IPHC-2020-MSAB015-08

Development of a framework to investigate fishing intensity and distributing the total constant exploitation yield (TCEY) for Pacific halibut fisheries

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PURPOSE

To provide an update of International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) activities relating to the definition and development of a framework to evaluate management procedures for distributing the TCEY.

1 INTRODUCTION

The Management Strategy Evaluation (MSE) at the International Pacific Halibut Commission (IPHC) has completed an initial phase of evaluating management procedures (MPs) relative to the coastwide scale of the Pacific halibut stock and fishery, and has embarked on developing a framework to additionally investigate MPs related to distributing the Total Constant Exploitation Yield (TCEY) to IPHC Regulatory Areas. The TCEY is the mortality limit composed of mortality from all sources except under-26-inch (66.0 cm, U26) non-directed discard mortality, and is determined by the Commission at each Annual Meeting for each IPHC Regulatory Area.

The development of an MSE framework aims to support the scientific, forecast-driven study of the trade-offs between fisheries management scenarios. Crafting this tool requires

- the definition and specification of a multi-area operating model;
- an ability to condition model parameters using historical catch and survey data and other observations;
- integration with, use of, or comparison against stock assessment outputs or data;
- identification and development of management procedures with closed-loop feedback into the operating model;
- definition and calculation of performance metrics to evaluate the efficacy of applied management procedures.

Updates on the recent efforts in these areas are outlined in Section 2. Likewise, a significant effort developing the software underpinning these simulations is underway, which is outlined in section 3.

2 FRAMEWORK ELEMENTS

The MSE framework includes elements that simulate the Pacific halibut population and fishery (Operating Model, OM) and management procedures with a closed-loop feedback (Figure 1). Specifications of some elements are described below, with additional technical details in document IPHC-2019-MSAB015-INF01.

