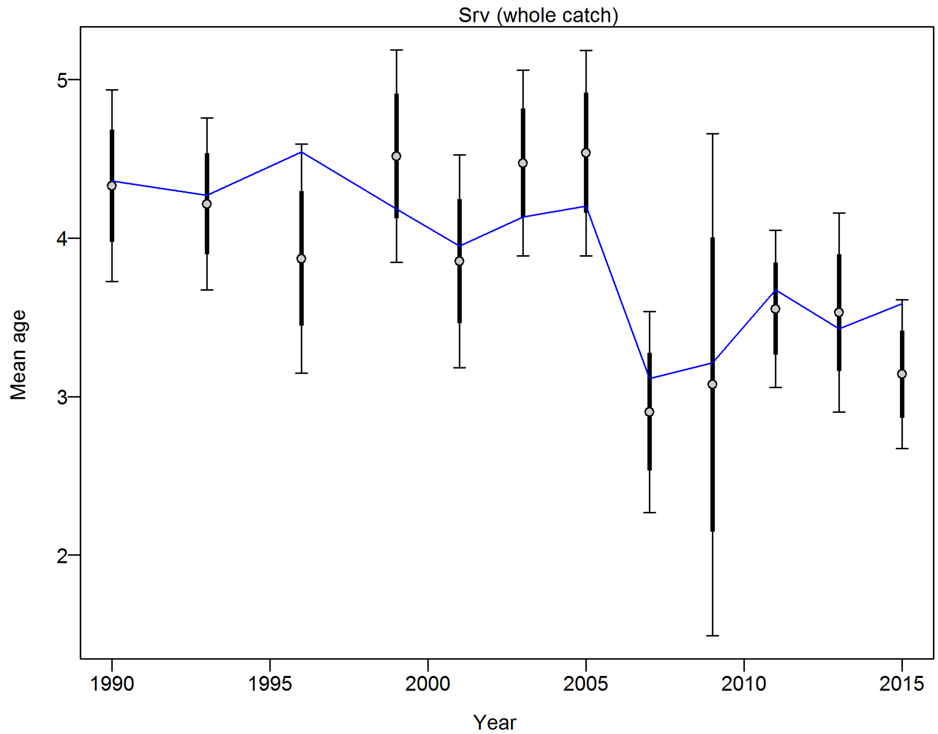


Figure 2.84 NMFS bottom trawl survey (Srv) mean age and Model 17.09.35 fit.

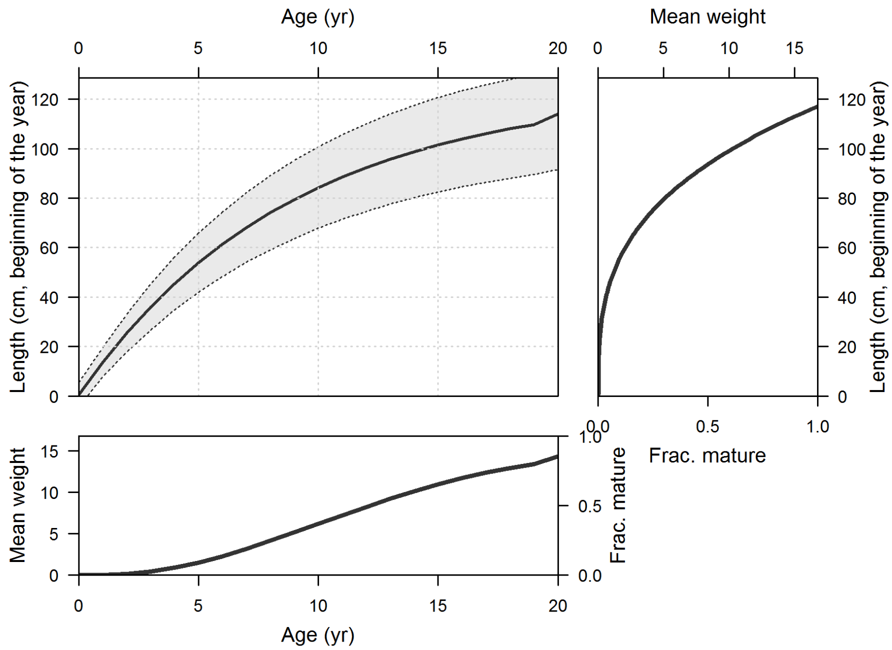


Figure 2.85 Model 17.09.35 length at age, weight at age, weight at length, and fraction mature at length, weight, and age.

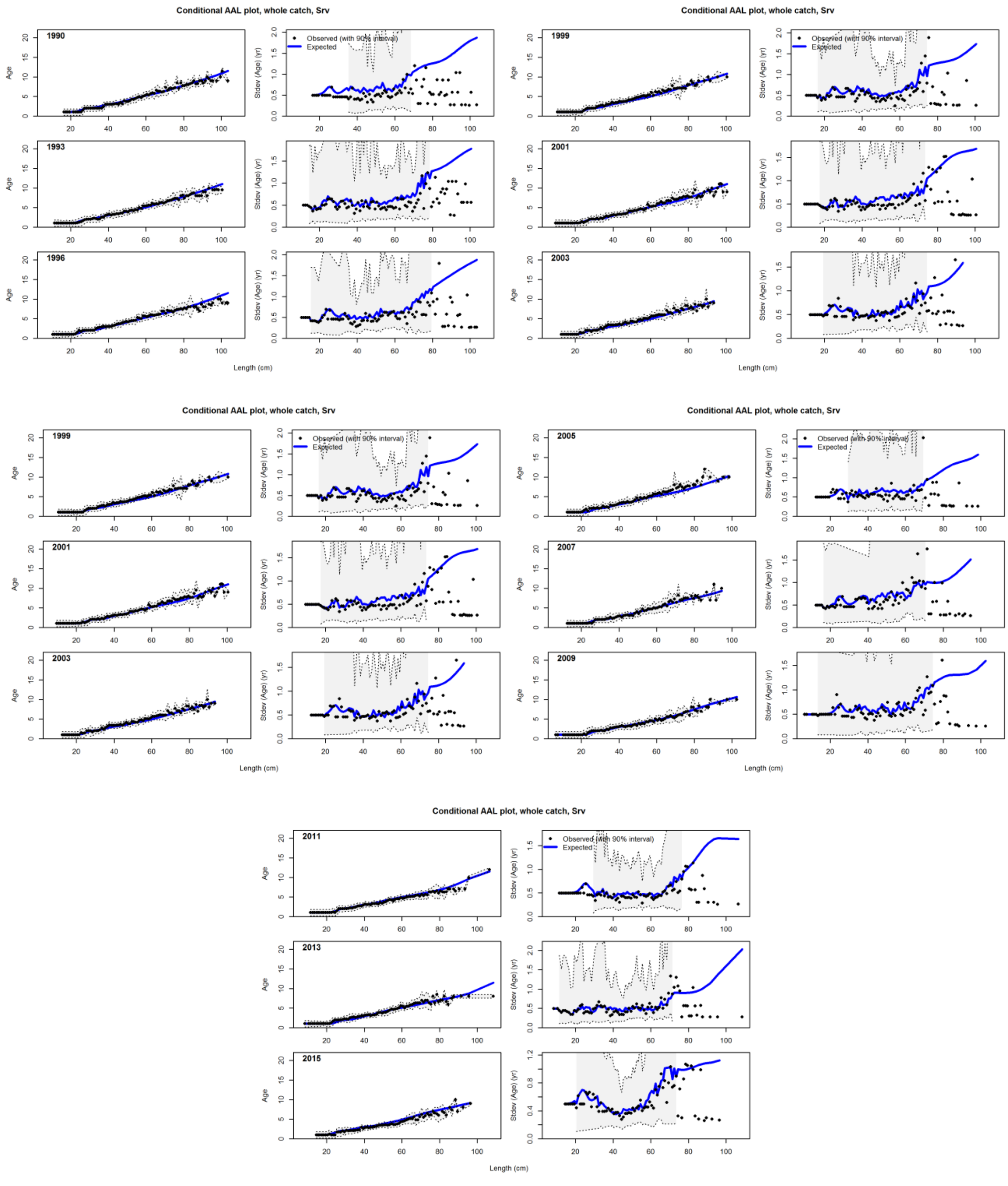


Figure 2.86 NMFS bottom trawl survey (Srv) conditional length-at-age data and Model 17.09.35 fit.

