DRAFT ANNEX
<u>Version 20-03: September 24 2020</u>

NB: This is a work in progress. While sections showing considerable numbers of modifications using the track changes option are virtually finalised, work is still in progress updating other sections.

SPECIFICATIONS FOR MSE TRIALS FOR BLUEFIN TUNA IN THE NORTH ATLANTIC

CONTENTS

1 BASIC CONCEPTS AND STOCK STRUCTURE

This first item intends to cover only the broadest overview issues. More detailed technical specifications are included under subsequent items.

In this document the term ‘Stock’ refers to fish originating from a natal spawning region either in the Mediterranean (East Stock) or the Gulf of Mexico / Slope Sea (West Stock). Hence ‘Eastern’ and ‘Western’ may be used to describe fish according to their stock of origin, for example ‘Eastern fish’ are fish that spawn in the Mediterranean.

In this document the term ‘area’ refers to the traditional East and West management areas (‘East Area’ and ‘West Area’).

The term ‘strata’ refers to seven smaller spatial definitions (described in Figure 1.1).

The two management areas are delineated by 45 degrees west in the North Atlantic. The West area includes strata 1-3, the East area includes strata 4-7.

The model is divided in to four time-steps per year (quarters): (1) Jan-Mar, (2) Apr – Jun, (3) July – Sept, (4) Oct-Dec. The term spatio-temporal strata refers to one of the seven spatial stratum in a particular year and quarter (e.g. stratum 6, quarter 3 in 1981).

Eastern fish (of the East Stock) can migrate to the West Area (management area) and Western fish (of the West Stock) can migrate to the East Area (management area). However, it is assumed that no Eastern fish enters the Gulf of Mexico and no Western fish enters the Mediterranean.

Spatial definitions

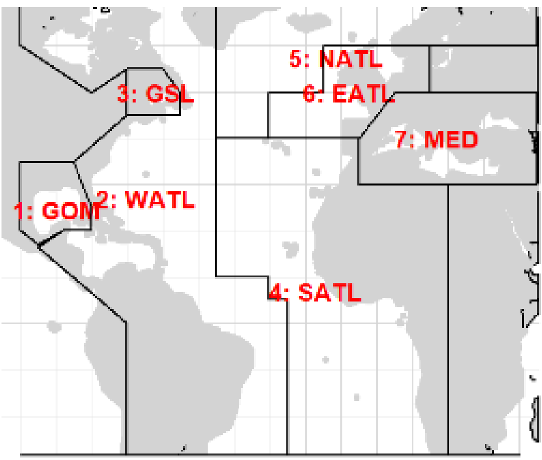


Figure 1.1. The seven spatial strata.

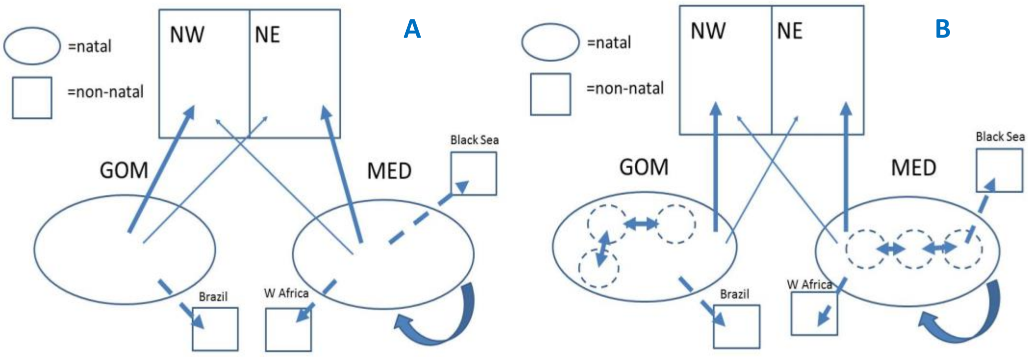
Baseline

The 7-stratum model of Figure 1.1 (the reported electronic tagging data and the stock of origin data do not have sufficient resolution to divide the Mediterranean stratum).

Alternative low priority future options

The MAST model (Taylor et al. 2011) which has strata similar to Figure 1.1, but where strata 4-6 are merged into a single East Atlantic stratum.

Stock mixing



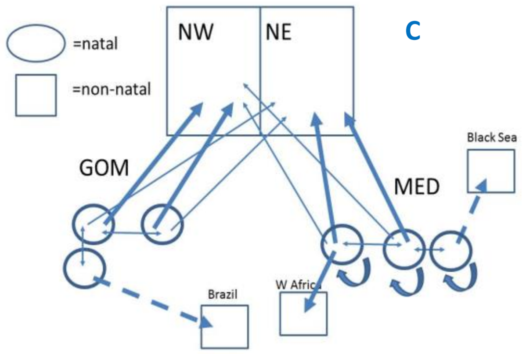


Figure 1.2. Mixing hypotheses suggested by Anon, (2014) and Arrizabalaga et al. (2019).

(A) A two stock model with no sub-stock structure.

(B) A two stock model with sub-stock structure.

Baseline

A two-stock model similar to Figure 1.2A but adhering to the spatial structure of Figure 1.1. The mixing proportions are determined by the stock of origin data (genetics and otolith chemistry).

2 PAST DATA AVAILABLE

Table 2.5 provides an overview of the data that may be used to condition operating models for Atlantic bluefin tuna. The table indicates those data that have been gathered, those that are currently available and those that have already been used in conditioning operating models.

I) Raw data

Operating models are fitted to the fishery, tagging and survey data that are currently available (Table 2.5, field ‘Used in OM’). Currently, the operating model is fitted to ICCAT Task II landings data scaled upwards to annual Task I landings.

The ICCAT catch-at-size dataset was used to estimate gear selectivity for each of the baseline fleet types. The operating models incorporate 18 fishing fleets, as described in Table 3.1.

The electronic tagging data from several sources (NOAA, DFO, WWF, AZTI, UNIMAR, IEO, UCA, FEDERCOOPESCA, COMBIOMA, GBYP, IFREMER, Stanford University) have been compiled by NOAA (M. Lauretta) and used to estimate movements among spatial strata. Tag tracks were provided by the seven spatial strata. These are converted to strata-quarter records by the following rule: for each tag, its strata position in a quarter is assigned as the strata in which the tag spent the most days during that quarter (Fig 2.1A).

In the model developed for movement, quarterly transitions between strata depend on stock (Eastern or Western) and age class (ages 1-4, 5-8, and 9+). Only tags that have either corresponding weight or length data can be assigned an age class (by cohort slicing) and can be used by the model. Similarly, only those tags that have entered either the Gulf of Mexico or the Mediterranean can be assigned a stock of origin. All other tags are removed and not used in the conditioning of operating models. The exception are tags released by AZTI in the Bay of Biscay, which are assumed to correspond to be of Eastern Stock of origin. By November 2018 data from 1,307 tags were available for the model, however only 598 tag transitions (quarterly movements) could be used for to provide transition information as the others lacked either age-class assignment or stock of origin assignment (Fig 2.1B).

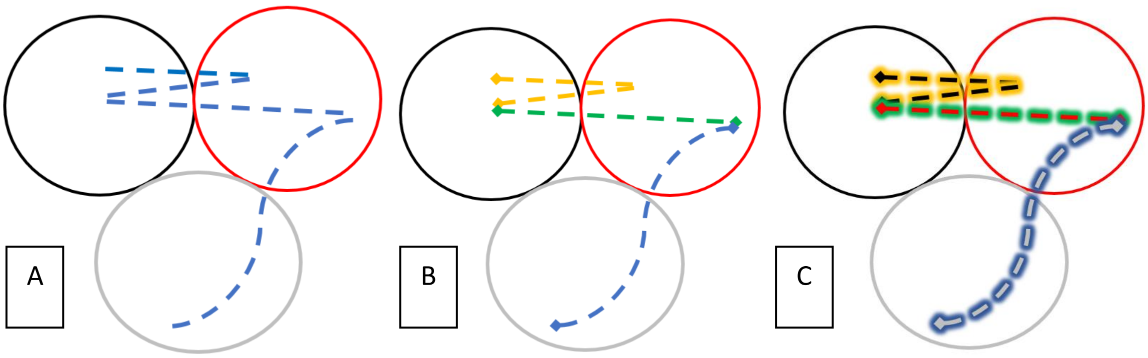


Figure 2.1A. Electronic tag data were used to inform quarterly transitions. This figure explains how each tag was allocated to an strata (represented as black, red, and gray circles) and quarter. The blue dashed line in (A) represents one electronic tag track. In (B) this track is spliced into quarters (here the track is split into different quarters through different colours 1=yellow, 2=green, 3=blue). Then (C) the track for each quarter was allocated to a spatio-temporal strata (a spatial strata, quarter, age class). This was done by counting the days (days are represented as dashes in these figures) the tag spent in each spatio-temporal strata; the strata where the tag spent the most days in a quarter was determined to be the location for the tag in that quarter.

All age classes

TO AREA

FROM AREA

Western Stock

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	7	0	0	0	0	0	0
WATL	44	45	0	0	0	0	0
GSL	1	1	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

Eastern Stock

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	12	0	1	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	4	0	4	1
NATL	0	2	0	3	1	0	0
EATL	0	1	0	8	0	9	0
MED	0	0	0	3	0	0	37

From Q1 To Q2

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	37	4	0	0	0	0	0
WATL	28	12	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	8	0	6	2	1	2
GSL	0	0	0	0	0	0	0
SATL	0	1	0	8	0	4	1
NATL	0	0	0	1	0	0	0
EATL	0	0	0	2	0	5	1
MED	0	0	0	0	0	0	17

From Q2 To Q3

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	2	18	3	0	0	0	0
WATL	0	18	2	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	7	0	1	0	1	0
GSL	0	0	0	0	0	0	0
SATL	0	1	0	2	2	3	3
NATL	0	0	0	0	1	1	0
EATL	0	0	0	1	0	5	0
MED	0	0	1	6	3	9	34

From Q3 To Q4

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	1	18	2	0	0	0	0
GSL	6	29	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	7	0	0	0	0	0
GSL	0	2	0	0	0	0	0
SATL	0	0	0	4	0	0	1
NATL	0	0	0	0	4	0	0
EATL	0	0	0	1	4	22	0
MED	0	0	0	2	0	0	47

TOTAL 598

Age class 1

TO AREA

FROM AREA

Western Stock

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

Eastern Stock

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	1	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	3	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	1	0	5	0	8	0
MED	0	0	0	1	0	0	6

From Q1 To Q2

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	1	0	0	1	0	0
GSL	0	0	0	0	0	0	0
SATL	0	1	0	4	0	2	1
NATL	0	0	0	0	0	0	0
EATL	0	0	0	1	0	3	0
MED	0	0	0	0	0	0	3

From Q2 To Q3

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	2	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	1	0
EATL	0	0	0	0	0	2	0
MED	0	0	0	0	0	0	0

From Q3 To Q4

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0

	GOM	WATL	GSL	SATL	NATL	EATL	MED
GOM	0	0	0	0	0	0	0
WATL	0	1	0	0	0	0	0
GSL	0	0	0	0	0	0	0
SATL	0	0	0	1	0	0	1
NATL	0	0	0	0	0	0	0
EATL	0	0	0	0	0	18	0
MED	0	0	0	1	0	0	5

TOTAL 74

Age class 2

TO AREA

estern Stock — Eastern Stock

FROM AREA

From Q1 To Q2

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	0	1	0	0	0	0	0	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	1	0	0	1
NATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0	0	0	0	2	0	0	30

From Q2 To Q3

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	0	2	0	0	0	0	0	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	1	0	0	0
NATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0	0	0	0	0	0	0	14

From Q3 To Q4

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	0	2	0	0	0	0	0	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	1	0	0	0
NATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0	0	0	0	0	0	0	5

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	0	1	0	0	0	0	0	0	0	0	0	0	0	0
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EATL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MED	0	0	0	0	0	0	0	0	0	0	1	0	0	38

TOTAL 100

Age class 3

TO AREA

Western Stock — Eastern Stock

FROM AREA

From Q1 To Q2

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	7	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	44	44	0	0	0	0	0	0	11	0	1	0	0	0
GSL	1	1	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	0	0	4	0
NATL	0	0	0	0	0	0	0	0	2	0	3	1	0	0
EATL	0	0	0	0	0	0	0	0	0	0	3	0	1	0
MED	0	0	0	0	0	0	0	0	0	0	0	0	0	1

From Q2 To Q3

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	37	4	0	0	0	0	0	0	0	0	0	0	0	0
WATL	28	10	0	0	0	0	0	0	7	0	6	1	1	2
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	3	0	2	0
NATL	0	0	0	0	0	0	0	0	0	0	1	0	0	0
EATL	0	0	0	0	0	0	0	0	0	0	1	0	2	1
MED	0	0	0	0	0	0	0	0	0	0	0	0	0	0

From Q3 To Q4

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	2	18	3	0	0	0	0	0	0	0	0	0	0	0
WATL	0	16	2	0	0	0	0	0	5	0	1	0	1	0
GSL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	1	0	1	2	3	3
NATL	0	0	0	0	0	0	0	0	0	0	0	1	0	0
EATL	0	0	0	0	0	0	0	0	0	0	1	0	3	0
MED	0	0	0	0	0	0	0	0	0	1	6	3	9	29

	W GOM	W WATL	W GSL	W SATL	W NATL	W EATL	W MED	E GOM	E WATL	E GSL	E SATL	E NATL	E EATL	E MED
GOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATL	1	17	2	0	0	0	0	0	6	0	0	0	0	0
GSL	6	29	0	0	0	0	0	0	2	0	0	0	0	0
SATL	0	0	0	0	0	0	0	0	0	0	3	0	0	0
NATL	0	0	0	0	0	0	0	0	0	0	0	4	0	0
EATL	0	0	0	0	0	0	0	0	0	0	1	4	4	0
MED	0	0	0	0	0	0	0	0	0	0	0	0	0	4

TOTAL 424

Figure 2.1B. Observed electronic tag transitions among spatial strata by stock and quarter. These are tags present in a particular stratum (row) that move to a stratum (column) in the following quarter. The solid line represents strata available to the Western Stock (i.e. excludes the MED), the dashed line represents strata available to the Eastern Stock (i.e. excludes the GOM). The shaded diagonal cells highlight tags that did not move strata from one quarter to the next. Age class 1 consists of 1-4 year olds; age class 2 consists of 5-8 year olds; age class 3 consists of 9+ year olds. These transitions are derived from 1307 individual tags.