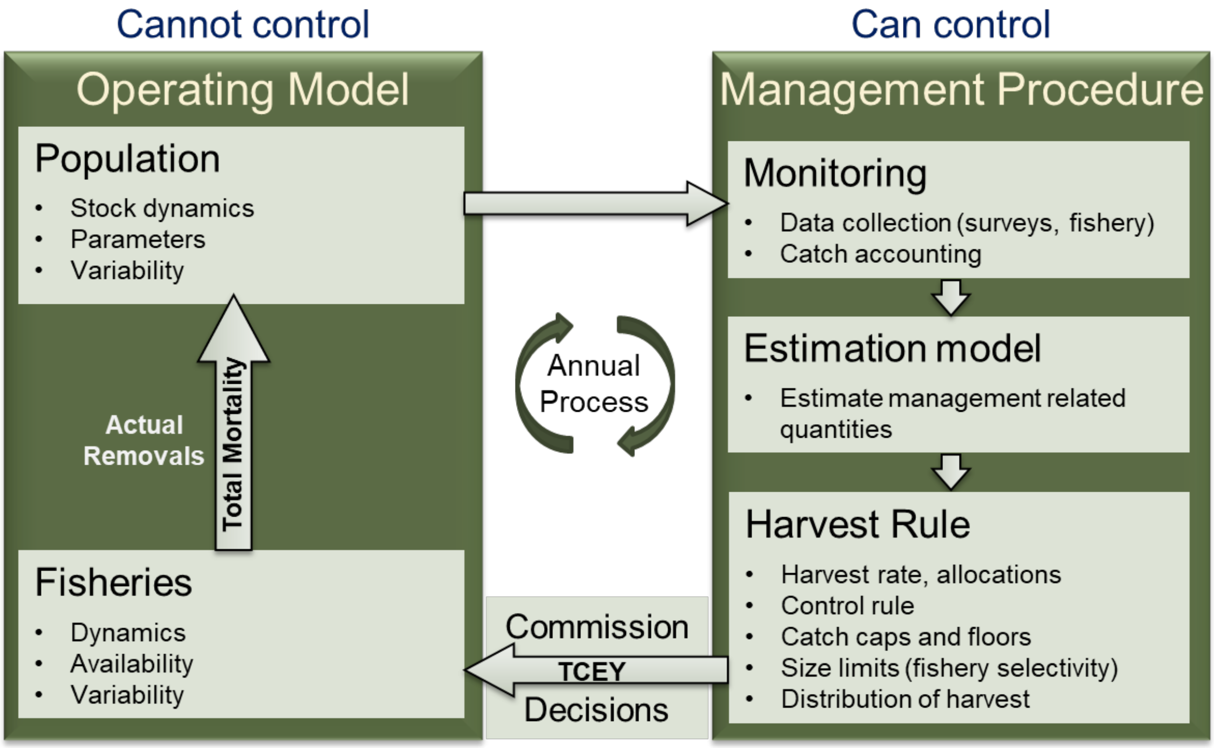

Figure 1: Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

2.1 Multi-area operating model

The generalized operating model is able to model multiple spatial components, which is necessary because mortality limits are set at the IPHC Regulatory Area level (Figure 2) and some objectives are defined at that level. Written in the programming language C++ with JavaScript Object Notation (JSON) input files, the OM is flexible, fast, modular, and easily adapted to many different assumptions. The operating model is a simulation tool and does not currently perform estimation or optimisation but will be a very useful tool for many investigations of the Pacific halibut fishery in the future.

The technical details of the multi-area operating model, which continues to be under development, are supplied in document IPHC-2019-MSAB015-INF01. Some background information on specific components and the incorporation of uncertainty is supplied below.

2.1.1 General process of the operating model

The use of multiple input JSON-formatted files allows for the simulation of many configurations of the Pacific halibut population and associated fisheries. Any number of areas/regions can be specified along with any number of fisheries that operate in those areas at a specified time in the year. Various parameters, such as natural mortality, movement probabilities, selectivity, etc., are specified and most can vary over time, region, sex, fishery, and age where relevant.

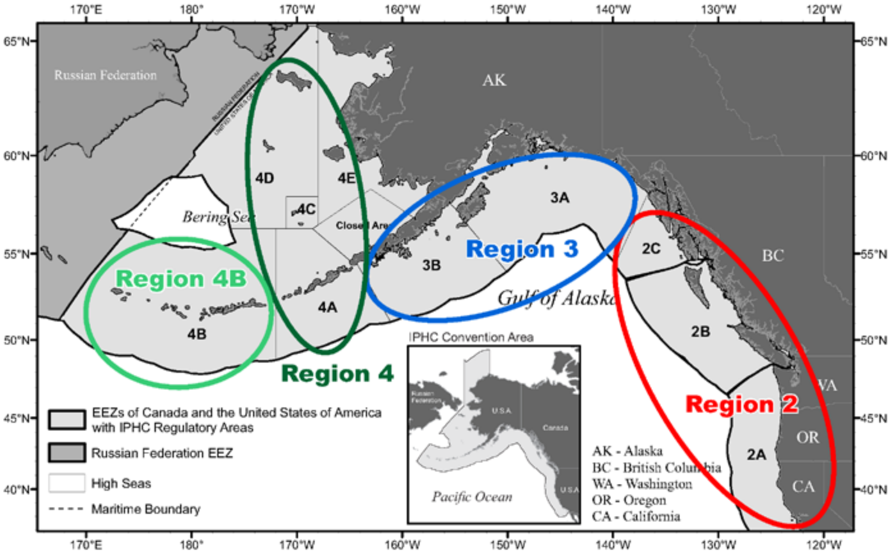

Figure 2: Biological Regions overlaid on IPHC Regulatory Areas. Region 2 comprises 2A, 2B, and 2C, Region 3 comprises 3A and 3B, Region 4 comprises 4A and 4CDE, and Region 4B comprises solely 4B.

The OM begins by calculating the unfished equilibrium population given an input set of biological parameters. It then simulates the annual process during what is called an “initial period” with a fixed mortality level for each fleet (i.e., catch + discard mortality). This initial period allows for the stock to distribute across modelled areas to an equilibrium state given recruitment deviations and fishing mortality. During a subsequent “main period”, the population and dynamics are simulated using input annual fishing mortality, time-varying parameters such as selectivity, recruitment variability, and annual movement between areas. The parameterized model that is run through the main period is called the conditioned model. It is from this point that closed-loop simulations, called the “projection period,” begin.

The projection period can occur in four different ways:

1. A script written for the R statistical language (R Core Team 2020) containing all of the details of the management procedure being evaluated is called by the OM at the beginning of the year to determine the total mortality (TM) for each fishery. The TMs are read back into the OM along with other projected annual processes (e.g., weight-at-age as described below) to simulate the fish population one year forward.