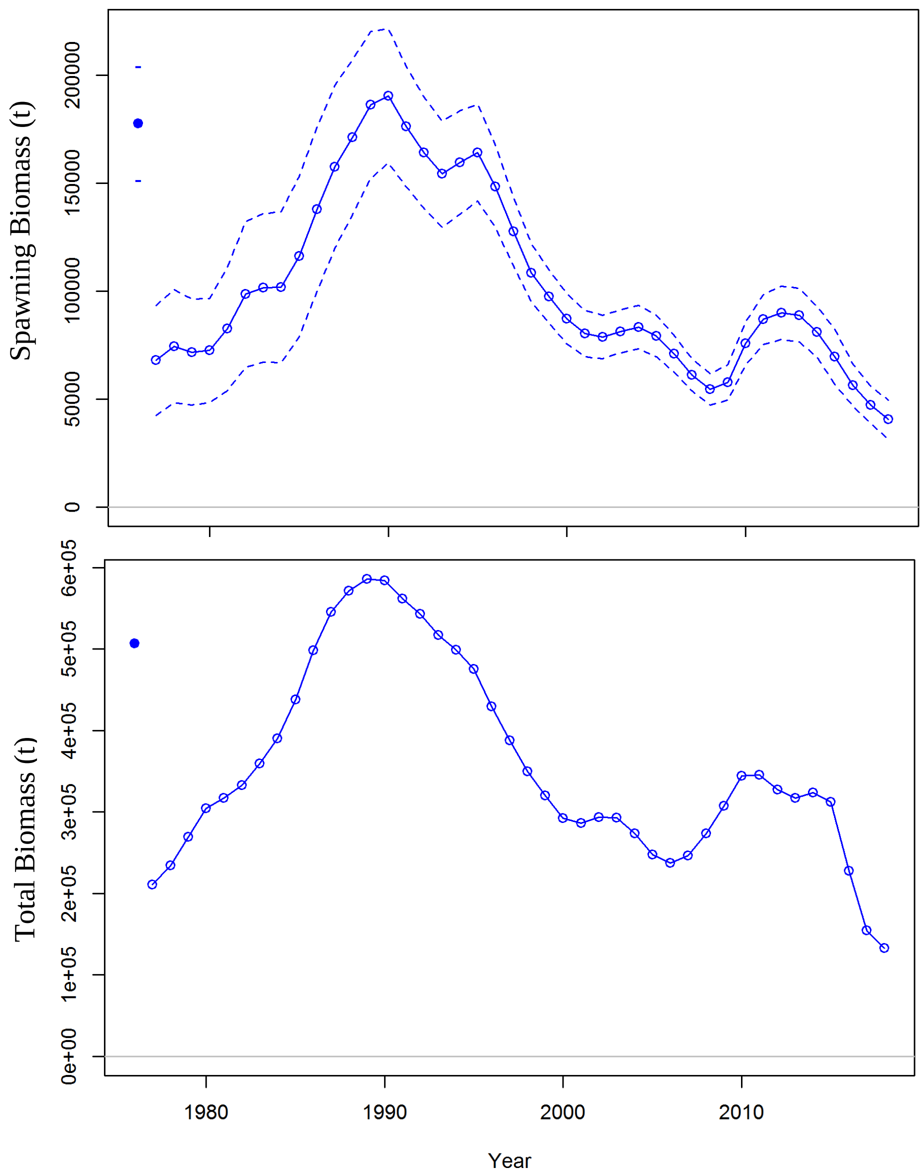


Figure 2.87 Model 17.09.35 predicted spawning output (femal spawning biomass; t) with 95% asymtotic error intervals (top) and total biomass (t).

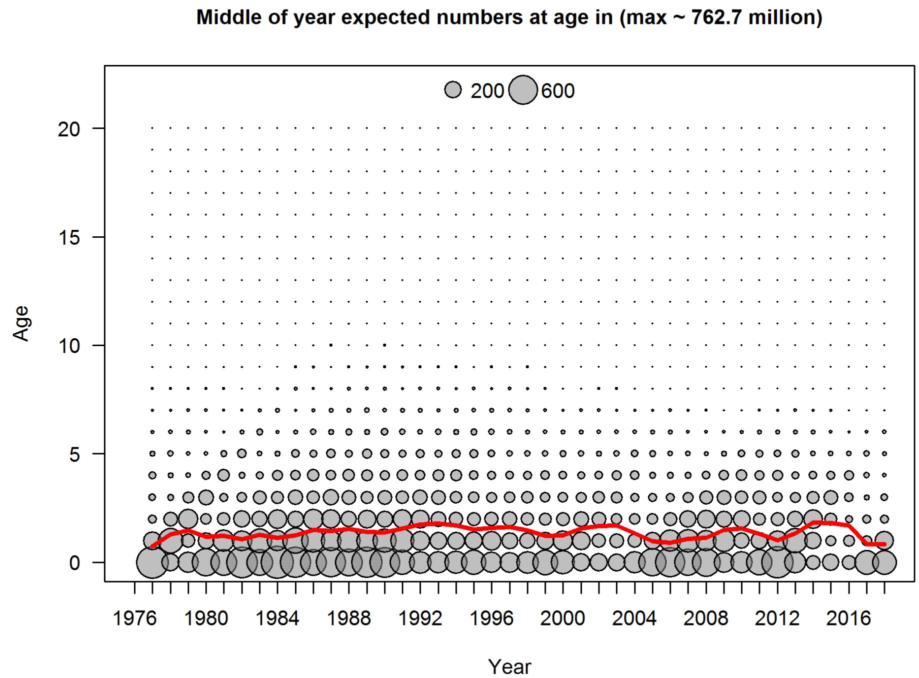


Figure 2.88 Model 17.09.35 predictions of middle of the year number at age (top) with mean age (red line)/.