Catch data provide scale to stock assessments. It follows that spatial stock of origin data are necessary to estimate the relative magnitude of the various stocks in a multi-stock model (to correctly assign catches to stock). Currently the model uses stock of origin data derived from the otolith microchemistry and genetic research of AZTI, UMCES, GBYP, and DFO (Table 2.5 and Table 2.6A-D).

There is uncertainty in regard to the stock of origin of bluefin tuna catches in the South Atlantic that were reported prior to 1970. For the Base Case, these are dealt with in the same way as all other catches: they are assigned to the strata of Figure 1.1 by uprating Task II catches (that are reported spatially) to the annual Task I catch data.

Analysed data

The operating models are also fitted to standardized CPUE indices (Table 2.1) and a range of fishery-independent indices (Table 2.2). These fishery-independent indices include a Western larval index in the Gulf of Mexico an Eastern larval index in the western Mediterranean (Ingram et al., 2015) and two aerial surveys in the Mediterranean (French Aerial survey: Rouyer et al., 2018).

In order to predict observed catch at size from model predicted catch at age, operating models made use of an inverse age-at-length key (probability of length class given age). These keys are developed from the base-case stock assessment growth curves for Eastern and Western stocks and a coefficient of variation (variability in length at age) determined by the growth model of Allioud et al. (2017).

Table 2.1. The standardized CPUE indices used to fit the operating models (many of which are used in stock assessments previously conducted by ICCAT). Many of these indices are available after 2016 but the operating model only uses data to 2016 due to the unavailability of CATDIS uprated catch data for more recent years at the time of model conditioning. The right-most column indicates the fishing fleets used to assign selectivity to each CPUE index; the fishing fleets are described in Table 3.1.

	Flag	Gear	Details	Fleet (selectivity) assigned
1	Spain	Baitboat	1952-2006, Q3, E Atl	3: BBold
2	Spain / France	Baitboat	2007-2014, Q3, E Atl	4: BBnew
3	Morocco / Spain	Trap	1981-2011, Q2, S Atl	12: TPold
4	Morocco / Portugal	Trap	2012-2016, Q2, S Atl	13: TPnew
5	Japan	Longline	1975-2009, Q2, S Atl	2: LLJPN
6	Japan	Longline	1990-2009, Q4, N Atl	2: LLJPN
7	Japan	Longline	2010-2016, Q4, N Atl	18: LLJPNnew
8	US (66cm - 114cm)	Rod and reel	1993-2016, Q3, W Atl	15: RRUSAFS (50 –125cm)
9	US (115cm - 144cm)	Rod and reel	1993-2016, Q3, W Atl	15: RRUSAFS (100 – 150cm)
10	US (177cm+)	Rod and reel	1993-2016, Q3, W Atl	16: RRUSAFB (175cm+)
11	US (<145cm)	Rod and reel	1980-1992 (gap in 1984), Q3, W Atl	15: RRUSAFS (50 – 150cm)
12	US (195cm+)	Rod and reel	1983-1992, Q3, W Atl	16: RRUSAFB (200cm+)
13	US	Longline	1987-1991, Q2, GOM	1: LLOTH
14	US	Longline	1992-2016, Q2, GOM	1: LLOTH
15	Japan	Longline	1974-1980, Q2, GOM	2: LLJPN
16	Japan	Longline	1976-2009, Q4, W Atl	2: LLJPN
17	Japan	Longline	2010-2016, Q4, W Atl	18: LLJPNnew
18	Canada GSL	Rod and reel	1984-2016, Q3, GSL	14: RRCAN
19	Canada SWNS	Rod and reel	1988-2016, Q3, W Atl	14: RRCAN

Table 2.2. Fishery-independent indices used in the fitting of operating models.

	Type	Details	Infers:
1	French aerial survey past	2000-2003, Q3, Med	Vulnerable biomass in Q3 in Med, according to the RRUSAFS selectivity due to similar assumed size of fish
2	French aerial survey recent	2009-2016 (gap in 2013), Q3, Med	Vulnerable biomass in Q3 in Med, according to the RRUSAFS selectivity due to similar assumed size of fish
3	Western Med Larval survey	2001-2015 (gaps in 2006-2011), Q2, Med	SSB eastern stock in Q2 in Med
4	Canadian acoustic survey	1994-2016, Q3, GSL, index in number of fish greater than 159cm	Number of combined eastern and western fish in Q3 for the GSL stratum according to the estimated vulnerable biomass available to the CANRR fleet for 150cm plus
5	USA Larval survey	1977-2016 (gaps in 1979-1980, and 1985), Q2, GOM	SSB western stock in Q2 in GOM stratum
6	Aerial survey – GBYP*	2010-2015 (gaps in 2012, 2014, and 2016), Q2, Med	SSB eastern stock in Q2 in Med

** Only the Balearic component is used for SSB (because there are problems with consistency regarding patchy or low biomass inference in other strata surveyed)*

In order to initialize the spatial-seasonal operating model at a plausible distribution of vulnerable biomass, a so-called "master index" was derived. This index allows a standardized effort to be derived for the catch series of any fleet simplifying the estimation of fishing mortality rates (for more detail see SCRS/2019/133). The only role of the master index is to initialize the model and it effectively plays no role in the likelihood.

The default master index ('Assess-Tag') was derived using electronic tagging data and East / West area trends estimated by the most recent Stock Synthesis assessments.

The electronic tagging data of known stock of origin p (fish that have been in either the Gulf of Mexico or the Mediterranean) were aggregated by quarter s, stratum-from a, stratum-to k, into a matrix T. Each row of this matrix was normalized to form a Markov movement matrix V such that the values summed to 1:

$$V_{p,s,a,k} = \frac{T_{p,s,a,k}}{\sum_k T_{p,s,a,k}} \tag{2.1}$$

For each stock, an even initial spatial distribution was repeatedly multiplied though this quarterly movement matrix until it stabilized on an asymptotic quarterly distribution $D_{p,s,a}$.

Then using the estimates of historical spawning stock biomass B from the most recent East and West Stock Synthesis stock assessments (assuming that the area trends of assessments reflect the stock trends), a predicted spawning biomass by season and stratum $\hat{B}$ was calculated:

$$\hat{B}_{p,s,a,y} = D_{p,s,a} B_{p,y} \tag{2.2}$$

This was summed over the two stocks (Eastern and Western) to get total biomass $\bar{B}$ that was assumed proportional to the master index I (red line Figure 2.2):

$$I_{s,a,y}^{Assess-Tag} \approx \bar{B}_{s,a,y} = \sum_p \hat{B}_{p,s,a,y} \tag{2.3}$$

Other approaches to index derivation were used to demonstrate that it has little impact on final model estimates (SCRS/2019/133) including derivation by GLM and assuming a flat, constant trend over time and space (Figure 2.2).

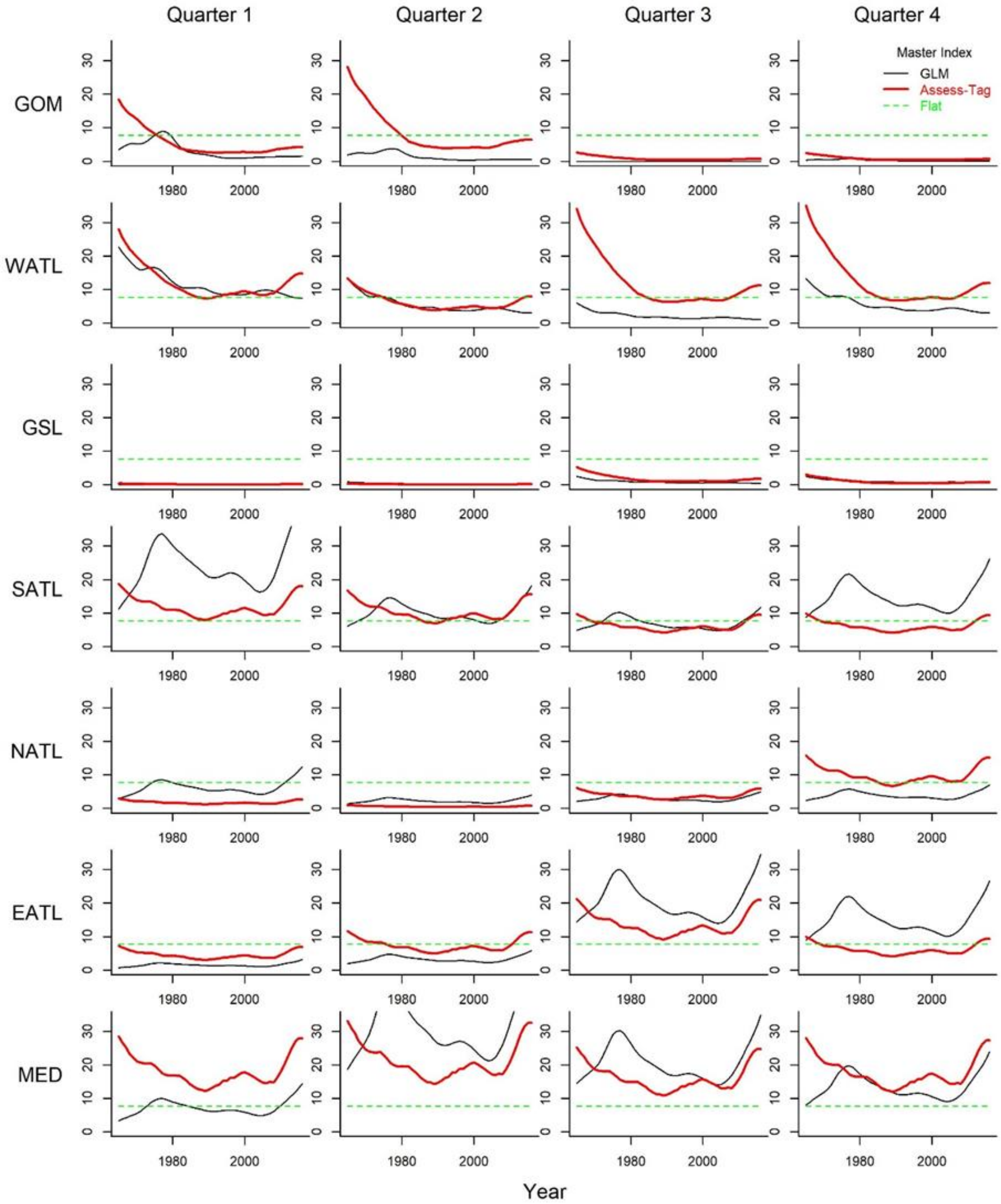


Figure 2.2. The seasonal / spatial master indices derived by various methods including by generalized linear modelling (GLM, Carruthers 2018) and 'Assess-Tag' described above and in (SCRS/2019/133). The master index is used as a way to initialize the model and has essentially no other role in model fitting. The default index used in OM conditioning is Assess-Tag described above but results have been shown to be invariant to the choice of master index. The magnitude of all points are relative and have an arbitrary mean value that is the green dashed line.

Assumptions

The following are the default assumptions made in the model. Some of them may be relaxed in the robustness trials.

The age-length key is static and not adjusted according to fishing mortality rate and length selectivity of fishing.

CPUE indices are considered to be proportional to vulnerable (i.e. selectivity-weighted) biomass.

Larval indices are assumed to be proportional to spawning stock biomass in the stratum in which they were collected in contrast to stock-wide spawning stock biomass (for scenarios where the two are not proportional). Non-larval fishery-independent indices may mirror fleet selectivities or are assumed to be proportional to spawning stock biomass.

Fish found in the GOM stratum are assumed to be all Western Stock fish (i.e. the model assumes that close to zero Eastern Stock fish move to the GOM). Fish found the MED stratum are all assumed to be Eastern Stock fish.

Table 2.5. Overview of data that may (includes all available years, not just those used in conditioning) be used to inform operating models for Atlantic bluefin tuna (available online here). Cells shaded green reflect sources for which data are available ('Collab', the Technical Team TT, or the ICCAT secretariat) and whether data that are available have also been used in conditioning preliminary operating models ('used in OM?'). Conventional tags are used only in defining the stock-specific areas of the GOM and Mediterranean.