2. A script written for the R statistical language calls the OM which reads in a saved state from disk using TileDB[1], containing the stock state at the start of the projection period as a result of development from the initial period to the end of the main period. After projecting the fish population and fisheries one year forward, the state is written back to disk and the R script performs external calculations such as the management procedure to determine total mortality.
3. The OM is self-sufficient and performs “no estimation error” closed-loop simulations using the spawning potential ratio (SPR) and simple procedures to determine the TM for each fishery.
4. The framework including the OM and management procedures are part of one executable with OM and MP specifications defined through JSON input files.

The first method, where the OM calls an R script containing the details of the management procedure, is currently used, and the other three methods are currently under development.

2.1.2 Population and fishery spatial specification

The emerging understanding of Pacific halibut diversity across the geographic range of its stock indicates that IPHC Regulatory Areas should be only considered as management units and do not represent relevant sub-populations (Seitz et al. 2017). The structure of two of the four current Pacific halibut stock assessment models was developed around identifying portions of the data (fishery-independent and fishery-dependent data) that correspond to differing biological and population processes within the larger Pacific halibut stock. This approach, referred to as ‘areas-as-fleets’ is commonly used in stock assessments (Waterhouse et al. 2014), and was the approach recommended for inclusion in the ensemble developed in 2014 during the SRB review of models and used in all assessments since (Cox et al. 2016, Stewart & Martell 2015, 2016).

Biological Regions (Figure 2) were therefore defined with boundaries that matched some of the IPHC Regulatory Area boundaries for the following reasons. First, data for stock assessment and other analyses are most often reported at the IPHC Regulatory Area scale and are largely unavailable for sub-Regulatory Area evaluation. Particularly for historical sources, there is little information to partition data to a portion of a Regulatory Area. Second, it is necessary to distribute TCEY to IPHC Regulatory Areas for quota management. If a Region is not defined by boundaries of IPHC Regulatory Areas (i.e. a single IPHC Regulatory Area is in multiple Regions) it will be difficult to create a distribution procedure that accounts for biological stock distribution and distribution of the TCEY to Regulatory Areas for management purposes. Further, the structure of the current directed fisheries do not delineate fishing zones inside individual IPHC Regulatory Areas, so there would be no way to introduce management at that spatial resolution. It is unlikely that there is a set of Regions that accurately delineates the stock biologically since different aspects of the stock differ over varying scales, biological boundaries may shift over time, and movement occurs among Biological Regions.

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[1] https://tiledb.com/

To a certain degree, Pacific halibut within the same Biological Region share common biological traits different from adjacent Biological Regions. These traits include sex ratios, age composition, and size-at-age, and historical trends in these data may be indicative of biological diversity within the greater Pacific halibut population. Furthermore, tagging studies have indicated that within a year, larger Pacific halibut tend to undertake feeding and spawning migrations within a Biological Region, and movement between Biological Regions typically occurs between years (Loher and Seitz 2006; Seitz et al. 2007; Webster et al. 2013).

Given the goals to divide the Pacific halibut stock into somewhat biologically distinct regions and preserve biocomplexity across the entire range of the Pacific halibut stock, Biological Regions are considered by the IPHC Secretariat, and supported by the SRB (paragraph 31 IPHC-2018-SRB012-R), to be the best option for biologically-based areas to meet management needs. They also offer an appropriate and parsimonious spatial separation for modeling inter-annual population dynamics.

However, as mentioned earlier, mortality limits are set for IPHC Regulatory Areas and thus directed fisheries operate at that spatial scale. Furthermore, since some fishery objectives have been defined at the IPHC Regulatory Area level, the TCEY will need to be distributed to that scale. Even though the population is modelled at the Biological Region scale, fisheries can be modelled at the IPHC Regulatory Area scale by using an areas-as-fleets approach within Biological Regions. This requires modelling each fleet with separate selectivities and harvest rates that operate on the biomass occurring in the entire Biological Region in each year. The following is a discussion of the pros and cons of this method.