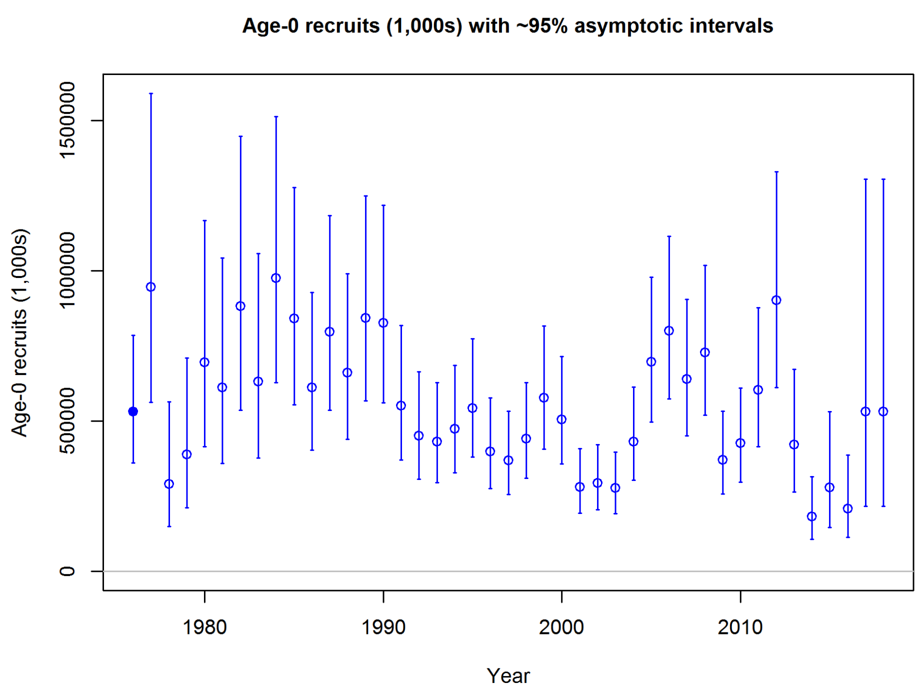


Figure 2.89 Model 17.09.35 age-0 recruitment (1000's) with 95% asymtotic error intervals.

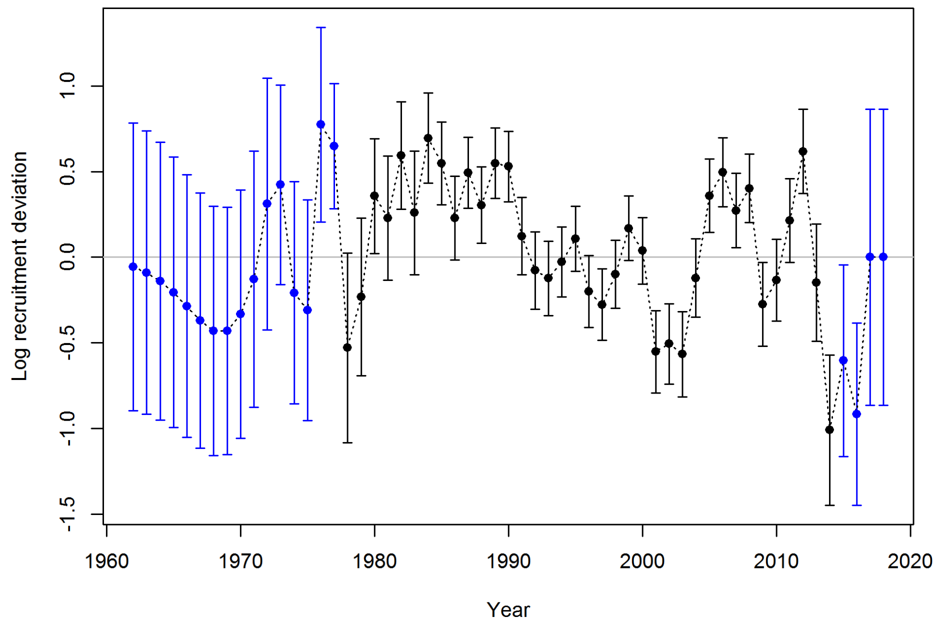


Figure 2.90 Model 17.09.35 log recruitment deviations with 95% asymtotic error intervals.

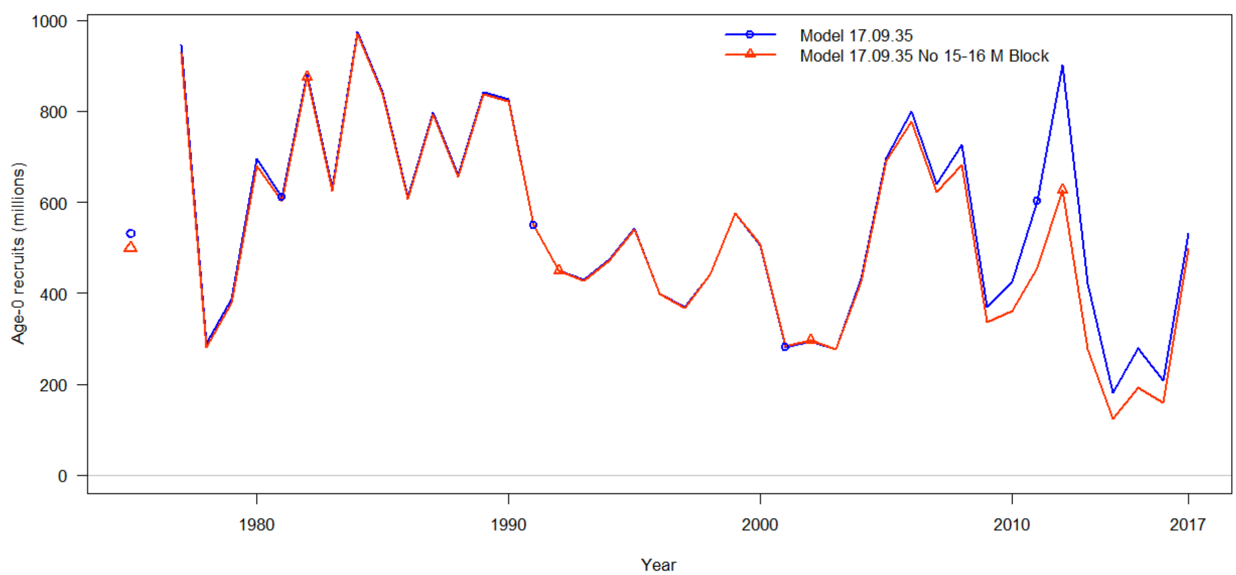


Figure 2.91 Model 17.09.35 Age-0 recruits with and without the 2015-2016 fitting block on natural mortality showing differences in estimated recruitment for 2005-2016 .

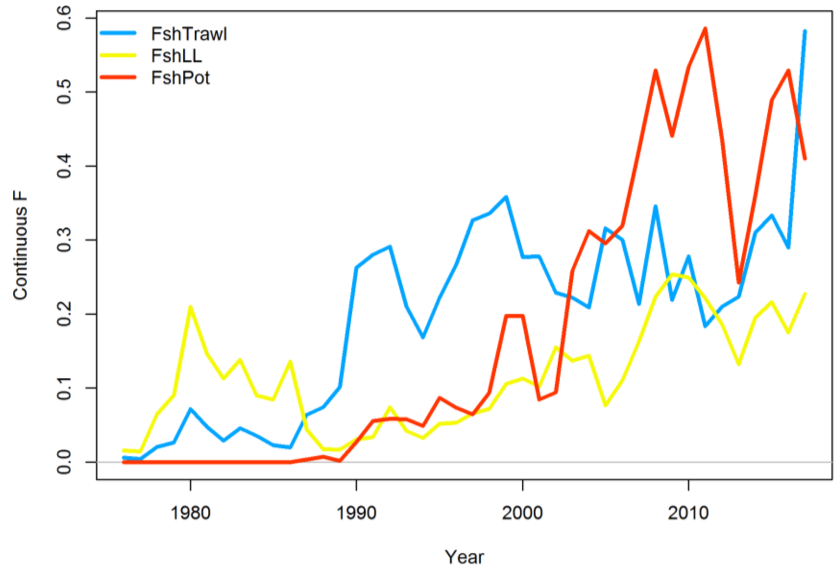


Figure 2.92 Model 17.09.35 continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries

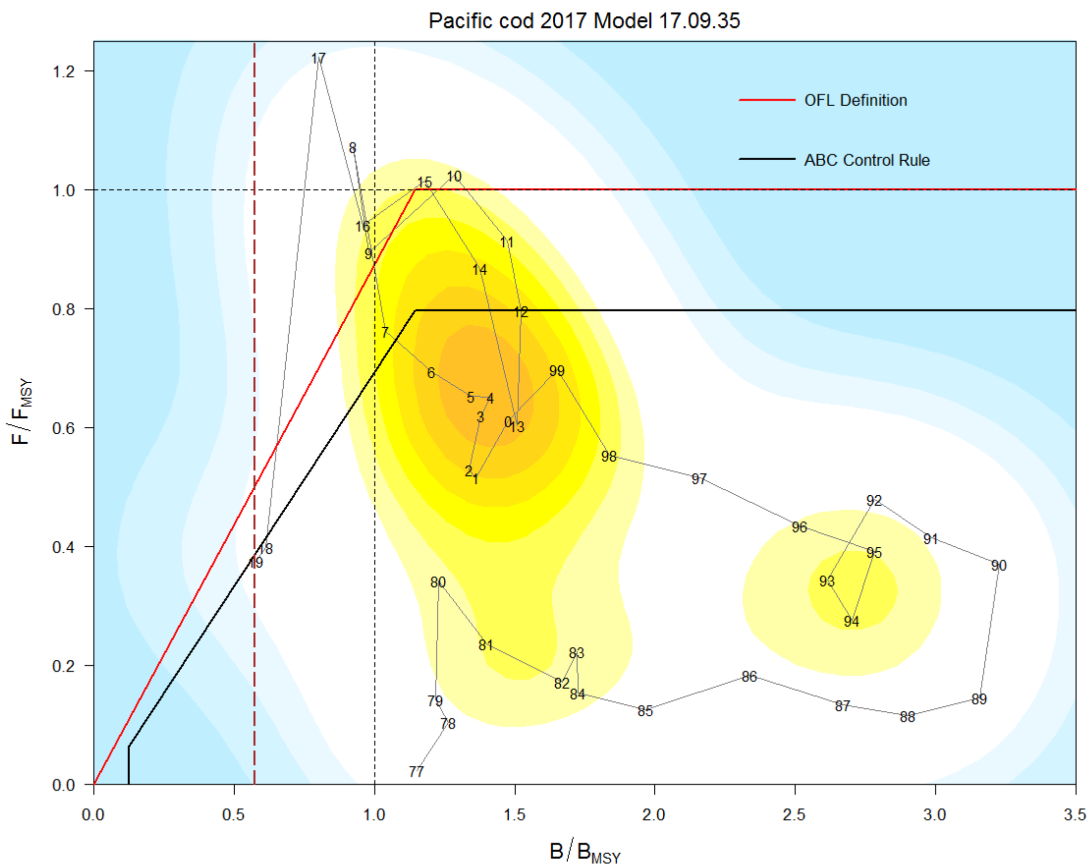


Figure 2.93 For Model 17.09.35 ratio of historical F/*Fmsy* versus female spawning biomass relative to *Bmsy* for GOA pacific cod, 1977-2019. Note that the proxies for *Fmsy* and *Bmsy* are *F35%* and *B35%*, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

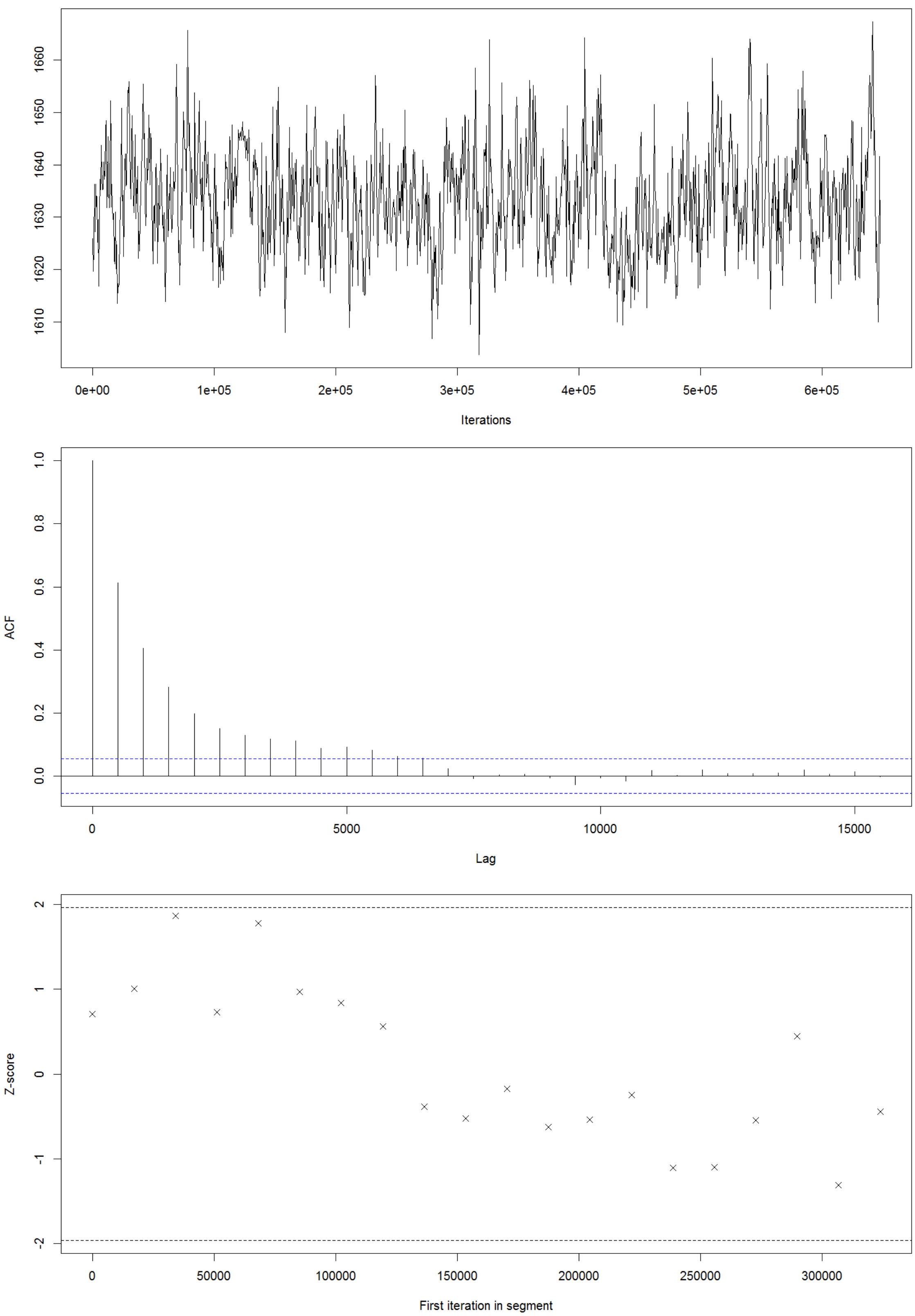


Figure 2.94 Model 17.09.35 MCMC trace (top), autocorrelation function plot (middle), Geweke diagnostic plot (bottom) for the objective function.