Type of data (Informs)	Year range	Til	Spatial range	Can be by quarter?	By age-class?	Contact	Collab	Available to: TC	TT	ICCAT	ALL	Used in OM?
1. CPUE indices (relative abundance, movement, performance at stakeholder level)												
1.1. ICCAT task II CPUE	1950-2017	∞	All	Y	N	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	Y
1.2. Japanese LL standardized spatial	1976-2017	∞	E, NE, W, C	Y	N	Ai Kimoto	Y	Y	Y	Y	Y	Y
							Y	Y	Y	Y	Y	Y
	1992-2017	∞	W	Y	N		Y	Y	Y	Y	Y	Y
	1975-2009	2009	E, Med	Y	N		Y	Y	Y	Y	Y	Y
1.3. USA LL standardized spatial	1974-1981	1981	GOM	Y	N	Matt Lauretta (NOAA)	Y	Y	Y	Y	Y	Y
	1992-2004	2004	GOM	Y	N		Y	Y	Y	Y	Y	Y
	2005-2018	∞	GOM	Y	N		Y	Y	Y	Y	Y	Y
1.4. USA HL standardized spatial	1980-2015	∞	W	Y	N		Y	N	N	N	N	N
1.5. USA RR standardized spatial	1993-2017	∞	W	Y	N		Y	Y	Y	Y	Y	Y
1.6. USA-CAN LL standardized spatial	1992-2014	∞	W, C	Y	N	M. Lauretta (NOAA) /	Y	N	N	N	N	N
1.7. USA-CAN HL standardized spatial	1993-2014	∞	W, C	Y	N	A. Hanke (DFO)	Y	N	N	N	N	N
1.8. CAN LL standardized		∞	W, GSL	Y	N		Y	N	N	N	N	N
1.9. CAN HL GSL standardized	1984-2017	∞	GSL	Y	N	Alex Hanke (DFO)	Y	N	N	N	N	Y
1.10 CAN HL SWNS standardized	1988-2017	∞	W	Y	N		Y	N	N	N	N	Y
1.11. CAN CMB RR	1984-2016	∞	W	Y	N	Alex Hanke (DFO)	Y	Y	Y	Y	Y	N
1.12. TWN LL standardized	1960-2004	2004	W, NE, E	Y	N	Julia Huang (NTOU)	N	N	N	N	N	N
1.13. MOR-SPN TRAP standardized	1982-2011	2011	WM	Y	N	N. Abid	Y	Y	Y	Y	Y	Y
1.14. MOR-POR TRAP standardized	2012-2016	∞	W, WM	Y	N	N. Abid	Y	Y	Y	Y	Y	Y
1.15. ESP TRAP standardized			W, WM	Y	N	Jose Miguel de la	N	N	N	N	N	N
1.16. ITA (SAR) TRAP standardised	1993-2010	2010	CM	Y	N	Pierantonio Addis	Y	Y	Y	Y	Y	N
1.17. SPN BB	1952 - 2006	2006	EATL	Y	N	Haritz Arrizabalaga	Y	Y	Y	Y	Y	Y
1.18. SPN-FR BB	2007-2014	2014	EATL	Y	N	Haritz Arrizabalaga	Y	Y	Y	Y	Y	Y
2. Larval indices (SSB, movement)												
2.1. USA	1977-2015	∞	GOM	Y	N	Walter Ingram (NOAA)	Y	Y	Y	Y	Y	Y
2.2. ESP	01-'05 '12-'15	2018	W Med	Y	N	Franciso Alemany (IEO)	Y	Y	Y	Y	Y	Y
3. Catches (stock size, harvest rate)												
3.1. ICCAT task I	1950-2016	∞	non-spatial	N	N	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	N
3.2. ICCAT task II			All	Y	N		Y	Y	Y	Y	Y	N
3.3. ICCAT CATDIS					N		Y	Y	Y	Y	Y	Y
3.4 GBYP	1512-1950		E, M	Y	N	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	Y

Table 2.5 continued.

Type of data (Informs)	Year range	Til	Spatial range	Can be by quarter?	By age-class?	Contact	Collab	Available to: TC	TT	ICCAT	ALL	Used in OM?
4. Catch composition (selectivity, depletion)												
4.1. ICCAT catch-at-size	1950-2016	∞	All	Y	N	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	Y
4.2. Stereo video caging	2014	ended	WM, EM	Y	N	Mauricio Ortiz (ICCAT)	N	N	N	N	N	N
4.3. Canadian fisheries						Alex Hanke (DFO)	N	N	N	N	N	N
4.4 GBYP Historical catches	1910-1950	=	E, M	Y	N	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	Y
5. Conventional tags (feasible movement, growth, GTG heterogeneity)												
5.1. ICCAT	1954-2014	2015	All	Y	Y	Carlos Palma (ICCAT)	Y	Y	Y	Y	Y	Stock defs
6. Electronic tags (movement)												
6.1. LPRC (n=316)	2005-2009	ended	W	Y	Y	Molly Lutcavage	Y	Y	N	N	N	Y
6.2. DFO (n=89)	2009-2018	∞	GSL,W,GOM	Y	Y	Alex Hanke (DFO)	Y	Y	N	N	N	Y
6.3. Stanford (n=391)	1996-2015	∞	All	Y	Y	Barbara Block	Y	Y	N	N	N	Y
6.4. GBYP (n=176)	2011-2017	2015	E, M	Y	Y	Antonio Di Natale	Y	Y	N	N	N	Y
6.5. WWF (n=86)	2008-2015	2015	All	Y	Y	Pablo Cermeno	Y	Y	N	N	N	Y
6.6. NOAA (n=31)	2010-2013	2013	GOM,W,GSL	Y	Y	Craig Brown	Y	Y	N	N	N	Y
6.7. DFO-Acadia (n=37)	2010-2011	ended	GSL	Y	Y	Mike Stokesbury	Y	Y	N	N	N	Y
6.8. UCA (n=46)	2009-2011	ended	W, SE, NE, E,	Y	Y	Antonio Medina	Y	Y	N	N	N	Y
6.9. DFO - Duke (n = 15)	2007-2008	ended	W	Y	Y	Alex Hanke (DFO)	Y	Y	N	N	N	Y
6.10. IEO (n=13)	2001	ended	SE, E, NE, M	Y	Y	F. Abascal	Y	Y	N	N	N	Y
6.11. IFREMER (n=47)			SE, E, M	Y	Y	Tristan Rouyer	Y	Y	N	N	N	Y
6.12. AZTI (n=20)	2005-2011	ended	SE, E, NE, W	Y	Y		Y	Y	N	N	N	Y
6.13. GBYP-Unimar (n=40)	2007-2015	ended	SE, E, NE, M	Y	Y		Y	Y	N	N	N	Y
7. Otolith microchemistry (stock of origin)												
7.1. AZTI (n=189)	2009-2011	2011	E	Y	Y	Igaratza Fraile	Y	Y	Y	Y	Y	Y
7.2. US+Can (n=3545)	1974-2015	∞	W, GSL	Y	Y	Alex Hanke (DFO)	Y	Y	Y	Y	Y	Y
7.3. GBYP (n=2237)	2009-2016	∞	All	Y	Y	GBYP	Y	Y	Y	Y	Y	Y
8. Otolith shape analysis (stock of origin)												
8.1. GBYP (n=172)	2011-2013	2015	E, W, C, WM	Y	N	GBYP	Y	N	N	N	N	N
9. SNP (population structure, genetic structure)												
9.1. Med HCMR					N	Gianpaolo Zmpicinini	N	N	N	N	N	N
9.2. GBYP (n=789)	2011-2015	∞	All		N	GBYP	Y	Y	N	N	N	Y
9.3 NOAA/VIMS/CSIRO	2015	∞	GOM/M	N	N	John Walter	N	N	N	N	N	N
9.4 GBYP Historical UB	200 BC - 1927	1927	E, M	Y	N	Alessia Cariani	Y	N	N	N	N	N
10. Other genetics on population structure (population structure, genetic structure)												
10.1. mtDNA					N	Barbara Block	N	N	N	N	N	N
10.2. Micro Sat/ mtDNA (n=320 / 147)	2003	ended	GOM, WM	Y	N	Carlsson	N	N	N	N	N	N
11. Fish. Ind. surveys (relative abundance, movement)												
11.1. ICCAT Aerial	2010-2015	∞	M	Y	N	Antonio Di Natale	Y	Y	Y	Y	Y	Y
11.2. French Aerial	2000-2016	∞	M	Y	N	Tristan Rouyer	Y	Y	Y	Y	Y	Y
11.3. USA Aerial	2015-	∞	W	Y	N	Molly Lutcavage	Y	Y	Y	Y	N	Y
11.4. USA Acoustic	2015-	∞	W	Y	N	Molly Lutcavage	Y	Y	Y	Y	N	Y
11.5. SOG Hydro acoustic curtain (OTN)	proposed		W, WM	Y	N	Mike Stokesbury	N	N	N	N	N	N
12. Growth, aging (age-length keys, length-age keys)												
12.1. Age-length keys (NOAA)				Y	N	John Walter	Y	N	N	N	N	N
12.2. Age-length keys (IEO)	2010-2012	ended	E, WM	Y	N	Enrique Rodriguez-Marin	Y	N	N	N	N	N
12.3. Age-length keys (DFO)	2010-2013	ended	GSL, W	Y	N	Alex Hanke (DFO)	Y	N	N	N	N	N
12.4. Derived from tagging	1963-2012	ended	Es, W s	Y	N	Lisa Allioud	Y	Y	N	N	N	Y
12.5 Age-length keys (GBYP)	2011-2015		E, M	Y	N	Antonio Di Natale	Y	N	Y	Y		N
12.6 Ageing calibration (GBYP)	2014		E, M	Y	N	Antonio Di Natale	Y	N	Y	Y		N
13. Maturity (Spawning biomass)												
13.1. Western (NOAA)	1975-1981	ended	GOM	Y	N	Guillermo Diaz (NOAA)	Y	N	N	N	N	N
13.2 Mediterranean			M	Y	N	GBYP	Y	N	N	N	N	N
14. Other ecological data (spatial distribution, covariates for CPUE standardization, steepness, natural mortality rate, spawning locations etc.)												
14.1. Larval ecology (IEO)		ended	WM	Y	N	Diego Alvarez Berastegui		N	N	N	N	N
14.2. Habitat model				Y	N	Jean-Noel Druon		N	N	N	N	N

Table 2.6A. Summary of the observed assignment scores from otolith microchemistry and genetics datasets (labelled 'Probability Eastern Origin' from dataset 'Joint East West Mixing Data 15042019.csv'). Each point in those datasets consists of an observed assignment score, i.e. the assigned probability (between 0% and 100%) of that point being of Eastern origin. The table summarises (median, 5th and 95th percentiles) the observed assignment scores in each spatial strata. A mixture model is applied to these data (SCR/2018/133) to generate stock-of-origin "pseudo-observations" that are used in the conditioning of the operating models.

Type	Percentile	GOM	WATL	GSL	SATL	NATL	EATL	MED
Otolith microchemistry	5th	0%	1%	4%	14%	6%	48%	32%
	Median	**7%**	**27%**	**23%**	**87%**	**75%**	**87%**	**84%**
	95th	48%	97%	89%	99%	97%	98%	97%
Genetics	5th	0%	0%	0%	4%	9%	29%	40%
	Median	**0%**	**45%**	**56%**	**82%**	**96%**	**98%**	**99%**
	95th	94%	100%	100%	100%	100%	100%	100%

Table 2.6B. The sample size of stock of origin data by type (otolith micro-chemistry and genetics) and the 7 spatial strata. Note that data are available for the Gulf of Mexico and the Mediterranean but these were not used directly in the operating model but were used to identify a western and eastern stock signature for interpreting the assignment data in a mixture model (Carruthers and Butterworth 2018).

	WATL	GSL	SATL	NATL	EATL	Total	%
Otolith Chemistry	2518	864	257	315	251	4205	76.7%
Genetics	165	64	491	429	127	1276	23.3%

Table 2.6C. Seasonal-spatial coverage of the otolith chemistry assignment data (that have covariate information regarding age class and quarter; from dataset 'Joint East West Mixing Data 15042019.csv'). Orange shaded cells represent quarter-strata for which there are no stock of origin data available for the mixture model approach (i.e. no otolith chemistry data were available for these spatio-temporal strata).

Quarter	WATL	GSL	SATL	NATL	EATL	Total	%
1: Jan-Mar	369	0	39	0	0	408	9.7%
2: Apr-Jun	310	0	155	0	14	479	11.4%
3: Jul-Sept	1534	604	33	4	216	2391	56.9%
4: Oct-Dec	305	260	30	311	21	927	22.0%
Total	2518	864	257	315	251		
%	59.9%	20.5%	6.1%	7.5%	6.0%		

Table 2.6D. Seasonal-spatial coverage of the genetics assignment data (that have covariate information regarding age class and season; from dataset 'Joint East West Mixing Data 15042019.csv'). Orange shaded cells represent quarter-strata for which there are no stock of origin data available for the mixture model approach (i.e. no genetic data were available for these spatio-temporal strata). Note that data are available for the Gulf of Mexico and the Mediterranean but these were not used in the operating model.

Quarter	WATL	GSL	SATL	NATL	EATL	Total	%
1: Jan-Mar	0	0	105	0	0	105	8.2%
2: Apr-Jun	0	0	268	1	8	277	21.7%
3: Jul-Sept	109	43	53	193	118	516	40.4%
4: Oct-Dec	56	21	65	235	1	378	29.6%
Total	165	64	491	429	127		
%	12.9%	5.0%	38.5%	33.6%	10.0%		

3 BASIC OPERATING MODEL DYNAMICS

Overview

The current operating model (modifiable multi-stock model, 'M3' v6.5) is based on conventional age-structured accounting (e.g. Quinn and Deriso 1999, Chapter 8) which is common to stock assessment models such as Stock Synthesis 3 (Methot and Wetzel 2013), CASAL (Bull et al. 2012), Multifan-CL (Fournier et al. 1998) and iSCAM (Martell 2015).

The standard age-structured equations are complicated somewhat by the quarterly temporal structure, in which age increments and recruitment occur in a particular quarter. In this version of the model, spawning occurs for all stocks in quarter 2 (spawning in the Mediterranean for the Eastern stock and Gulf of Mexico and West Atlantic strata for the Western stock is thought to occur after a period of movement early in the year).

Equations

Numbers of individuals N, for stock s, in a model year y, in the first quarter m=1, age class a, and stratum r are calculated from individuals that have moved $\vec{N}$, in the previous year, final quarter (m=4) of the same age class, subject to combined natural and fishing mortality rate Z:

$$N_{s,y,m=1,a,r} = \vec{N}_{s,y-1,m=4,a,r} \cdot e^{-Z_{s,y-1,m=4,a,r}} \quad (3.1)$$

Where total mortality rate is calculated from annual natural mortality rate M, divided by the fraction of the year represented by the quarter t_m (i.e. 0.25), and fishing mortality rate F (per quarter), summed over all fleets f:

$$Z_{s,y,m,a,r} = t_m\, M_{s,a} + \sum_f F_{s,y,m,a,r,f} \quad (3.2)$$

Fishing mortality rate at age is derived from fishing mortality rate by length class F_l and the conditional probability of fish being in length class l, given age a (an inverse age-length key, LAK):

$$F_{s,y,m,a,r,f} = \sum_l F_{l,y,m,l,r,f} \cdot LAK_{s,a,l} \quad (3.3)$$

The fishing mortality rate at length is calculated from an index of fishing mortality rate I (calculated from dividing the value of the catch for that fleet by the value of the 'master index' in that year-quarter-stratum – a simple way to preserve scale), an estimated catchability coefficient q, a quarter and strata specific deviation F_D (constrained to mean 1) a quarter, strata and year specific deviation F_A (constrained to mean 1), and a length selectivity function s, by fleet:

$$F_{l,y,m,l,r,f} = q_f \cdot I_{y,m,rf} \cdot F_{D,m,r} \cdot F_{A,y,m,r} \cdot s_{f,l} \tag{3.4}$$

For most fleets, selectivity is calculated by a double-normal equation using the mean length L_l for a length class l:

$$s_{f,l} = \begin{cases} 2^{-\left(\frac{L_l - l_{max,f}}{\sigma_{f,A}{}^2}\right)^2} & L_l \leq l_{max,f} \\ 2^{-\left(\frac{L_l - l_{max,f}}{\sigma_{f,D}{}^2}\right)^2} & L_l > l_{max,f} \end{cases} \tag{3.5}$$

where $l_{max,f}$ is the fleet-specific length at maximum vulnerability, and $\sigma_{f,A}$ and $\sigma_{f,D}$ are parameters controlling the width of the ascending and descending limbs of the selectivity, respectively. Large values of $\sigma_{f,D}$ approximate a 'flat topped' logistic selectivity.