First, modelling the population dynamics at the IPHC Regulatory Area scale would require intra-annual dynamics to be modelled, dividing the year into seasons to model movement between IPHC Regulatory Areas. There is evidence that such intra-annual movements occur (Loher and Seitz, 2006) and fisheries in adjacent IPHC Regulatory Areas may intercept the same pool of fish (Loher 2011). Using Biological Regions assumes that all fisheries within a Region have access to the pool of Pacific halibut in that Region in that year. This greatly simplifies the calculations and eliminates the need to parameterize intra-annual movement. However, if a fishery does not interact with the pool of fish in a Biological Region, harvest rates determined for each fishery may be inaccurate because the biomass to which selectivity is applied would be incorrect , and some fisheries may intercept ages/sizes of Pacific halibut that they commonly do not interact with. This is unlikely to occur and will have very little effect on the results of this MSE because harvest rates are not explicitly used in the management procedures (mortality limits are used for management) and similarity of age/size compositions were used to define Biological Regions.

Additionally, calculating statistics specific to IPHC Regulatory Areas requires assumptions about distribution of biomass within a Biological Region. For example, simulating the observed proportion of biomass in each IPHC Regulatory Area (e.g., to mimic the current interim management procedure) requires simulating a survey biomass for each IPHC Regulatory Area. Likewise, determining some objectives related to IPHC Regulatory Area may be difficult to calculate (such as the proportion of O26 fish in each IPHC Regulatory Area). The distribution of the population within a Biological Region is currently approximated assuming specified proportions of the population in each IPHC Regulatory Area within a Biological Region. These proportions are constant over ages and allows for the calculation of statistics specific to IPHC Regulatory Areas. Future improvements to the framework will allow for different option such as determining proportions from historically observed distributions and accounting for year to year variability.

Fisheries were defined by IPHC Regulatory Areas (or combinations of areas if fishing mortality in that area was small) in four general categories (e.g., sectors) consistent with the definitions in the stock assessment ((IPHC-2020-AM096-09 Rev_2): **directed** representing the O32 mortality from the directed fisheries, sublegal directed fishery **discards** representing the U32 mortality from the directed fisheries, **non-directed** discard mortality representing the mortality from non-directed fisheries, and **recreational/subsistence** combined into one fishery. Table 1 shows the summed mortality for each of these sectors by IPHC Regulatory Area or Biological Region. Twenty-five fisheries were defined as a sector/area combination based on the amount of mortality in the combination and data availability (Table 2).

Table 1: Summed mortality (millions of net pounds) from 1992 through 2019 by fisheries and IPHC Regulatory Area or Biological Region. Darker colors indicate higher values.

Year	2A	2B	2C	3A	3B	4A	4CDE	4B
Commercial	17.5	259.8	205.5	551.2	252.4	78.2	72.5	62.8
Sublegal discards	0.5	7.1	5.2	16.7	10.7	2.1	1.3	0.8
Non-directed discard mortality	28.3			109.8		167.8		16.2
Recreational/Subsistence	12.1	39.2	70.3	134.9	1.3	1.7	2.3	0.1

2.1.3 Maturity

Spawning biomass for Pacific halibut is currently calculated from a maturity-at-age ogive that is assumed to be constant over years. There is currently no evidence (IPHC-2020-SA-02) for skip spawning or maternal effects (increased reproductive output or offspring survival for larger/older females) and they are not modelled, but could be added. Stewart & Hicks (2017) examined the sensitivity to a trend in declining spawning potential (caused by a shift in maturity or increased skip spawning) and found that under that condition there was a bias in both scale and trend of recent estimated spawning biomass. Ongoing research on maturity and skip spawning will help to inform future implementations of the basis for and variability in the determination of spawning output.

Table 2: The twenty-five fisheries in the OM, the IPHC Regulatory Areas they are composed of, and the 2019 mortality (millions of net pounds) for each.

Fishery	IPHC Regulatory Areas	2019 Mortality
Directed2A	2A	0.89
Directed 2B	2B	5.22
Directed 2C	2C	3.67
Directed 3A	3A	8.16
Directed 3B	3B	2.31
Directed 4A	4A	1.45
Directed 4B	4B	1.00
Directed 4CDE	4CDE	1.65
Discards2A	2A	0.03
Discards2B	2B	0.13
Discards2C	2C	0.06
Discards3A	3A	0.32
Discards3B	3B	0.15
Discards4A	4A	0.09
Discards4B	4B	0.03
Discards4CDE	4CDE	0.07
NonDirected2	2A, 2B, 2C	0.46
NonDirected3	3A, 3B	2.13
NonDirected4	4A, 4CDE	3.84
NonDirected4B	4B	0.17
RecSubsist2A	2A	0.48
RecSubsist2B	2B	1.27
RecSubsist2C	2C	2.26
RecSubsist3	3A, 3B	3.9
RecSubsist4	4A, 4CDE	0.06