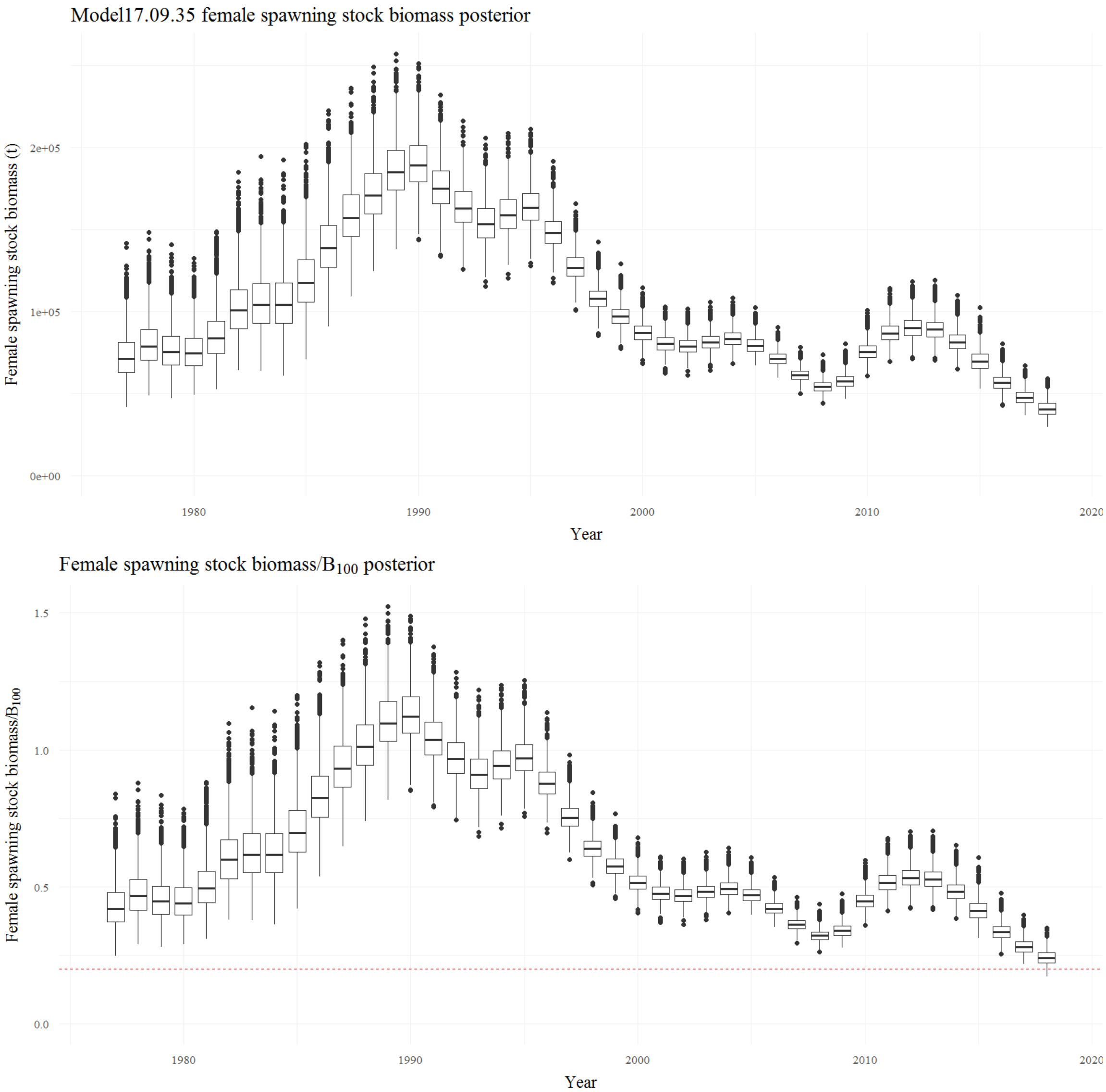


Figure 2.95 Model 17.09.35 MCMCposterior distribitions of female spawning biomass (top) and Female spawning biomass/$B_{100\%}$ (bottom) with $B_{20\%}$ (red dotted line) 1977-2018.

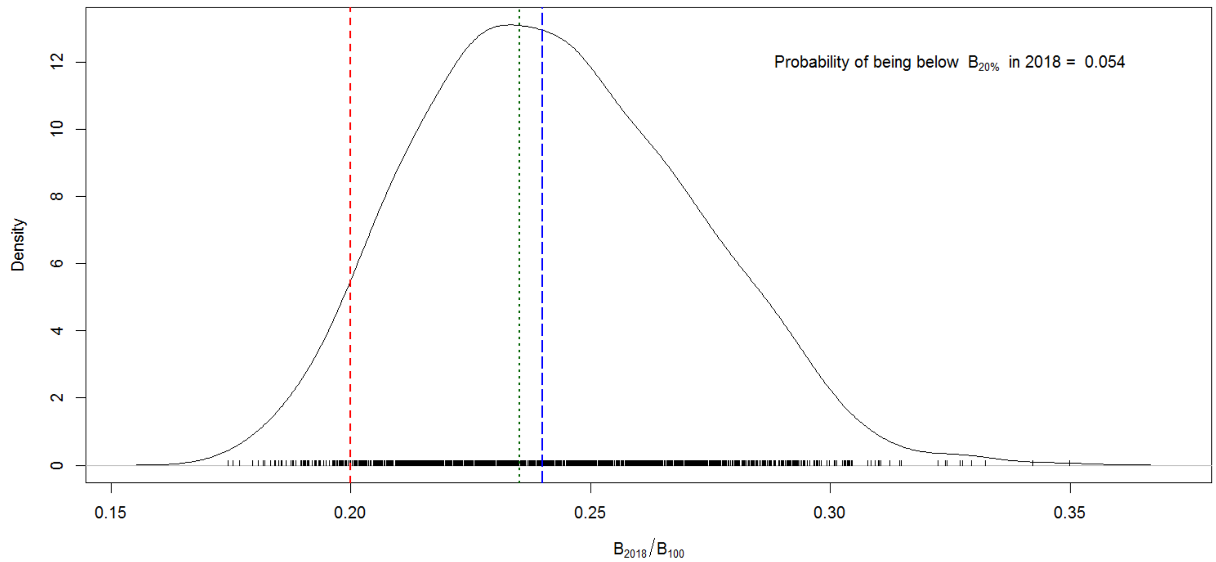


Figure 2.96 Model 17.09.35 MCMCposterior distribitions of spawning stock biomass/$B_{100\%}$ (bottom) with $B_{20\%}$ (red dashed line) from the projection model, MLE estimate (green dotted line) and posterior 50% (blue dashed line) for beginning year 2018.