To ensure numerical stability and prevent the estimation of unrealistic values, the length at maximum vulnerability l_{max} and the two standard deviation parameters, σ_A and σ_D were derived from estimated parameters θ_{lmax}, θ_A and θ_D, respectively, and the longest length class L_{nl} (mean length of the maximum length class):

$$l_{max} = \rho_L + (\rho_U - \rho_L) \cdot \left(\frac{1}{20} + \frac{19}{20} \cdot \frac{e^{\theta_{lmax}}}{1+e^{\theta_{lmax}}}\right) \tag{3.6}$$

$$\sigma_A = 2\, l_{max} \cdot \left(\frac{e^{\theta_A}}{1+e^{\theta_A}}\right) \tag{3.7}$$

$$\sigma_D = (\rho_U - \rho_L) \cdot e^{\theta_D} \tag{3.8}$$

The ρ terms are the upper (ρ_U) and lower bounds (ρ_L) (lengths) for the truncation of the length selectivity function.

These parameterizations allow for unbounded estimation of the θ parameters. Each of these parameters has an extremely weak prior prescribed which still allows the model to converge in extreme cases where there is little or no data to inform a parameter. For example, if data suggest there is asymptotic (near logistic) selectivity, l_{max} tends to L_{nl} and there are no data above this length class to estimate the descending limb parameter θ_D.

In general, age or length structured models are much better informed by the data if at least one fleet selectivity either has the descending limb parameters fixed or can be assumed to have the form of a logistic ('flat topped') ogive. Without such a constraint, the declining frequency of older/longer classes can be attributed to either mortality rates or dome-shaped selectivity and this parameter confounding can lead to poorly defined estimation and numerical instability during fitting. In this case at least one fleet is assumed to have a 2-parameter logistic form for its selectivity function:

$$s_{f,l} = \frac{1}{1+e^{\left(l_{inf,f}-L_l\right)/\sigma_{S,f}}} \tag{3.9}$$

where l_{inf} is the inflection point (the length at 50% vulnerability) and σ_S is a slope parameter controlling how steeply selectivity increases with length. Similarly to the 3-parameter double-normal function, there is a reparameterization to ensure numerical stability during fitting:

$$l_{inf} = \rho_L + (\rho_U - \rho_L) \cdot \left(\frac{1}{20} + \frac{17}{20} \cdot \frac{e^{\theta linf}}{1+e^{\theta linf}}\right) \tag{3.10}$$

$$\sigma_S = (\rho_U - \rho_L) \cdot \left(0.005 + 0.11 \cdot \frac{e^{\theta S}}{1+e^{\theta S}}\right) \tag{3.11}$$

Again, the estimation of the θ parameters can be unbounded.

All selectivity θ parameters are assigned a vague normal prior with mean 0.

In the spawning quarter ms, and spawning strata rs, ages advance by one and recruitment occurs. The model includes a plus group which is the final age class n_a:

$$N_{s,y,ms,a,r} = \begin{cases} \vec{N}_{s,y,ms-1,a-1,r} \cdot e^{-Z_{s,y,ms-1,a-1,r}} & 1 < a < n_a \\ \vec{N}_{s,y,ms-1,a-1,r} \cdot e^{-Z_{s,y,ms-1,a-1,r}} + \vec{N}_{s,y,ms,a,r} \cdot e^{-Z_{s,y,ms,a,r}} & a = n_a \end{cases} \tag{3.12}$$

Recruitment is calculated based on stock-wide spawning stock biomass and recruits enter the model in proportion to spawning stock biomass in the spawning strata (Gulf of Mexico and West Atlantic for the West stock, the Mediterranean for the East stock) in the spawning season (quarter 2 for both stocks). The model does not force all the SSB back to the spawning stratum at the spawning time. It is not possible to estimate recruitment for only those fish that exist in the spawning stratum in the spawning season as that leads to numerical instability and can result in unrealistic estimates of recruits per spawner.

Recruitment (fish in their first year) is calculated from a Beverton-Holt stock recruitment relationship with fixed steepness:

$$N_{s,y,ms,1,rs} = \exp\left(\varepsilon_{R,s,y} - \sigma_{R,s}^2/2\right) \cdot \frac{\frac{4}{5} \cdot h_s \cdot R_{0,s} \cdot SSB_{s,y}}{\frac{1}{5} \cdot SpR_S \cdot R_{0,s} \cdot (1-h_s) + (h_s - 0.2) \cdot SSB_{s,y}} \cdot \nabla_{rs} \tag{3.13}$$

where ε_R is a random normal deviate with variance σ_R^2 and $\sigma_R^2/2$ is the bias correction to ensure that on average over years, recruitment strengths have a mean of 1. The ∇_{rs} term is the fraction of spawning stock biomass among designated spawning areas. In the East, there is only 1 area, the Mediterranean ($\nabla_{rs} = 1$), but in the West spawning can occur in either the Gulf of Mexico or the West Atlantic and recruits are distributed by ∇_{rs}.

Spawning stock biomass SSB, is calculated from moved stock numbers in the previous year, and quarter prior to spawning quarter ms, weight of individuals at age w, and the fraction of individuals mature at age m:

$$SSB_{s,y} = \sum_a \sum_r \vec{N}_{s,y,ms-1,a,r} \cdot e^{-Z_{s,y,ms-1,a,r}} \cdot w_{s,a} \cdot m_{s,a} \quad (3.14)$$

where weight is calculated from length at age *l*:

$$w_{s,a} = \alpha_s \cdot l_{s,a}^{\beta_s} \quad (3.15)$$

and the fraction mature at age is assumed to be a logistic function of age with parameters for the age at 50% maturity γ, and slope ϑ:

$$m_{s,a} = 1/\left(1 + e^{(\gamma_s - a)/\vartheta_s}\right) \quad (3.16)$$

Stock numbers for quarters that are not the first quarter of the year and are not the spawning quarter are calculated:

$$N_{s,y,m,a,r} = \vec{N}_{s,y,m-1,a,r} \cdot e^{-Z_{s,y,m-1,a,r}} \quad (3.17)$$

In each quarter, before mortality and recruitment, fish are moved according to an age-class-specific Markov transition matrix *mov* that represents the probability of a fish moving from statum *k* to stratum *r* at the end of the quarter *m*:

$$\vec{N}_{s,y,m,a,r} = \sum_k N_{s,y,m,a,k} \cdot mov_{s,m,\mathrm{a},k,r} \quad (3.18)$$

The movement matrix is calculated from a log-space matrix *lnmov* and a logit model to ensure each row (*k*) sums to 1:

$$mov_{s,m,\mathrm{a},k,r} = e^{lnmov_{s,m,\mathrm{a},k,r}} / \sum_r e^{lnmov_{s,m,\mathrm{a},k,r}} \quad (3.19)$$

Size/age stratification for movement models will initially be attempted for three age groups: 1-4, 5-8 and 9+ years (this will be kept the same for the Western Atlantic and the Eastern Atlantic/Mediterranean, but should be re-evaluated for the East as future data become available).

Due to the relatively incomplete coverage (over stocks, quarters and spatial strata) of electronic tagging data to be able to explicitly inform individual movements to/from each strata, a parsimonious gravity modelling approach was used to estimate movement (e.g. MAST Taylor et al., 2011, Carruthers et al., 2010). For a movement matrix of dimension n_{strata} x n_{strata}, rather than estimating a parameter for each possible transition (which would result in (n_{strata} -1) x n_{strata} parameters), the gravity model estimates only the attractivity *g* of each strata (n_{strata}-1 parameters) identically for all strata of departure. Unmodified, this is simply a spatial distribution model, mixing all tagged fish in every time step and redistributing them by fractions over all strata. There is however evidence of stock viscosity, where fish remain in the same strata over several time steps. This is particularly the case for spawning strata in spawning seasons, for example. The gravity model incorporates a single additional parameter per movement matrix (resulting in n_{strata} parameters per movement matrix) that is added to the positive diagonal (probability of staying in the same strata, i.e. when the ‘from strata’ *k* is the same as the ‘to strata’ *r*) to make fish more likely to stay in proportion to the attractivity of that strata:

$$lnmov_{s,m,2,k,r} = \begin{cases} g_{s,m,2,r} & k \neq r \\ g_{s,m,2,r} + e^{v_{m,2}} & k = r \end{cases} \tag{3.20}$$

In this equation, the subscript "2" refers to the second movement age-class (ages 5-8). Since the *lnmov* variables are used in a logit model to determine fractional probabilities across all strata, the estimation is indeterminate if all g terms are freely estimated. To solve this, the first strata in each row of the g terms is fixed at 0 (e.g. $g_{s,m,2,k,1} = 0$). This means that for each stock s, season m and age class a, the movement matrix (n_{strata} x n_{strata}) requires the estimation of n_{strata} parameters (n_{strata} -1 g parameters and one v parameter). The g and v parameters are assigned weak normal priors with mean 0 (with very low weight). Previous studies (Carruthers et al. 2011) have demonstrated that the simplified gravity modelling approach is estimable from spatial abundance indices alone, which means that the estimation will not fail for spatio-temporal strata that are sparse in terms of electronic tagging data.

For the two other movement age classes (a=1 and a=3), the g parameters and v parameters are calculated as penalized deviations from the age class 2 parameters. This allows the model to borrow information across the age classes easily when data are sparse (e.g. if data are available for age class 2 only, age classes 1 and 3 use age class 2 parameters; if age class 1 data only are available, age classes 2 and 3 borrow age class 1 parameters). For example, for age class 1:

$$g_{s,m,1,r} = g_{s,m,2,r} + \theta_{G,s,m,1,r} \tag{3.21}$$

Note that due to data sparsity it is not possible to estimate stock-specific viscosity v. It is still possible for East and West stocks to have radically different spatial distributions as determined by the g terms, but their seasonal propensity to stay in a given stratum is linked for the two stocks.

Movements from a stratum k to a stratum r that are considered to be implausible (e.g. from the Eastern Mediterranean to the Gulf of Mexico) are assigned a large negative number (essentially zero movement) in the corresponding cells in these movement matrices. For each stratum k, from which individuals can move, one value is assigned zero and all other possible movements are assigned an estimated parameter ψ (since rows must sum to 1, there is one less degree of freedom):

$$lnmov_{s,m,a,k,r} = \begin{cases} 1e^{-10} & no\ movement\ from\ k\ to\ r \\ 0 & first\ assigned\ possible\ movement\ from\ k\ to\ r \\ \Psi_{s,m,k,r} & other\ possible\ movements\ from\ k\ to\ r \end{cases} \tag{3.22}$$

Compared with spatially aggregated models, initialization is more complex for spatial models, particularly those that need to accommodate seasonal movement by age and may include regional spawning and recruitment. The equilibrium unfished age structure / spatial distribution cannot be calculated analytically. For any set of model parameters it is necessary to determine these numerically by iteratively multiplying an initial guess of age structure and spatial distribution by the movement matrix. The solution used here is to iterate the transition equations above given a fishing mortality rate averaged over the first five years of model predictions, until the spatial distribution of stock numbers converges for each of the quarters.

Prior to this iterative process an initial guess at the spatial and age structure of stock numbers $\widehat{N}$ is made based on the movement matrix and natural mortality rate at age M:

$$\hat{N}_{s,m,a,r} = \bar{R}_s \cdot \mathrm{e}^{-\sum_1^{a-1} M_{s,a}} \cdot \sum_k \frac{1}{n_r} \cdot mov_{s,m,a,k,r} \tag{3.23}$$

In the years 1864 to 1964, the model does not predict catches from estimates of fishing mortality rate and instead this historical 'spool-up' phase removes catches from the model without error. These historical catches are reconstructed for each age-class and spatio-temporal strata. This is intended to account for meaningful landings prior to 1965 that are not accompanied by sufficient length composition data to estimate fleet selectivities in a conventional statistical catch-at-length model that is applied for the years 1965 – 2016.

Stock numbers for historical years (e.g. 1864-1964) are calculated using the same equations as model years (e.g. 1965 – 2016). The exception is that rather than using effort data, selectivities and an inverse age-length key, fishing mortality rate at age is derived from mean historical catches and the assumption is made that these are taken without error in the middle of the time step with natural mortality rate occurring both before and after fishing:

$$F_{i=1,m,a,r,f} = \begin{cases} -\log\left(1 - \frac{\bar{C}_{m,a,r,f}}{\hat{N}_{s,m,a,r} e^{-(t_m M_{s,a})/2}}\right) & i = 1 \\ -\log\left(1 - \frac{\bar{C}_{m,a,r,f}}{\vec{N}_{s,y-1,n_m,a,r}\, e^{-(t_m M_{s,a})/2}}\right) & i > 1, m = 1 \\ -\log\left(1 - \frac{\bar{C}_{m,a,r,f}}{\vec{N}_{s,y,m-1,a,r} e^{-(t_m M_{s,a})/2}}\right) & i > 1, m > 1 \end{cases} \tag{3.24}$$

where *i*=1 is the first year and calculates fishing mortality rates from asymptotic numbers $\hat{N}$.