2.1.4 Weight-at-age

Empirical weights-at-age by region for the population, fisheries, and survey are determined using observations from the FISS and the fisheries, as is done with the stock assessment models (IPHC-2019-AM095-08 and as described in detail in Stewart and Martell (2016). Smoothed observations of weight-at-age from NMFS trawl surveys were used to augment ages 1-7 fishery and survey weights-at-age. Population weight-at-age is smoothed across years to reduce observation error. Finally, survey and population weight-at-age prior to 1997 is scaled to fishery data because survey observations are limited if present at all.

2.1.5 Movement

Many data sources are available to inform Pacific halibut movement. Decades of tagging studies and observations have shown that important migrations characterize both the juvenile and adult stages and apply across all regulatory areas. The conceptual model of halibut ontogenetic and seasonal migration, including main spawning and nursery grounds, as per the most current knowledge, was presented in IPHC-2019-MSAB014-08 and was used to assist in parameterizing movement rates in the OM.

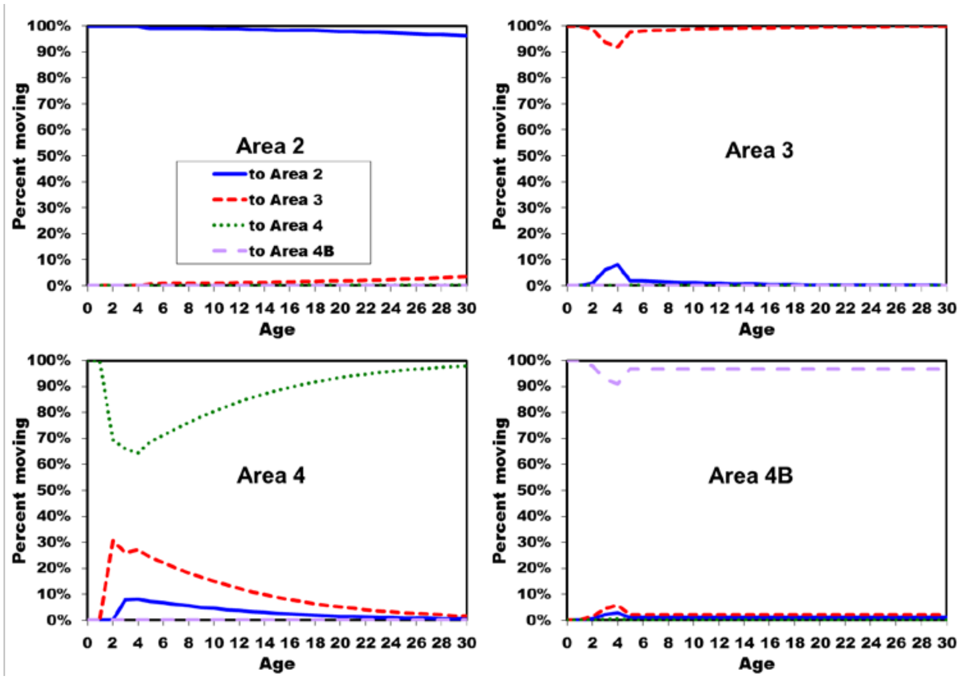

Figure 3: Estimated aggregate annual movement rates by age from Biological Regions (panels) based on currently available data (from IPHC-2019-AM095-08).

In 2015, the many sources of information were assembled into a single framework representing the IPHC's best available information regarding movement-at-age among Biological Regions. Key assumptions in constructing this hypothesis included:

- ages 0-1 do not move (most of the young Pacific halibut reported in Hilborn et al. (1995) were aged 2-4),
- movement generally increases from ages 2-4,
- age-2 Pacific halibut cannot move from Region 4 to Region 2 in a single year, and
- relative movement rates of Pacific halibut age 2-4 to/from Region 4 are similar to those observed for 2-4 year-old Pacific halibut compared to older Pacific halibut in Region 3.

Based on these assumptions, appreciable emigration is estimated to occur from Region 4, decreasing with age. Pacific halibut age-2 to age-4 move from Region 3 to Region 2 and from Region 4B to Regions 3 and 2, and some movement of older Pacific halibut is estimated to occur from Region 2 back to Region 3 (Figure 3).