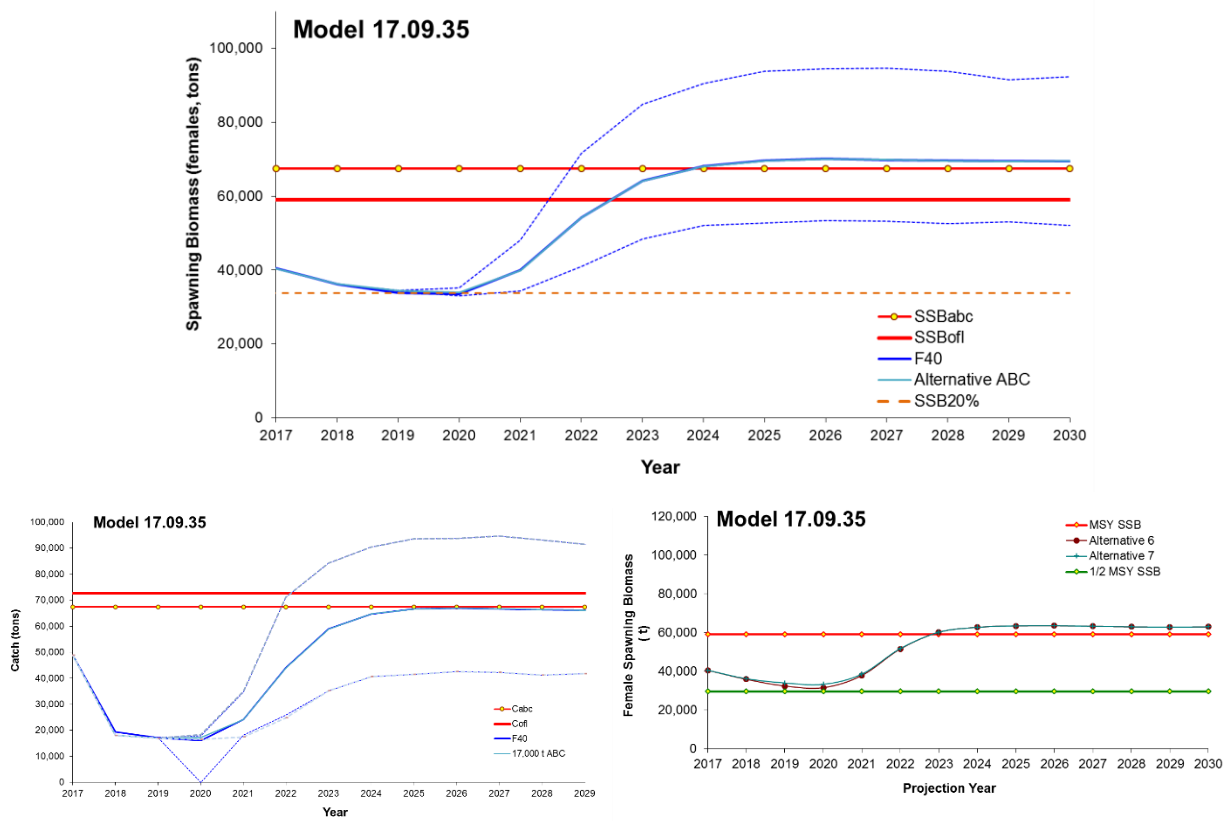


Figure 2.97 Model 17.09.35 projections of female spawning biomass (top), catch (bottom left), and female spawning biomass from scenarios 6 and 7 for status determination (bottom right).

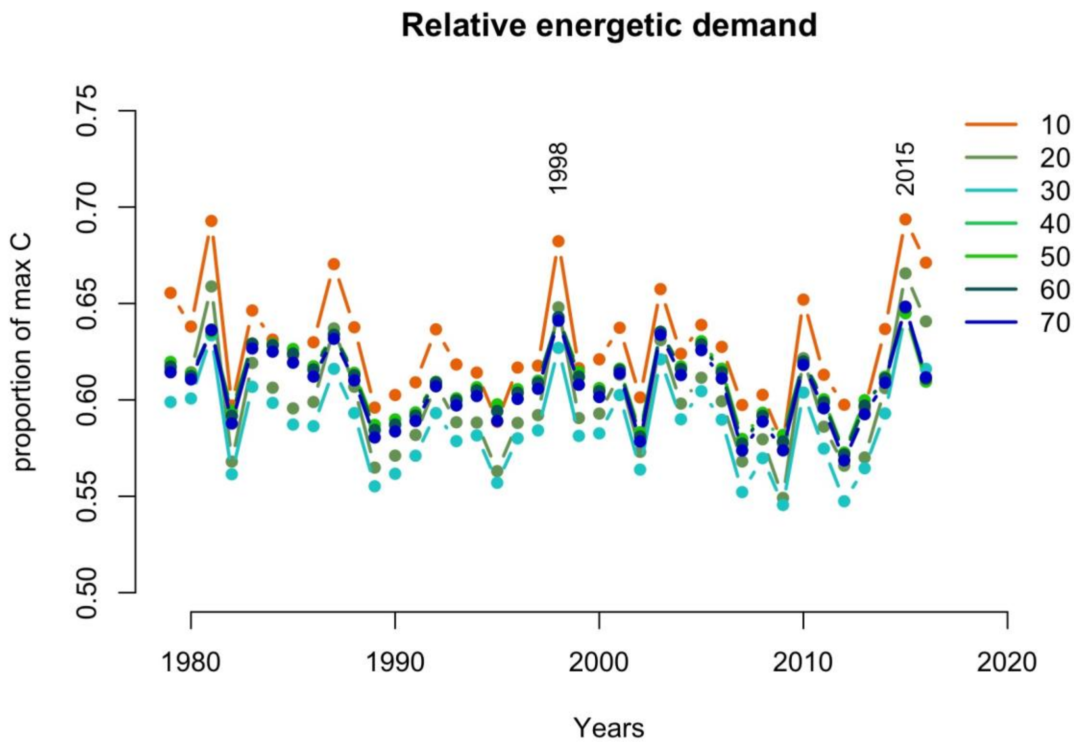


Figure 2.98 Relative energetic demand for Pacific cod of 10-70 cm FL based on the adult bioenergetic model for Pacific cod (Holsman and Aydin, 2015) and CFSR age-specific depth-preference corrected water temperatures (Barbeaux, unpublished data).