The following selections apply for the Base Case OM:

Beverton-Holt with fixed steepness (see Section 9A for a detailed account of the stock-specific recruitment assumptions).
Recruitment calculated from stock-wide SSB. Recruits are subsequently placed in the MED strata (Eastern stock) or in the GOM or WATL strata in proportion to the relative SSB in each of those strata (Western stock).
Gravity movement model used to calculate a Markov movement matrix by quarter, stock and age class (e.g. Carruthers et al. 2011).

Alternative options

Recruitment calculated from spawning strata SSB
Markov movement matrix by quarter and stock (note: the gravity model chosen for the Base Case is a specific case of the more general Markov model).

Fleet structure and exploitation history

Table 3.1. Fishing fleets included in the operating model, based on the selectivities of fleets active historically in the Atlantic. Catch and length composition by fleet are prepared by year, quarter, and strata from the revised CATDIS (Kimoto et al. (in press)) and screened Task 2 Size.

The columns of "Strata" and "Quarter" list the strata and quarters that have catches in the revised CATDIS (Kimoto et al. (in press)).

No.	Name	Gear	Flag	Strata	Quarter	Start-End	Selectivity type/Bounds on fleet selectivity
1	LLOTH	LL	All except Japan	All	All	1964-2016	DN; 12.5 – 412.5
2	LLJPNold	LL	Japan	All	All	1964-2009	DN; 12.5 – 362.5
3	BBold	BB	EU.Spain, EU.France	Bay of Biscay (EATL)	2,3,4	1960-2006	DN; 12.5 – 237.5
4	BBnew	BB	EU.Spain, EU.France	Bay of Biscay (EATL)	2,3,4	2007-2016	DN; 12.5 – 287.5
5	PSMEDold	PS	All except EU.Croatia	MED	1,3,4	1960-2008	DN; 12.5 – 362.5
6	PSMEDoldQ2	PS	All except EU.Croatia	MED	2	1960-2008	DN; 12.5 – 312.5
7	PSMEDnew	PS	All except EU.Croatia	MED	All	2009-2016	DN; 12.5 – 362.5
8	PSNOR	PS	Norway	NATL, EATL	3,4	1964-2016	DN; 112.5 – 337.5
9	PSHRV	PS	EU.Croatia	MED	All	1991-2016	DN; 12.5 – 287.5.
10	PSWold	PS	USA, Canada	ATW	2,3,4	1964-1984	DN; 12.5 – 337.5
11	PSWnew	PS	USA, Canada	ATW	All	1985-2015	DN; 62.5 – 312.5
12	TPold	TP	EU.Spain, Morocco, EU. Portugal	St. Gibrartar (SATL, MED)	All	1964-2011	DN; 37.5 – 337.5
13	TPnew	TP	EU.Spain, Morocco, EU. Portugal	St. Gibrartar (SATL)	2,3,4	2012-2016	DN; 37.5 – 362.5
14	RRCAN	RR	Canada	ATW, GSL	All	1964-2016	Logistic; 12.5 – 362.5
15	RRUSAFS	RR	USA	ATW	2,3,4	1964-2016	DN; 12.5 – 162.5
16	RRUSAFB	RR	USA	ATW	2,3,4	1964-2016	DN; 62.5 – 362.5
17	OTH	other	other	All	All	1964-2016	DN; 12.5 – 362.5
18	LLJPNnew	LL	Japan	WATL, SATL, NATL, EATL	All	2010-2016	DN; 62.5 – 312.5

* Selectivity type DN means double normal. Bounds are the middle point in a length bin (width of length bin is 25cm) that are the lowest and highest for which lengths have be observed for each fleet.

<u>Base Case</u>

An 18-fleet model based on the definitions of Table 3.1.

<u>Alternative options</u>

A proposal for alternatives may need to be developed and reviewed in the future.

4 MANAGEMENT OPTIONS

Notes:

a) The following section is included to provide some suggestions on possible structures to Candidate MP (CMP) developers of management options to be included in the CMPs. The suggestions offered are illustrative – clearly they will need to be discussed with stakeholders as the process develops.

b) As above, for convenience they have been set out in Base Case and alternative option form. It is recommended that many of the choices for the final CMP options be made later in the process, so that they can be informed by results from trials which show the pro/con trade-offs amongst such options.

c) The specifics of future CMPs will be left to their developers to determine based on the results of their application to the finalised trials. However, those candidates need to take account of the broad desired characteristics/limitations set out below.

d) HCRs need not to explicitly include reference points

e) In March 2019 Panel 2 met and began setting their recommendation on what their objectives would be for the MSE. They also provided some guidance on preferences for some management options. This advice will be incorporated below where applicable.

Spatial strata for which TACs are set

<u>Base Case</u>

Conventional West and East/Mediterranean regions (Figure 1.1):

West: strata 1-3 (GOM, WATL, GSL)
East: strata 4-7 (SATL, NATL, EATL, MED)

<u>Alternative options</u>

Various possibilities exist. For example, separating out central Atlantic strata.

A more complex 10 strata option could separate both the central Atlantic and the Caribbean (CAR):
West: strata 1-4 (GOM, CAR, WATL, GSL).
East+Med: strata 5-10 (SCATL, NCATL, NEATL, EATL, SEATL, MED).

However, it is suggested that consideration of such more complex options be postponed to a "second round".

Management period length for the setting of TACs

The management period is the number of years a TAC is set before the management procedure is used again to calculate a new TAC. The length of the management period must be set when implementing a CMP, managers should be consulted on desirable management period lengths to make certain the period length is suitable for other management actions needed beyond TAC setting (e.g. fleet allocation planning, consultations, etc.). Panel 2 has indicated they would prefer to see a 3-year management cycle, similar to what is currently used in Bluefin Tuna management plans (Anon., 2019).

Base Case

Every three years both a West Area TAC and an East+Med Area TAC are set.

Alternative options

i) Every two years
ii) Every four years

Upper limits on TACs

The "upper limits on TAC" allows CMP developers to put restrictions on the maximum level the TAC can achieve in the running of the CMPs.

Base Case

No upper limit

Alternative options

West	e.g. 5 000, 6 000 tons
East +Med	e.g. 30 000, 40 000 tons

Minimum extent of TAC change

The "minimum extent of TAC change" allows the CMP developer to avoid having small changes in TAC between management periods by setting a value and implementing the TAC change only if the extent of the change is at least equal to the set value. Managers might find this desirable to avoid having "trivial" increases or decreases being incorporated in management recommendations. This restriction should be used only if it is requested by managers; otherwise it should be kept at no minimum as is the case in the base case below.

Base Case

No minimum.

Alternative options

West	e.g. 200, 300 tons
East +Med	e.g. 1 000, 2 000 tons

Maximum extent of TAC change

The “maximum extent of TAC change” allows CMP developers to limit the maximum allowed increase or decrease in TAC between management periods. This may help to achieve TAC stability between consecutive management periods. CMP developers can also incorporate a “maximum extent of TAC change” in the actual design of their CMP, so there are two ways to incorporate this type of constriction. Panel 2 has provided several values of maximum extent of TAC change they would like to see (Anon 2019). The values they would like to see are 20%, 30%, 40%, and outcomes where no restriction in TAC is implemented.

Base Case

West	No restriction
East +Med	No restriction

Alternative options

West	20%, 30%, 40%
East + Med	20%, 30%, 40%

Note that developers of candidate CMPs should consider including options which:

a) Override such restrictions on the maximum extent of TAC reduction if abundance indices drop below specified thresholds.

b) Allow for greater TAC increases (in terms of tonnage) if a TAC has had to be reduced to a low level and indices confirm subsequent recovery.

Technical measures

No “technical measures” are currently being implemented in the MSE. Size restrictions might be considered on a fleet and/or spatial stratum basis. However, for a “first round” it is suggested that these not be included explicitly, but instead be considered to be implemented implicitly through the selectivity prescriptions for future catches by the various fleets which are set out under Section 6 below.

5 RECRUITMENT AND SPATIAL DISTRIBUTION SCENARIOS IN THE OPERATING MODEL

See also Section 9 of this document for additional detail on specified trials.

Recruitment deviations are estimated in two-year time blocks (i.e. the same deviation in the two years). This is necessary because the model is fitted to length-composition data (without age composition data). Due to variability in growth there are multiple age classes in each length class and, therefore, adjacent cohorts have poorly informed relative strengths. In traditional statistical-catch-at-length models this often leads to strong negative correlation between adjacent years in estimates of annual recruitment deviations, a poorly defined estimation problem and numerical instability of parameter estimation.

Western stock

Functional forms fitted to assessment outputs for the years 1965+

a) Beverton-Holt with steepness *h* fixed to 0.6 until 1974, then *h* fixed to 0.9 as of 1975. Two values of R_0 (unfished recruitment) are estimated, one for each time period (mimics the hockey-stick approach after 1975 used in past assessments).
b) Beverton-Holt with steepness *h* fixed to 0.6. A single value of R_0 is estimated.

Eastern stock

Functional forms fitted to assessment outputs for the years 1965+

a) Beverton-Holt with h = 0.98. Two values of R_0 (unfished recruitment) are estimated, for the periods 1950-1987 and 1988+ respectively.
b) Beverton-Holt with steepness *h* fixed to 0.7. A single value of R_0 is estimated (to include scenarios where recruitment overfishing could occur to test a CMP's ability to react adequately to this).

Note that, for the Eastern stock, 1965-1987 represents "low" recruitment and 1988+ "high" recruitment.

Future regime shifts

Western stock

a) None
b) After 10 years of projection, there is a change back to the pre-1974 stock-recruitment relationship (applicable only to OMs with a change in 1975).

Eastern stock

a) None
b) After 10 years there is a change back to the 1965-1987 relationship (applicable only to OMs with a change in 1988).

Statistical properties of recruitment deviations:

Base Case

For historical years, log recruitment deviations ε_R (also called "residuals") are estimated in two-year time blocks *t*, starting from a lognormal prior with standard deviation σ_R = 0.354. This value is calculated from an annual value of 0.5 – (a common value obtained from the RAM legacy database) using the equation for standard error: $0.354 = 0.5/2^{0.5}$.

Treating these blocks as contiguous (similarly to adjacent years for the indices below) estimates of autocorrelation $\rho_{R,2}$ and standard deviation $\sigma_{R,2}$ can be estimated for each stock *s*, post model conditioning (not within model fit) for greater numerical stability:

$$\rho_{R,s,2} = \frac{\sum_1^{n_t-1} \varepsilon_{R,s,t,}\varepsilon_{R,s,t+1}}{\sum_1^{n_t} \varepsilon_{R,s,t}{}^2} \tag{5.1}$$

The standard deviation σ_R is calculated by:

$$\sigma_{R,s,2} = \sqrt{\frac{1}{n_t - 1} \sum_1^{n_t} \left(\varepsilon_{R,s,t} - \bar{\varepsilon}_{R,s}\right)^2} \tag{5.2}$$

For future projection years, annual recruitment deviations (1-year blocks) for each stock are simulated from lognormal distributions with variance and autocorrelation derived from the historical residuals for that stock. It is necessary therefore that the estimated statistical properties for 2-year blocks (autocorrelation $\rho_{R,s,2}$ and standard deviation $\sigma_{R,s,2}$) are converted to annual equivalents ($\rho_{R,s,1}$ and $\sigma_{R,s,1}$).

For future projection years and for each stock separately, the annual variance in recruitment deviations $\sigma^2_{R,s,1}$ and annual first order autocorrelation in recruitment deviations $\rho_{R,s,1}$ can be derived analytically from 2-year blocked estimates of variance $\sigma^2_{R,s,2}$ and 'lag-1' $\rho_{R,s,2}$ autocorrelation by inverting the relationships:

$$\sigma^2_{R,s,2} = \sigma^2_{R,s,1}\left(1 + \rho_{R,s,1}\right)/2 \tag{5.3}$$

$$\rho_{R,s,2} = \rho_{R,s,1}\left(1 + \rho_{R,s,1}\right)/2 \tag{5.4}$$

It follows that $\sigma_{R,s,1}$ is calculated by:

$$\sigma^2_{R,s,1} = 2\sigma^2_{R,s,2}/\left(1 + \rho_{R,s,1}\right) \tag{5.5}$$

If $\rho_{R,s,2}$ is positive, $\rho_{R,s,1}$ is given by:

$$\rho_{R,s,1} = \frac{\left(-1 + \sqrt{1 + 8 \cdot \rho_{R,s,2}}\right)}{2} \tag{5.6}$$

Since equation 5.4 is quadratic, there are two solutions for $\rho_{R,1}$ given a negative value of $\rho_{R,2}$ (Figure 5.1).

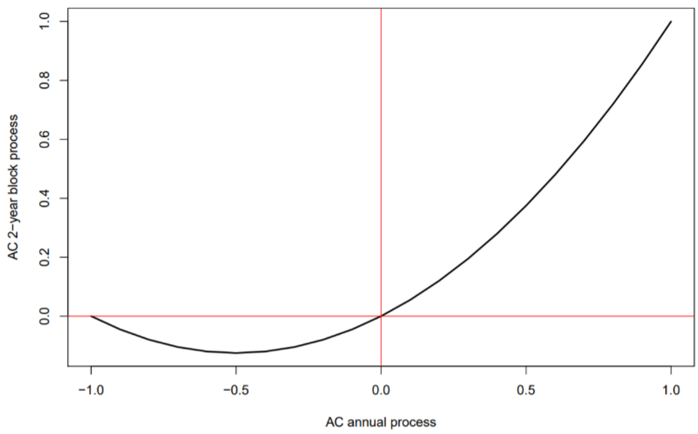


Figure 5.1. $p_{R,s,2}$ as a function of $p_{R,s,1}$ (courtesy of C. Fernandez)

In such cases, the larger value of $\rho_{R,s,1}$ (i.e. the one of smaller absolute magnitude) is used. If $\rho_{R,s,2}$ is less than -0.125, there is no solution to Equation 5.4, so the value corresponding to the lower possible value of $\rho_{R,s,2}$, i.e. $\rho_{R,s,1}$ = -0.5, is used. Note that this can occur because of higher lag AC effects; the model used here assumes that there are no AC effects beyond a 1-year lag.