The conceptual model and assembled movement rates were used to inform the development of the MSE operating model framework and is being used as a starting point to incorporate variability and alternative movement hypotheses in Pacific halibut movement dynamics. Movement in the OM is modelled using a transition matrix as the proportion of individuals that move from one Biological Region to another for each age class in each year.

2.1.6 Fishery and survey selectivity and retention

Selectivity and retention determine the age composition of fishery mortality and ensure the removal of appropriate numbers-at-age from the population when mortality occurs in the annual time-step. Selectivity represents the proportion at each age that is encountered by the gear. Retention represents the proportions-at-age that are retained and landed if caught (i.e., 1 - retention is the proportion-at-age that is released). The product of selectivity and retention is called the "keep curve" and represents the proportions-at-age from the population that are landed. Some fish that are not retained may survive; thus a discard mortality rate is used to indicate the proportion of fish that are not retained and die after release.

Parameters for selectivity and retention were determined from the estimated parameters in the recent stock assessment (IPHC-2020-AM096-09 Rev_2) including annual deviations in selectivity for the directed fisheries and the survey.

2.1.7 Uncertainty in the operating model

Uncertainty is important to consider, as the goal of an MSE is to develop management procedures that are robust to uncertainty. The OM should simulate potential states of the population in the future, uncertainties within the management procedure, and variability when implementing the management procedure.

2.1.7.1 Projected population variability

Variability in the projected population is a result of initializing the population with a range of parameters to recreate a range of historical trajectories and including additional variability in certain population processes in the projection. Uncertainty in input parameters was determined from the stock assessment models when conditioning the OM. An entire set of parameters was sampled from a multinormal distribution to account for correlations between them. These sets of parameters resulted in multiple historical population trajectories from which to begin the projections. The major sources of uncertainty in the OM are described in Table 3.

Table 3: Major sources of variability in the operating model (OM).

Process	Uncertainty
Natural Mortality (M)	Estimate appropriate uncertainty when conditioning OM
Steepness	Estimate appropriate uncertainty when conditioning OM
Recruitment	Random, lognormal deviations
Size-at-age	Annual and cohort deviations in weight-at-age with bounds
Regime Shifts	Autocorrelated indicator based on properties of the PDO for regime shift
Sector mortality	See section on allocating mortality to sectors within an area
Selectivity	See section on directed fishery selectivity
Implementation	See section on implementation variability

Projected weight-at-age

Weight-at-age varies over time historically, and the projections capture that variation using a random walk from the previous year. It is important to simulate time-varying weight-at-age because it is an influential contributor to the yield and status of Pacific halibut. This variability was implemented using the same general procedure as in the coastwide MSE (IPHC-2018-MSAB011-08), with a few modifications to allow for slight departures between regions and fisheries.

The method used to simulate weight-at-age was as follows.

1. A single deviation was generated from a normal distribution with a constant standard deviation (0.05) and the exponential was used as a multiplier on the current year's weight-at-age for all regions and fisheries to determine the weight-at-age for those regions and fisheries in the next year. This made all weights for each age, region, and fishery increase or decrease similarly.
    a. A random walk was used where the weight-at-age in the next year was generated from the weight-at-age in the current year. The deviation in (1) was also correlated with past deviations to simulate periods of similar trends (ρ=0.5).
2. Deviations for each age 6 and greater were generated from a normal distribution with a constant coefficient of variation for each age (0.01), resulting in standard deviations scaled by the mean weight-at-age observed over all historical years with observations. This allows for larger deviations for older fish and provides a mechanism for the mean weight of a specific age to depart from the overall trend simulated in step 1.
    a. This was done separately for the population weight-at-age in each Biological Region and for each fishery. This allows for them to slightly deviate from each other capturing potential different trends for each as well as observation error.

The overall deviate in 1) above is the main driver of weight-at-age and captures the observation that weight-at-age varies over time.

A random walk can traverse to extremely high or low values. Therefore, boundary conditions were set to limit the range over which weight-at-age could vary. The boundary limits were determined from the observed range of weight at each age and expanded 5% beyond the minimum and maximum weight at each age observed. The random walk simulations remained within the bounds by applying the following algorithm.

1. If a weight-at-age was simulated to be beyond the bounds, the deviations for only the ages where the age-specific bounds were exceeded were reduced by one-half and applied again to determine if it still exceeded the bounds.
2. Repeat step (1) until no age-specific bounds were exceeded.