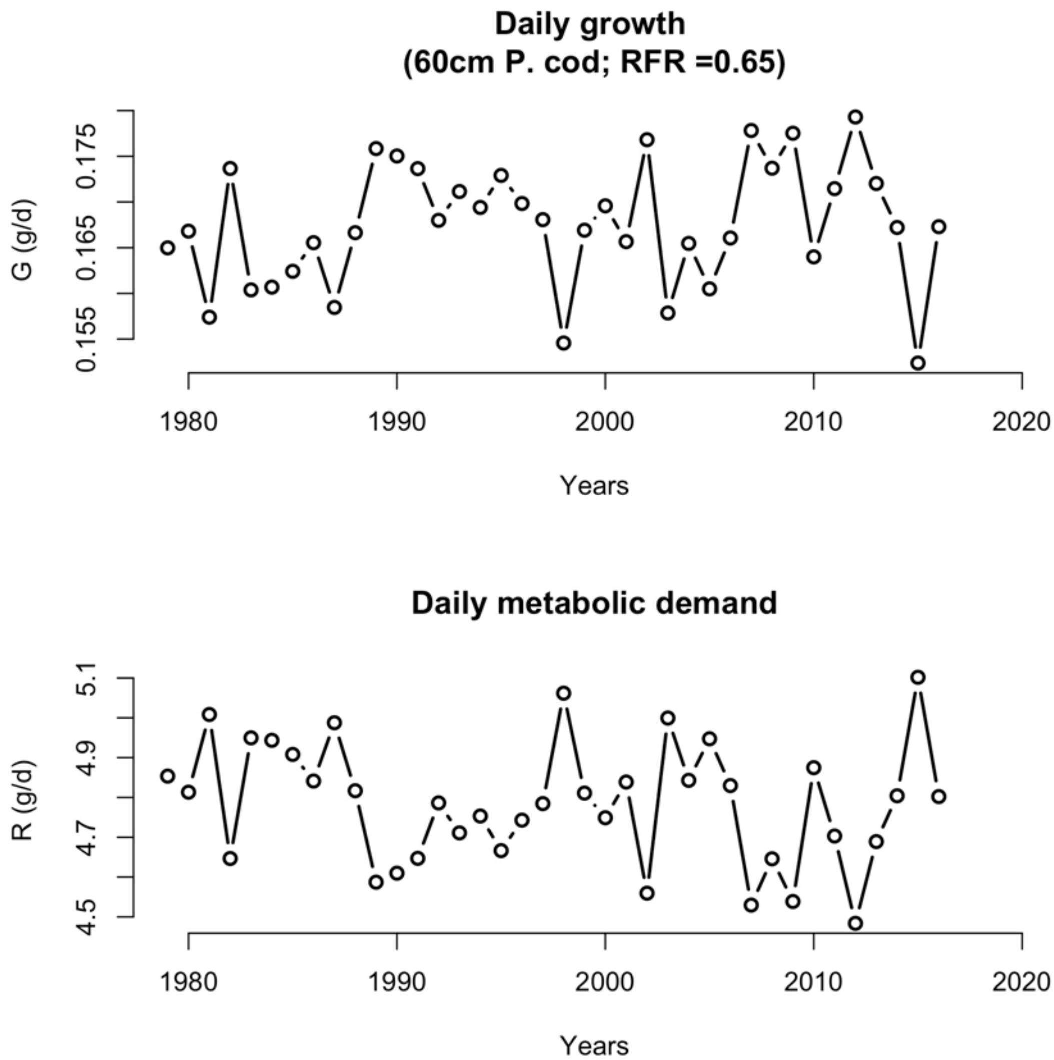


Figure 2.99 Daily model estimates of growth (top panel) and metabolic demand (bottom panel) based on the adult Pacific cod bioenergetics model (Holsman and Aydin, 2015), a fixed relative foraging rate (RFR) =0.65 (across years), annual indices of GOA prey eenergy density, and an intermediate P. cod energy density of 3.625 kJ/g reported in Vollenweider et al. 2011.

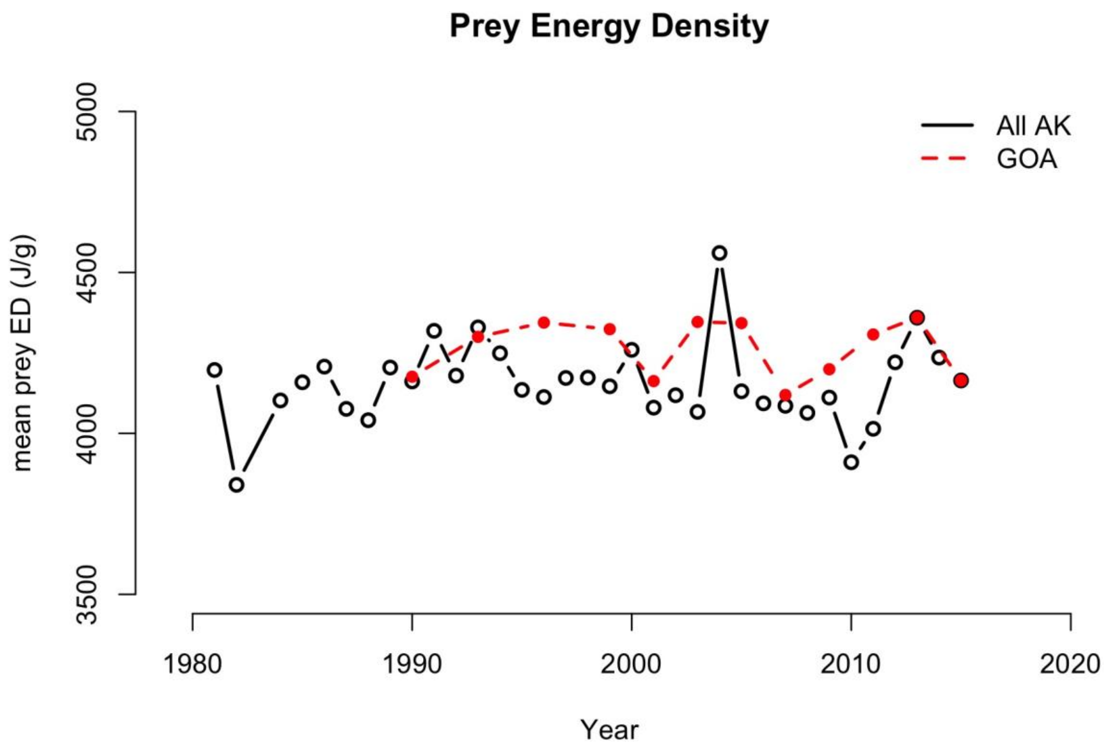
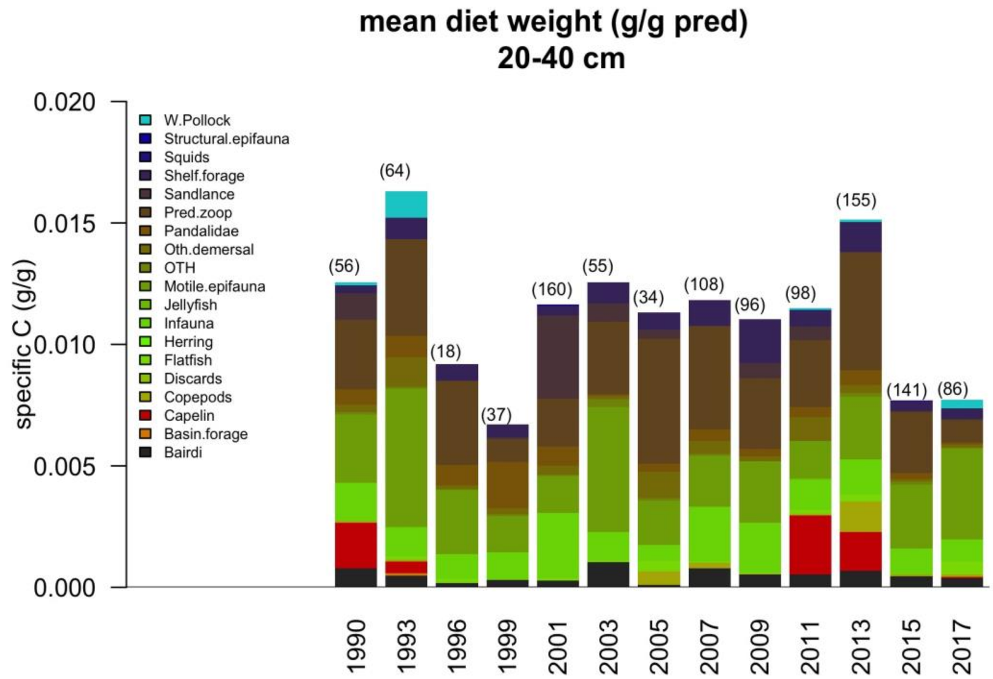


Figure 2.100 Average prey energy density based on mean energy density of prey items and diet composition from GOA Pacific cod stomach samples. Diet data from NOAA REEM Food Habits database.