For the simulation of future recruitment, stochastic residuals are generated by first sampling uncorrelated normal recruitment residuals for each projection year *y* and simulation *j*:

$$\varepsilon_{R,U,s,y,j} \sim N\left(0, \sigma^2_{R,s,1}\right) \tag{5.6}$$

For the first projection year immediately after the last year of model conditioning the autocorrelated residual error is calculated from the last 2-year-block residual in time T:

$$\varepsilon_{R,s,y,j} = \rho_{R,s,1}\varepsilon_{R,s,T} + \sqrt{1-{\rho_{R,s,1}}^2}\,\varepsilon_{R,U,s,yj} - \left(1-\rho_{R,s,1}\right)\left(\sigma^2_{R,s,1}\right)/2 \tag{5.7}$$

For all subsequent projection years autocorrelated residuals are calculated by:

$$\varepsilon_{R,s,y,j} = \rho_{R,s,1}\varepsilon_{R,s,y-1,j} + \sqrt{1-{\rho_{R,s,1}}^2}\,\varepsilon_{R,U,s,y,j} - \left(1-\rho_{R,s,1}\right)\left(\sigma^2_{R,s,1}\right)/2 \tag{5.8}$$

Possible future spatial distributional changes (movement)

Plausible options for future distributional changes (in relative terms) in response to changes in abundance and to possible environmental changes will be considered in a "second round".

6 FUTURE CATCHES

I) Base Case

a) Future catches will be taken to equal future TACs (up to a maximum harvest proportion U_{max} = 90% in each stratum-quarter).
b) The catch by fleet in 2017 was calculated from ICCAT Task 1 (Table 6.1 below).
c) The allocation of future catches amongst fleets will be set equal to the average decided by the Commission for the period 2018-2020 (Table 6.1 below).
d) The spatial distribution (Section 1) of these future catches will be set equal to the average over 2014-2016 (last three years of model-estimated spatio-temporal catch distribution).
e) The selectivity function for each fleet for the most recent period for which this is estimated in the conditioning of the operating model in the trial concerned will be taken to apply for all future years.

f) TAC and catches are fixed into projection model (2017 and after) based on TACs for 2017-2019 and TACs as reflected in the recommendations: [Rec. 17-06], [Rec.17-07], and [Rec. 18-02] (for catch reconstruction methods see SCRS/2019/133).

Table 6.1. Recent allocations (tons) by fleet

No	Fleet	Area (East, Med, West)	Country	2017	2018	2019	2020
1	LLOTH	Med	all others except Japan	1183.780	1809.660	2068.916	2310.204
1	LLOTH	East	all others except Japan	303.116	344.944	471.857	548.716
1	LLOTH	West	all others except Japan	223.705	288.546	288.546	288.546
18	LLJPN	East	Japan	1910.610	2279.000	2528.000	2801.000
18	LLJPN	West	Japan	345.827	407.480	407.480	407.480
4	BBnew	East	France and Spain in Bay of Biscay	867.174	1063.048	1176.124	1298.459
7	PSMEDnew	Med	All PS except Croatia in Med	13883.699	16293.163	18652.732	20837.709
8	PSNOR	Med	Norway	47.140	97.782	224.711	282.064
9	PSHRV	Med	Croatia	586.634	687.673	760.820	839.954
11	PSWnew	West	USA,Canada	0	0	0	0
13	TPnew	East	Spain,Morocco and Portugal	3362.447	4141.503	4616.081	5118.636
14	RRCan	West	Canada	344.120	427.690	427.690	427.690
15	RRUSAFS	West	USA	197.541	261.130	261.130	261.130
16	RRUSAFB	West	USA	597.108	878.632	878.632	878.632

II) Alternative options

Clearly many are possible, but are probably best delayed until a "second round". Were substantial changes to eventuate during a period when a CMP was in operation, this would in any case likely necessitate re-tuning and re-testing or a modified CMP.

The impacts of possible IUU catches should perhaps be considered under robustness trials (see Section 9 below).

III) Equations for calculating projected catch in numbers by stock, fleet, spatial strata, year and quarter based on TACs specified in weight by management area.

Management procedures provide TAC advice in weight by East and West management area. In order to project the simulated stocks accounting for feedback from these TAC recommendations they must be converted to an estimate of fishing mortality rate at age for each fleet (e.g. LLJPN), spatial strata (e.g. West Atlantic), year and quarter. These catches cannot exceed the maximum available number of fish in any spatial strata at any time, they must be allocated across fleets in a plausible way, the TACs must sum to the management area totals by weight and optionally, there should be the ability for missed quota in one fleet to be reallocated (traded) to other fleets where catches may still be possible.

Under MSE projections (after 2017), TACs by East-West management area are distributed among fleets according to a management-area-specific fraction of the TAC among fleets *A*, a fleet specific seasonal and spatial fraction *D*, and the predicted age composition of catches $\hat{V}_{s,y,m,a,r,f}$

$$C_{s,y,m,a,r,f} = \begin{cases} A_{f,west} \cdot D_{f,m,r} \cdot TAC_{y,west} \cdot \hat{V}_{s,y,m,a,r,f,west} & r \leq 3 \\ A_{f,east} \cdot D_{f,m,r} \cdot TAC_{y,east} \cdot \hat{V}_{s,y,m,a,r,f,east} & r \geq 4 \end{cases} \quad (6.1)$$

where *west* is the west management area, *east* is the east management area, *A* are fractions (sum to 1 for each management area) of the 2020 allocations (Table 6.1), *D* terms are fractions (sum to 1 for each fleet) calculated from the model predicted fishing mortality rates over the last three historical years (2015-2017), and

$$\hat{V}_{s,y,m,a,r,f,west} = \frac{\vec{N}_{s,y,m,a,r} \cdot S_{f,a}}{\sum_m \sum_a \sum_{r=1}^{3} \vec{N}_{s,y,m,a,r} \cdot S_{f,a}} \quad (6.2)$$

$$\hat{V}_{s,y,m,a,r,f,east} = \frac{\vec{N}_{s,y,m,a,r} \cdot S_{f,a}}{\sum_m \sum_a \sum_{r=4}^{7} \vec{N}_{s,y,m,a,r} \cdot S_{f,a}} \quad (6.3)$$

where $S_{f,a}$ is the fleet selectivity at age.

Equations 6.1 – 6.3 keeps both the allocations among fleets and the spatio-temporal distribution of catches by fleet constant, whilst allowing for varying catch at age in response to availability of numbers at age. Dynamic spatio-temporal fishing distribution (*D* by projection year) would require a fleet dynamics model that has not been developed for Atlantic bluefin tuna.

It is possible for MPs to prescribe catches that are higher than the available stock biomass (are not possible). In these cases, the harvest rate *U* exceeds 1. *U* is calculated as the predicted catch weight for the fleet C_w divided by the total biomass *B* across all fleets in that year, quarter and spatial strata:

$$U_{y,m,r,f} = C_{W,y,m,r,f} / B_{y,m,r,f} \quad (6.4)$$

where catch weight C_W is calculated by the sum product of the catches at age (*C* of Equation 6.1) and weight at age.

To avoid catches exceeding available biomass a somewhat arbitrary maximum harvest rate U_{max} is used (the default value is 90%).

In cases where $U_{y,m,r,f} > U_{max}$ there are two options that have been currently implemented in the ABTMSE R framework: (1) remove these catches and (2) reallocate these catches. Reallocation is selected as the default setting (it can be switched off) in order to approximate quota trading among fleets which may be expected to occur when quotas cannot be caught by one or more fleet.

The reallocation rule redistributes catches in excess of the maximum harvest rate C_{Umax}, across all fleet-spatial strata (*f*, *r*) (in the same management area) that are below the U_{max} constraint:

$$C_{Umax,y,m,r,f} = \begin{cases} C_{W,y,m,r,f} \cdot \left(U_{y,m,r,f} - U_{max}\right)/U_{y,m,r,f} & U_{y,m,r,f} \geq U_{max} \\ 0 & U_{y,m,r,f} < U_{max} \end{cases} \tag{6.5}$$

$$\vec{C}_{W,y,m,r,f} = \begin{cases} C_{W,y,m,r,f} - C_{Umax,y,m,r,f} & U_{y,m,r,f} \geq U_{max} \\ C_{W,y,m,r,f} + C_{D,y,m,r,f} \cdot \sum_f C_{Umax,y,m,r,f} & U_{y,m,r,f} < U_{max} \end{cases} \tag{6.6}$$

Where the reallocated catches by weight $\vec{C}_W$ either remove catches above U_{max} (where $U > U_{max}$) or redistribute the total C_{Umax} in proportion to the catches of fleets below the U_{max} constraint C_D given by:

$$C_{D,y,m,r,f} = \frac{\theta_{C,y,m,r,f} C_{W,y,m,r,f}}{\sum_f \theta_{C,y,m,r,f} C_{W,y,m,r,f}} \tag{6.7}$$

where θ_C is 1 where $U < U_{max}$ and 0 otherwise.

Note that when all fleets exceed the U_{max} constraint, Equation 6.6. ensures that in all cases, catches above the constraint are removed without reallocation. This reallocation rule is simple, numerically robust and does not require additional fleet dynamics models. The relatively fine temporal resolution of the operating model (quarterly) means that although it is theoretically possible for C_{Umax} catches to be reallocated to other fleets such that the new catches $\vec{C}_W$ then exceed U_{max}, these catch reallocations are generally very small, occur very progressively and consequently, this rarely occurs.

7 GENERATION OF FUTURE DATA FOR INPUT TO CANDIDATE MANAGEMENT PROCEDURES

Note that these are for use as input to CMPs, so need to be chosen carefully from a set of those highly likely to be regularly (i.e. annually) available. This is because the application of a CMP relies on these data being available in this way, so difficulties can (and have in other cases) obviously arise should they fail to do so. Though any CMP proposed should include a rule to deal with the absence of just one future value from an input series, any more than that would require re-tuning and re-testing of a modified CMP, ideally this is avoided given the associated extra costs.

Consideration is also needed of the "delays" associated in such data becoming available for input to an CMP. When a TAC is set for year y, the last year of finalised data at the time of setting the TAC is y-2 for surveys and CPUE indices and y-3 for catch data. For years y-2 and y-1 the catch is assumed to be equal to the TAC.

TAC implementation year = y
Commission decision year = y-1
SCRS advice year = y-1
CPUE/Independent last data year = y-2
Therefore CPUE/independent data would have to be finalized up until year y-2 and provided to SCRS meeting that takes place in Sept of year y-1.

In the closed loop projections of the ABTMSE package, the most recent (last available) index observation of the simulated dataset (dset) is y-2, and the most recent (last available) catch observation is y-1.

I) Base Case

Indices are simulated in projections based on the operating model-specific fit to the indices (or values specified during the February 2020 MSE technical team meeting), including lognormal error (STD) and lag-1 autocorrelation in residuals (AC) (Table 7.1)

Table 7.1. Index selection and simulation for potential inclusion in CMPs

Index	Details	Selectivity	Selected for CMPs	STD value*	AC*
Canada GSL RR	1984-2016, Q3, GSL	14: RRCAN	No	-	-
Canada SWNS RR	1988-2016, Q3, W Atl	14: RRCAN	Yes	OM-estim	OM-estim
US RR 66-114	1993-2016, Q3, W Atl	15: RRUSAFS (50 –125cm)	Yes	OM-estim	OM-estim
US RR 115-144	1993-2016, Q3, W Atl	15: RRUSAFS (100 – 150cm)	Yes	OM-estim	OM-estim
US RR 177+	1993-2016, Q3, W Atl	16: RRUSAFB (175cm+)	Yes	OM-estim	OM-estim
JPN LL West2	2010-2016, Q4, W Atl	18: LLJPNnew	Yes	OM-estim	0
US GOM PLL2	1992-2016, Q2, GOM	1: LLOTH	Yes	OM-estim	OM-estim
GOM LAR SUV	1977-2016 (gaps 1979-1980, 1985), Q2, GOM	SSB	Yes	OM-estim	OM-estim
CAN ACO SUV	1994-2016, Q3, GSL	14: RRCAN (150cm+)	No**	OM-estim	OM-estim
MOR POR TRAP	2012-2016, Q2, S Atl	13: TPnew	Yes	0.45	0.2
JPN LL NEAtl2	2010-2016, Q4, N Atl	18: LLJPNnew	Yes	0.45	0
FR AER SUV2	2009-2016 (gap 2013), Q3, Med	15: RRUSAFS	Yes	0.8	0.2
GBYP AER SUV BAR	2010-2015 (gaps 2012, 2014, 2016), Q2, Med	SSB	Yes	0.45	0.2
MED LAR SUV	2001-2015 (gaps 2006-2011), Q2, Med	SSB	Yes	OM-estim (years 2012-2016)	OM-estim (years 2012-2016)

* OM-estim means OM-specific estimates from the index residuals of the corresponding OM fit (see VI below). When the estimated AC is < 0, it is fixed at AC=0 for the projections with that OM.

** The Canadian acoustic survey index will be simulated in the BFT MSE package, but should not be used in CMPs at this time because of uncertainty about calibration in the change to a different vessel..

These generated indices must maintain the same methods for their construction in future years; changes to how the indices are constructed would not be allowed during an accepted MP's period of use.

Some CMPs may use annual catch (removals) observations in addition to the simulated indices. For the base case, simulated annual catch data are assumed to have been observed with error and a log-normal CV of 2.5% (95% of observations are within +/- 5% of the true catch that was taken).

While not all of the indices are being used for projections, this does not imply that they should be discontinued or not updated and reviewed by the SCRS BFT species group. It will also be important to have these updated indices for model re-conditioning when the MSE is re-run (which would be done at a set interval to be determined by the Commission).

II) Alternative options

Catch-at-length series could also be considered for inclusion as CMP inputs, but raise further technical complications regarding the specification of how they are generated, so have been deferred from consideration until a "second round".

A 'perfect information' observation error model (suitable for CMP testing) that includes essentially no observation error or autocorrelation in indices, or observation error in catches.

A 'bad' observation error model that is the same as the base-case but includes the estimated non-linearity in indices with biomass, and a 10% lognormal CV in annual catch data.