Linkage between average recruitment and environmental conditions

The average recruitment (R_0) is related to the Pacific Decadal Oscillation index[2], expressed as a positive or negative regime (IPHC-2020-SA-02). R_0 is multiplied by $e^{I\delta}$, where I is an indicator of the negative (0) or positive (1) regime, and δ is a parameter determining the magnitude of that multiplier. The parameter δ was determined from the stock assessment.

The regime was simulated in the MSE by generating a 0 or 1 to indicate the regime in that future year, as described in IPHC-2018-MSAB011-08. To encourage runs of a regime between 15 and 30 years (an assumption of the common periodicity, although recent years have suggested less), the environmental index was simulated as a semi-Markov process, where the next year depends on recent years. However, the probability of changing to the opposite regime was a function of the length of the current regime with a probability of changing being equal to 0.5 at 30 years, and a very high probability of changing at 40 years. The simulated length of a regime was most often between 20 and 30 years, with occasional runs between 5 and 20 years or greater than 30 years.

Time-varying selectivity

Time-varying selectivity is estimated in the stock assessment for only the directed fishery in historical years in order to allow for spatial availability and changes in weight-at-age in these coastwide models. The coastwide MSE followed a similar approach by linking changes in selectivity to weight-at-age. Changes in selectivity may be related to changes in weight-at-age because weight-at-age is a proxy for changes in size. Changes in spatial availability is also a factor in time-varying coastwide selectivity, and the multi-area OM may alleviate some of that variability.

A similar approach is used when projecting in the multi-area OM, and the details are still being developed.

Implementation variability

Implementation variability consists of two components. The first is the departure from the management procedure during the decision-making process. For example, the MP may result in a total mortality of 40 Mlbs, but the decision may be to implement a total mortality of 36 Mlbs for various economic and social reasons. The second component of implementation variability is the fact that the fisheries do not achieve the mortality limits exactly. In recent years, the actual total fishery mortality has been slightly less than mortality limits, although some sectors have exceeded the limits.

Both components of implementation variability are modelled in the OM, although the details are still being determined.

2.2 Management Procedure

The management procedure consists of three elements. Monitoring (data generation) is the code that simulates the data from the operating model and are used by the estimation model. It simulates the data collection and sampling process and can introduce variability, bias, and any

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[2] https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.htmlTable?time,PDO

other properties that are desired. The Estimation Model (EM) is analogous to the stock assessment and simulates estimation error in the process. Using the data generated, it produces an annual estimate of stock size and status and provides the advice for setting the catch levels for the next time step. Simplification of the full stock assessment ensemble are necessary to keep simulation times within reason. The Harvest Rule is the application of the estimation model output along with the scale and distribution management procedures (Figure 1) to produce the mortality limit for that year. The details of the management procedures are in development and concepts described in IPHC-2020-MSAB015-07 are being considered.

2.2.1 Uncertainty in the management procedure

The major source of uncertainty in the management procedure is from the generation of data. The data generation step simulates the process of observation by resampling from probability distributions that approximate the uncertainty in the observed data. These simulated data are then fed into two stock assessment models to approximate the stock assessment ensemble. The two models are the short coastwide and long coastwide models using stock synthesis and slightly simplified to reduce run time. Extensive testing showed that the averages of these two estimation models provide a reasonable approximation to the full stock assessment while keeping run times to a reasonable amount. Using actual stock assessment models will better characterize the variability than the simpler approach (autocorrelated estimation error about the true population values) used in the coastwide MSE for simulating estimation error. The estimated values from the data generation and estimation model steps are used in the application of the harvest rule to determine mortality limits by IPHC Regulatory Area, and the simulated application of this rule will therefore include errors in the status as well as the size of the population, which will be propagated into management actions.

3 RECOMMENDATIONS

That the MSAB:

a) **NOTE** paper IPHC-2020-MSAB015-08 which provides an update on the development of the IPHC MSE framework, a description of the specifications of the multi-area operating model, and a brief overview of the implementation of management procedures.

b) **RECOMMEND** alternative specifications and additional features needed to evaluate management procedures related to coastwide scale and distribution of the TCEY in 2020, also **NOTING** document IPHC-2020-MSAB015-INF01.

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5 APPENDICES

Nil