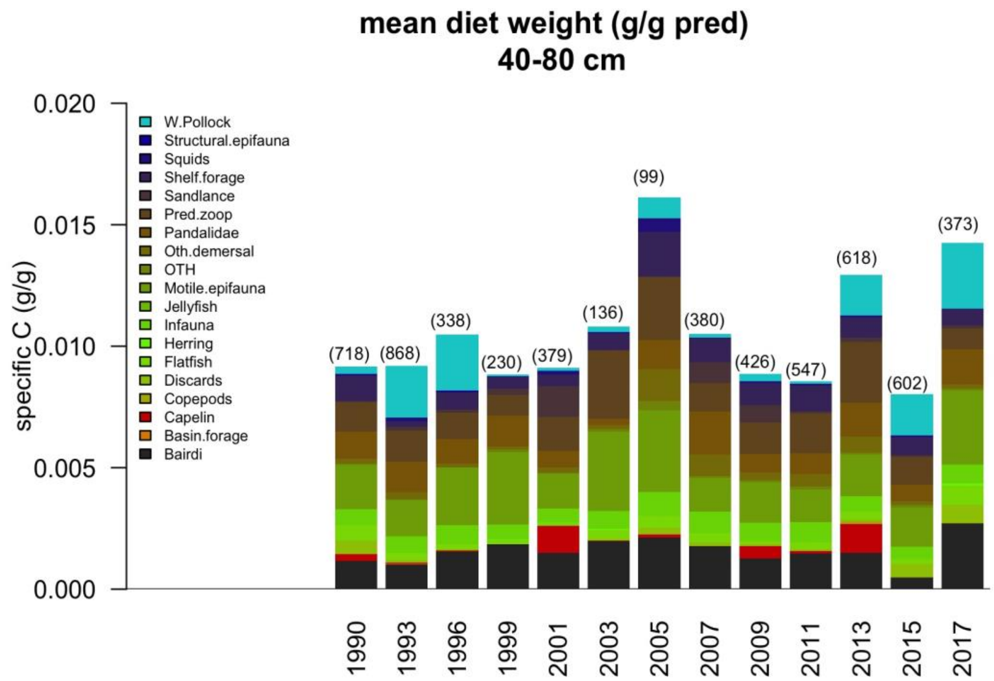


Figure 2.101 Specific weight (g prey/ g pred) of prey in the diets of GOA Pacific cod, averaged across all survey diet samples and fish sizes. Diet data from NOAA REEM Food Habits database.

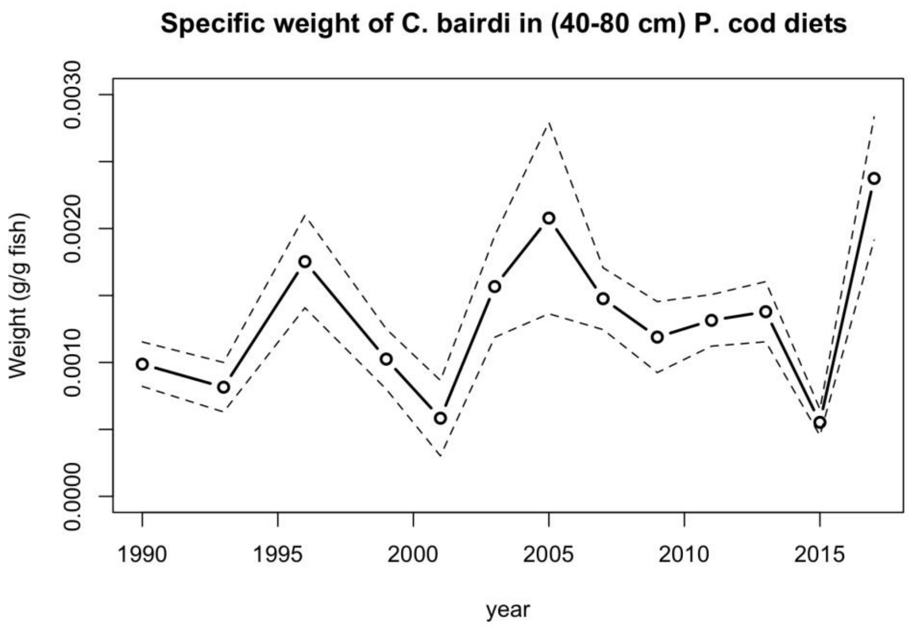


Figure 2.102 Specific weight (g prey/ g pred) of Chionoecetes bairdi in the diets of Pacific cod in the Gulf of Alaska, AK. Diet data from NOAA REEM Food Habits database.

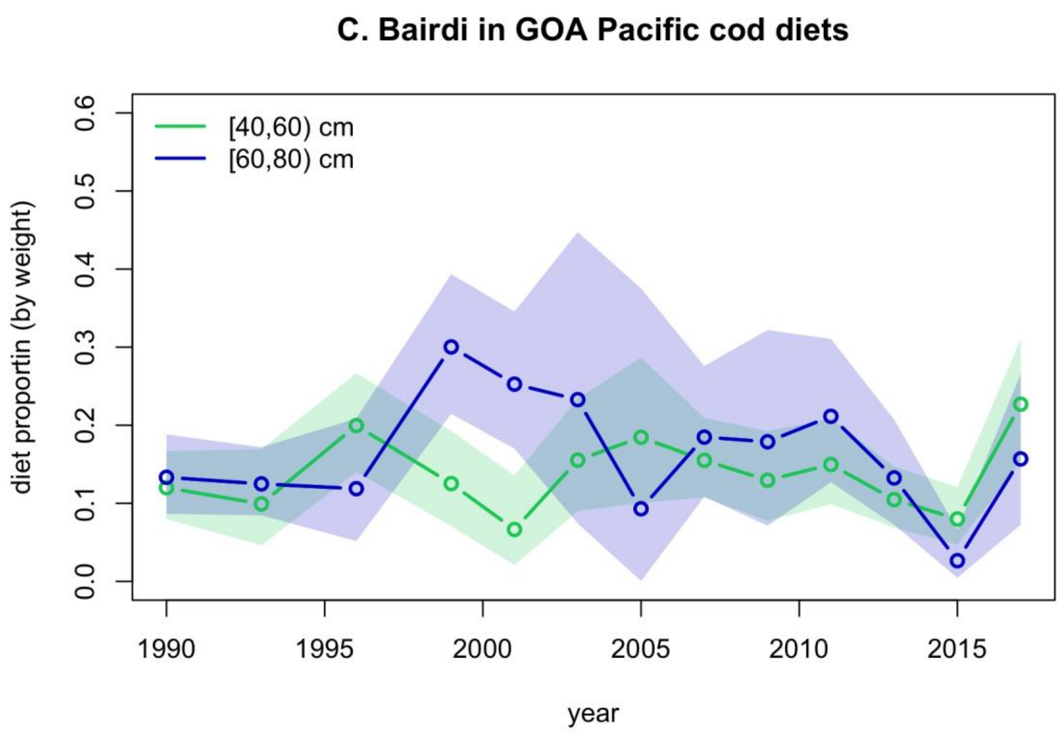


Figure 2.103 Proportion by weight of of Chionoecetes bairdi in the diets of different size classess of Pacific cod in the Gulf of Alaska, AK. Diet data from NOAA REEM Food Habits.