III) Relationships with abundance

For base case trials, abundance indices are taken to be linearly proportional to the appropriate component of the underlying model biomass in the spatial stratum and quarter concerned. Possible alternatives to this are considered under Robustness trials (see Section 9 below).

IV) Statistical properties

<u>Base Case</u>

Residuals are taken to be log normally distributed; The standard deviation and lag-1 autocorrelation of the log residual error (specified in Table 7.1) are invariant over time.

<u>Alternative options</u>

a) Fix σ values for all trials based on a central trial from the Reference set (see Section 9 below).
b) If additional CPUE indices to those initially suggested are included, residuals need to be examined for correlation, with this being taken into account in generating future values.
c) In a "second round", take correlations amongst indices into account.

V) Other aspects

Note that consideration should at some stage also be given to new data types that are only now becoming available (e.g. genetic tagging). These will not at this stage have been collected over a sufficient length of time to be able to serve as CMP inputs, but the overall testing process can be used to provide insight into their potential future utility.

VI) Equations for the simulation of indices

The fishery dependent CPUE indices and some of the fishery independent indices identified in Table 7.1 correspond to the length selectivity of a fleet and are assumed to correspond to either vulnerable numbers or vulnerable biomass. Most of the fishery-independent indices are assumed to correspond to spawning stock biomass. For all indices, the observed index and the model predicted index are specific to a particular quarter and spatial strata (Tables 2.1 and 2.2). To simplify the algebra of this section - which focuses on simulating indices in the future according to their statistical properties - equations are provided for a single index and its corresponding quarter and spatial strata (represented by a single subscript i). For a more detailed breakdown of the calculation of model predicted indices see Section 8 below.

When an operating model is fitted, a maximum likelihood estimate of the model predicted index $\hat{I}$, is calculated for historical years where there are observations I. The log residual is assumed to be normally distributed and is calculated by:

$$\varepsilon_{i,y} = ln(I_{i,y}) - ln(\hat{I}_{i,y}) \tag{7.1}$$

For annual indices (without gaps), the first order (lag-1) autocorrelation of residuals ρ is calculated by:

$$\rho_i = \frac{\sum_1^{n_y-1} \varepsilon_{i,y,}\varepsilon_{i,y+1}}{\sum_1^{n_y} \varepsilon_{i,y}{}^2} \tag{7.2}$$

The standard deviation σ is calculated by:

$$\sigma_i = \sqrt{\frac{1}{n_y - 1} \sum_1^{n_y} \left(\varepsilon_{i,y} - \bar{\varepsilon}\right)^2} \tag{7.3}$$

After calculating these statistics based on the fit to historical data, the future errors must be simulated for each index. There are two situations that must be covered: (1) no observations of the index after the period of model fitting and (2) observations of the index that have occurred after model fitting and whose values are already known.

The first situation is the simplest. For a given simulation j, for all years after the last year of model fitting, uncorrelated residuals are drawn from a normal distribution with mean 0 (no bias correction was applied in model fitting):

$$\varepsilon_{U,i,y,j} \sim N(0, \sigma_i^2) \tag{7.4}$$

For the first projection year immediately after the last year of model conditioning, the autocorrelated residual error is calculated by:

$$\varepsilon_{i,y,j} = \rho_i \varepsilon_{i,y-1} + \sqrt{1 - \rho_i{}^2}\, \varepsilon_{U,i,yj} - (1 - \rho_i)(\sigma_i^2)/2 \tag{7.5}$$

For all subsequent projection years autocorrelated residuals are calculated by:

$$\varepsilon_{i,y,j} = \rho_i \varepsilon_{i,y-1,j} + \sqrt{1-\rho_i{}^2}\,\varepsilon_{U,i,y,j} - (1-\rho_i)(\sigma_i^2)/2 \tag{7.6}$$

In the second situation where index observations have occurred after model fitting, residuals must be calculated for those observations in order to calculate projected autocorrelation in residuals correctly. Since the residual error of these observations is now based on projected biomass subject to simulation-specific process errors, these residuals are calculated specific to each simulation *j*:

$$\varepsilon_{i,y,j} = ln\left(I_{i,y}\right) - ln\left(\hat{I}_{i,y,j}\right) \tag{7.7}$$

Then, for subsequent projection years after the last observation (2019 or before), error terms are calculated from equation 7.6.

8 PARAMETERS AND CONDITIONING OF OPERATING MODELS

Fixed parameters

Table 8.1. The parameters that are fixed (user specified)

Parameter	Number of parameters	Symbol
Steepness	$\geq n_{stocks}$	*h*
Maximum length	n_{stocks}	*Linf*
Growth rate	n_{stocks}	*K*
Age at length zero	n_{stocks}	t_0
Natural mortality rate at age	$n_{ages} \cdot n_{stocks}$	*M*
Selectivity of at least one fleet	*2-3*	*Θ*
Maturity at age	$n_{ages} \cdot n_{stocks}$	*mat*

Table 8.2. Parameter values of Base Case and alternative options

Parameter	Western stock		Eastern stock
Steepness (Bev. -Holt)	0.6 changing to 0.9 in 1975 0.6		0.98 0.7
Type	***Richards growth (****Ailloud et al., 2017)*		***von Bert. Growth*** *(Cort, 1991)*
A2	34		
***L1* (cm)**	33.0		
***L2* (cm)**	270.6	***Linf (cm)***	318.8
K	0.22	***K***	0.093
p_0	-0.12	***t0***	-0.97

Natural mortality rate at age (Eastern and Western)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15+**
High	0.38	0.30	0.24	0.20	0.18	0.16	0.14	0.13	0.12	0.12	0.11	0.11	0.11	0.10	0.10
Low	0.36	0.27	0.21	0.17	0.14	0.12	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.08	0.07

Selectivity of at least one fleet	Fleet#14 ‘CAN RR’ is assumed to be logistic (Table 3.1)													
Spawning fraction														
Age class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14+**
Younger	0	0	0	0.25	0.5	1	1	1	1	1	1	1	1	1
Older (East)	0	0	0	0.15	0.3	0.45	0 .6	0 .75	0.9	1	1	1	1	1
Older (West)	0	0	0	0	0	0	0	0.01	0.04	0.19	0.56	0.88	0.98	1

Estimated parameters

The majority of parameters estimated by the model relate to movement probabilities and annual recruitment deviations (Table 8.3).

Table 8.3. The parameters estimated by the model. The example is for a bluefin tuna operating model of 7 strata (Figure 1.1), 4 quarters, 18 fleets, 52 years and 3 movement age classes.

Parameter	**Number of parameters**	
Unfished recruitment (recruitment level 1)	$2 \cdot n_{stocks}$	4
Length at modal selectivity	n_{fleets}	18
Ascending precision of selectivity	n_{fleets}	18
Descending precision of selectivity	n_{fleets} -1	17
Recruitment deviations	$(n_{years} / 2 - 2) \cdot n_{stocks}$	48
Fleet catchability (q)	n_{fleets}	18
F deviation (FD)	$n_{quarters} \cdot n_{strata}$	28
Annual F (FA) deviation	$n_{quarters} \cdot n_{strata} \cdot (n_{years} -1)$	1428
Movement	$n_{strata} \cdot n_{quarters} \cdot n_{stocks} \cdot n_{mov\text{-}ages}$	144
	Total	1723

Table 8.4. Prior probability distributions for model parameters with mean μ and standard deviation σ, and lower and upper bounds LB and UB, respectively.

Parameter	**Prior**	**Likelihood component**
All operating models		
Unfished recruitment	log-uniform(LB = 11, UB = 16.5)	$-lnL_{rec}$
All Selectivity parameters (θ)	lognormal(μ = 0, σ = 4) (LB = -5.0, UB = 5.0)	$-lnL_{sel}$
Fishing fleet catchability (q) (mean F per fleet)	log-uniform(LB = -10.0, UB = 1.0)	$-lnL_{q}$
F deviation (FD)	lognormal(μ = 0, σ = 1)	$-lnL_{FD}$
Annual F deviation (FA)	lognormal(μ = 0, σ = 1)	$-lnL_{FA}$
Movement parameters (g, v, θ_G)	lognormal(μ = 0, σ = 4) (LB = -8.0, UB = 8.0)	$-lnL_{mov}$
Recruitment deviations (2-year blocks)	lognormal(μ = 0, σ = 0.353)	$-lnL_{recdev}$
Unfished recruitment change (applicable only to the level 1 and 3 recruitment scenarios)	lognormal(μ = 0, σ = 0.4)	$-lnL_{R0dif}$
Asymptotic western stock mixing	Lognormal($\mu_{specified}$, σ = 0.025)	$-lnL_{mix}$
Mean spawning stock biomass by area	Lognormal($\mu_{specified}$, σ = 0.025)	$-lnL_{muSSB}$

A summary of likelihood functions can be found in Table 8.5.

For each fleet f, total predicted catches in weight $\hat{C}$, are calculated from the Baranov equation:

$$\hat{C}_{y,m,r,f} = \sum_s \sum_a w_{s,a} \cdot N_{s,y,m,a,r} \cdot (1 - e^{-Z_{s,y,m,a,r}}) \cdot \left(\frac{F_{s,y,m,a,r,f}}{Z_{s,y,m,a,r}}\right) \tag{8.1}$$

Similarly, predicted catches in numbers at age (CAA) are given by:

$$\widehat{CAA}_{s,y,m,a,r,f} = N_{s,y,m,a,r} \cdot (1 - e^{-Z_{s,y,m,a,r}}) \cdot \left(\frac{F_{y,m,a,r,f}}{Z_{s,y,m,a,r}}\right) \tag{8.2}$$

This can be converted to a prediction of total catches in numbers by length class *CAL* using a stock specific inverse age-length key, *LAK*:

$$\widehat{CAL}_{y,m,l,r,f} = \sum_s \sum_a \widehat{CAA}_{s,y,m,a,r,f} \cdot LAK_{s,a,l} \quad (8.3)$$

For fishery independent indices of spawning stock biomass, the model predicts spawning stock biomass indices $\widehat{Is}$, for a specific index *i*, and stratum *r*:

$$\widehat{Is}_{i,s,y,r} = q_i \, SSB_{s,y,r} \quad (8.4)$$

For fishery independent indices and fishery dependent indices based on vulnerable biomass (noting that the Canadian acoustic survey this is calculated by vulnerable numbers) the model predicts exploitable biomass indices $\hat{I}$, by fleet:

$$\hat{I}_{i,y,m,r,f} = q_i \;\; V_{y,m,r,f} \quad (8.5)$$

where exploitable biomass *V* is calculated as:

$$V_{y,m,r,f} = \sum_l \left(s_{f,l} \cdot \sum_s \sum_a \left(N_{s,y,m,a,r,f} \cdot LAK_{s,a,l} \cdot w_{s,a}\right)\right) \quad (8.6)$$

The model predicts stock of origin composition of catches (fraction of Eastern origin) by movement age class ac, $\hat{R}$, from predicted catch numbers at age:

$$\hat{R}_{y,m,r,f,ac} = \begin{cases} \sum_f \sum_{a=1}^{4} \widehat{CAA}_{s=1,y,m,a,r,f} / \sum_s \sum_f \sum_{a=1}^{4} \widehat{CAA}_{s,y,m,a,r,f} & ac = 1 \\ \sum_f \sum_{a=5}^{8} \widehat{CAA}_{s=1,y,m,a,r,f} / \sum_s \sum_f \sum_{a=5}^{8} \widehat{CAA}_{s,y,m,a,r,f} & ac = 2 \\ \sum_f \sum_{a=9} \widehat{CAA}_{s=1,y,m,a,r,f} / \sum_s \sum_f \sum_{9} \; \widehat{CAA}_{s,y,m,a,r,f} & ac = 3 \end{cases} \quad (8.7)$$

A log-normal likelihood function (without constant terms) is assumed for total catches by fleet. The negative log-likelihood is calculated as:

$$-lnL_c = \sum_y \sum_m \sum_r \sum_f \frac{\left(\ln(\hat{C}_{y,m,r,f}) - \ln(C_{y,m,r,f})\right)^2}{\sigma^2_{catch}} \quad (8.8)$$

Similarly, the negative log-likelihood components for indices of exploitable biomass and spawning stock biomass are calculated as:

$$-lnL_i = \sum_y \sum_m \sum_r \sum_f \frac{\left(ln(\hat{I}_{y,m,r,f}) - ln(I_{y,m,r,f})\right)^2}{\sigma^2_{i,y}} -lnL_i = \sum_y \sum_m \sum_r \sum_f \frac{\left(ln(\hat{I}_{y,m,r,f}) - ln(I_{y,m,r,f})\right)^2}{\sigma^2_{index}}$$

(8.9)

and

$$-lnL_{SSB} = \sum_s \sum_y \frac{\left(ln(\hat{Is}_{s,y}) - ln(Is_{s,y})\right)^2}{\sigma^2_{S,y}} -lnL_{SSB} = \sum_s \sum_y \frac{\left(ln(\hat{Is}_{s,y}) - ln(Is_{s,y})\right)^2}{\sigma^2_{S}}$$
(8.10)

The negative log-likelihood component for length composition data is calculated (for positive observations of length composition only) by:

$$-lnL_{CAL} = -\sum_y \sum_m \sum_l \sum_r \sum_f \hat{p}_{y,m,l,r,f} \left(\ln(\hat{p}_{y,m,l,r,f}) - \ln(p_{y,m,l,r,f})\right)^2 \quad (8.11)$$

where the model predicted fraction, $\hat{p}$, of catch numbers in each length class is calculated as:

$$\hat{p}_{y,m,l,r,f} = \widehat{CAL}_{y,m,l,r,f} / \sum_l \widehat{CAL}_{y,m,l,r,f} \quad (8.12)$$

The negative log-likelihood component for electronic tagging data of known stock of origin (SOO), released in year *y*, quarter *m*, stratum *r* and caught in the subsequent quarter in stratum *k* is calculated from a multinomial likelihood function as:

$$-lnL_{ET} = -\sum_s \sum_y \sum_m \sum_r \sum_k ET_{s,y,m,k} \cdot ln(mov_{s,m+1,k}) \quad (8.13)$$

The negative log-likelihood component for stock of origin data is calculated assuming a normal likelihood function (without constants) comparing $\hat{r}$ estimated from the operating model, with *r* derived applying a mixture model (SCRS/2018/133) to assignment scores from genetics and otolith microchemistry data:

$$-lnL_{SOO} = \sum_i \frac{(r_i - \hat{r}_i)^2}{\sigma_{i,s}{}^2} \quad (8.14)$$

Where the operating model estimated logit fraction Eastern fish for the i^{th} strata, $\hat{r}_i$ is calculated from the operating model predicted ratio of Eastern fish in the catch $\hat{R}_i$ (see equation (8.7)): $\hat{r}_i = ln\left(\hat{R}_i / (1 - \hat{R}_i)\right)$.

For OMs in which R_0 changes in some past year, the following prior distribution is used for the extent of the change (see Table 8.4):

$$\sum_y \sum_m \sum_r \sum_f \frac{\left(\ln(R_{0,1}) - \ln(\mathrm{R}_{0,2})\right)^2}{\sigma^2_{R0dif}} \quad (8.15)$$

The prior was required to ensure models could converge – without it there was very little data to inform the estimates of R0 in the later period. The highest possible value for the standard deviation σ^2_{R0dif} (the vaguest prior) was chosen that could allow models to reliably converge across all reference case operating models.

The latest version of M3 (v6.6+) allows for "priors" for western stock mixing and SSB scale (in order to bracket operating model scenarios). Western mixing is defined as the mean fraction of western spawning stock biomass found in the East areas, W_{mix}. The model estimates can then be compared with a specified prior level of mixing $\widehat{W}_{mix}$ via a log-likelihood function:

$$-lnL_{mix} = \frac{\left(ln(\widehat{W}_{mix}) - ln(\mathrm{W}_{mix})\right)^2}{\sigma^2_{mix}} \tag{8.16}$$

Similarly, mean spawning stock biomass by area can be specified as a prior $\widehat{SSB}_{mu,area}$ (1968-2015 in the West, 1974-2015 in the East – the years of the VPA assessments for purposes of comparison).

$$-lnL_{SSBmu} = \frac{\left(ln(\widehat{SSB}_{mu,west}) - ln(\mathrm{SSB}_{mu,west})\right)^2}{\sigma^2_{SSBmu}} + \frac{\left(ln(\widehat{SSB}_{mu,east}) - ln(\mathrm{SSB}_{mu,east})\right)^2}{\sigma^2_{SSBmu}} \tag{8.17}$$

The global penalised negative log-likelihood $-lnL_T$, to be minimized is the summation of the weighted negative log-likelihood components for the data and priors (Table 8.4):

$$\begin{aligned} -lnL_T = -[\omega_c \cdot lnL_c + \omega_i \cdot lnL_i + \omega_{SSB} \cdot lnL_{SSB} + \omega_{CAL} \cdot lnL_{CAL} + \\ \omega_{ET} \cdot lnL_{ET} + \omega_{SOO} \cdot lnL_{SOO} + \omega_{sel} \cdot lnL_{sel} + \omega_{FD} \cdot lnL_{FD} + \omega_{FA} \cdot lnL_{FA} + \\ \omega_{mov} \cdot lnL_{mov} + \omega_{recdev} \cdot lnL_{recdev} + \omega_{R0dif} \cdot lnL_{R0dif} + \omega_{mix} \cdot lnL_{mix} + \\ \omega_{SSBmu} \cdot lnL_{SSBmu} \,] \end{aligned} \tag{8.18}$$

Table 8.5. Summary of the negative log-likelihood function contributions from various data

Type of data	Disaggregation	Function	Likelihood component
Total catches (weight)	year, quarter, strata, fleet	Log-normal	lnL_c
Index of exploitable biomass (assessment CPUE index)	year, quarter, strata, fleet	Log-normal	$lnLi$
Index of spawning stock biomass (e.g. a larval survey)	year, quarter, strata, stock	Log-normal	lnL_{SSB}
Length composition	year, quarter, strata, fleet	Log-normal	lnL_{CAL}
Electronic tag (known stock of origin)	stock, year, quarter, strata, age class	Multinomial	lnL_{ET}
Stock of origin	year, quarter, strata, movement age class	Normal	lnL_{SOO}

A likelihood weighting scheme (the ω values of equation 8.18, Table 8.6) was selected that balanced the contribution of the various data sources, could pass established 'red face tests'.

Table. 8.6. Likelihood weightings for various components of equation 8.18.

Likelihood component	Symbol	Weighting (ω)
Total catches (weight)	ω_c	*0.02*
Index of exploitable biomass (assessment CPUE index)	ωi	*1*
Index of spawning stock biomass (e.g. a larval survey)	ω_{SSB}	*2 (GOM_LAR_SUV & MED_LAR_SUV = 20)*
Length composition	ω_{CAL}	*1 or 0.05* (Reference grid L and H)
Stock of origin	ω_{SOO}	*1*
Electronic tag (known stock of origin)	ω_{ET}	*5*
Recruitment deviations (prior)	ω_{recdev}	*1*
Movement (prior)	ω_{mov}	*1*
Selectivity (prior)	ω_{sel}	*1*
F deviation from master index (prior)	ω_{FD}	*1*
F deviation from master index (prior)	ω_{FA}	*1*
Difference in early/late R0 estimates for recruitment levels 1 and 3.	ω_{Rodiff}	*1*
“Prior” for western stock mixing	ω_{mix}	*1*
“Prior” for scale of mean SSB by area	ω_{SSBmu}	*1*

Characterising uncertainty

Base Case

Include within-model uncertainty via MCMC sampling of posteriors for model parameters.

Alternative options

Include within-model uncertainty (parameter uncertainty) via Monte Carlo sampling from the inverse Hessian matrix of model parameters.

Concentrate on among-model uncertainty using the maximum posterior density estimates of model parameters and a prior model weight based on expert judgement. Uniform weights will be used to start, possibly updated later using a Delphi-type approach.

9 TRIAL SPECIFICATIONS

Interim Reference set

There are five major uncertainty axes in conditioning and projections in the interim grid: recruitment; natural mortality/maturity (in combination); western stock mixing; scale of the biomass in the East and West areas; weighting of length composition data in the likelihood for operating model conditioning. These axes assume that the options of East and West Area (or western and eastern stock) are linked across rows of the table below. This design has the intention of capturing extremes.

Table 9.1. Factors and levels of key uncertainty factors the reference set operating models

	Western stock	Eastern stock
Recruitment		
1	B-H with h=0.6 (“high R0”) switches to h = 0.9 (“low R0”) starting from 1975	50-87 B-H h=0.98 switches to 88+ B-H *h*=0.98
2	B-H with h=0.6 fixed, high R0	B-H with h=0.7 fixed, high R0
3	Historically as in Level 1. In projections, “low R0” switches back to “high R0” after 10 years	Historically as in Level 1. In projections, 88+ B-H with *h*=0.98 switches back to 50-87 B-H with *h*=0.98 after 10 years.
Spawning fraction both stocks		Natural Mortality rate both stocks
A	Younger (E+W same)	High
B	Older (E+W older but different for the 2 stocks)	Low
Western stock mixing into East area		
I	1% western stock biomass in East area on average from 1965-2016	
II	20% western stock biomass in East area on average from 1965-2016	
Scale	West area	East area
--	15kt	200kt
-+	15kt	400kt
+-	50kt	200kt
++	50kt	400kt
Length composition weighting in likelihood		
L	0.05	
H	1	

The western stock recruitment scenarios are intended to capture two alternative hypotheses for historical recruitment. The ‘high then low recruitment’ hypothesis is captured by level 1, in which a Beverton-Holt stock recruitment relationship with fixed moderate steepness (R0 estimated) shifts to a higher steepness (mimicking the hockey-stick relationship assumed in assessments) after 1975 (second R0 estimated, but lower than for the pre-1975 period). The ‘high recruitment’ hypothesis is captured by level 2, a Beverton-Holt recruitment relationship with fixed moderate steepness throughout the time series. The third level for western stock recruitment evaluates the robustness of CMPs to a future shift between these alternative recruitment scenarios. In this third scenario recruitment mimics level 1, but 10-years into the projections the higher steepness and lower R0 switches back to moderate steepness and higher R0.

Similarly, the eastern stock recruitment level 1 has two periods of differing unfished recruitment, level 2 assumes a single unfished recruitment value throughout and the third level, as for the West, considers a shift between recruitment scenarios after 10 years. Until very recently level 1 (low then high recruitment) was the prevailing hypothesis; however, recent assessments have estimated lower recruitments providing some support for level 2.

The rationale for recruitment level 3 for both stocks is that if recruitment shifts have occurred in the past they could occur in the future as well.

Combinations for Reference Set

A full cross of (1, 2, 3) x (A, B) x (I, II) x (--, -+, +-, ++) x (L, H) , i.e. 96 scenarios in total (only 64 of which require OM fitting since Recruitment levels 1 and 3 differ only in projection years). Discussion will be required regarding whether, in addition to considering results for each of these scenarios individually, they should also be considered for all scenarios in combination, and if so, how the scenarios should be weighted (if at all) in such a combination.

Table 9.2. The factorial design and labelling of the reference set operating models (Recruitment level 3 OMs do not require estimation and change only in projection years)

Length Comp Wt	**L**							
Scale	--				-+			
Mixing	**I**		**II**		**I**		**II**	
Spawn. Frac. / M	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Recruitment: 1	OM_1	OM_4	OM_7	OM_10	OM_13	OM_16	OM_19	OM_22
Recruitment: 2	OM_2	OM_5	OM_8	OM_11	OM_14	OM_17	OM_20	OM_23
Recruitment: 3	OM_3	OM_6	OM_9	OM_12	OM_15	OM_18	OM_21	OM_24

Length Comp Wt	**L**							
Scale	+-				++			
Mixing	**I**		**II**		**I**		**II**	
Spawn. Frac. / M	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Recruitment: 1	OM_25	OM_28	OM_31	OM_34	OM_37	OM_40	OM_43	OM_46
Recruitment: 2	OM_26	OM_29	OM_32	OM_35	OM_38	OM_41	OM_44	OM_47
Recruitment: 3	OM_27	OM_30	OM_33	OM_36	OM_39	OM_42	OM_45	OM_48

Length Comp Wt	**H**							
Scale	--				-+			
Mixing	**I**		**II**		**I**		**II**	
Spawn. Frac. / M	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Recruitment: 1	OM_49	OM_52	OM_55	OM_58	OM_61	OM_64	OM_67	OM_70
Recruitment: 2	OM_50	OM_53	OM_56	OM_59	OM_62	OM_65	OM_68	OM_71
Recruitment: 3	OM_51	OM_54	OM_57	OM_60	OM_63	OM_66	OM_69	OM_72

Length Comp Wt	**H**							
Scale	+-				++			
Mixing	**I**		**II**		**I**		**II**	
Spawn. Frac. / M	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Recruitment: 1	OM_73	OM_76	OM_79	OM_82	OM_85	OM_88	OM_91	OM_94
Recruitment: 2	OM_74	OM_77	OM_80	OM_83	OM_86	OM_89	OM_92	OM_95
Recruitment: 3	OM_75	OM_78	OM_81	OM_84	OM_87	OM_90	OM_93	OM_96

Robustness trials

Table 9.3. Robustness tests, including priority and OMs on which the test is to be conducted. In the column of "Updated Priority", "NA", "1", and "2" indicate "no longer applicable or superseded by other treatments", "to be ready for the April 2020 BFT intersessional meeting", and "to be conducted after the April 2020 BFT intersessional meeting", respectively.

	Robustness test description	**Updated Priority**	**OMs***	**Notes**
Highest priority				
1	**Senescence.** An increase in natural mortality rate for older individuals as applied in CCSBT	1	1AII--H 2AII--H 1BII--H 2BII--H	Important, may change OMs
2	**Western stock growth curve for eastern stock.**	1	1AII--H 2AII--H 1BII--H 2BII--H	Important, may change OMs
3	**'Brazilian catches'.** Catches in the South Atlantic during the 1950s are reallocated from the West area to the East area.	1	1AII--H 2AII--H 1BII--H 2BII--H	Key questions of BFT SG participants
Other				
4	**Western Contrast.** Increased precision (CV of 15%) of the GOM_LAR_SUV index to create greater contrast in current western stock status	NA		No longer needed
5	**Gulf of Mexico SSB.** Prior on higher GOM SSB in quarter 2 and lower GOM SSB in quarter 3	NA		Superseded by seasonal vector
6	**Time varying mixing.** Western mixing alternates between 10 and 30% every three years	2	1AII--H 2AII--H	Key question of BFT SG participants
7	**Persistent change in mixing.** Western mixing increases from 20% to 30% after 10 years	2	1AII--H 2AII--H	Key question of BFT SG participants
8	**Upweighting of CPUE indices**	NA		No longer needed
9	**Upweighting of 'fishery independent' indices.**	NA		No longer needed

10	**Upweighting of genetic stock of origin data.** 5x log-likelihood factor on genetics, ignore microchemistry SOO data by increasing imprecision to a logit CV of 500%	NA		No longer needed
11	**Greater influence of microchemistry stock of origin data.** 5x log-likelihood factor on microchemistry data, and ignore genetics SOO data by increasing imprecision to a logit CV of 500%.	NA		No longer needed
12	**Greater influence of the Length composition data.**	NA		Now in main grid
13	**Greater influence of the historical landings data.**	NA		Now good fit to landings
14	**Catchability Increases**. CPUE-based indices are subject to a 2% annual increase in catchability.	2	1AII--H 2AII--H	
15	**Decreasing catchability.** 2% annual decline in the catchability of CPUE-based indices.	2	1AII--H 2AII--H	
16	**Non-linear indices.** Hyperstability / hyper depletion in OM fits to data is simulated in projection years for all indices.	2	1AII--H 2AII--H	
17	**Unreported overages.** Future catches in both the West and East areas are 20% larger than the TAC as a result of IUU fishing (not accounted for by the CMP).	2	1AII--H 2AII--H	
18	**Zero western stock mixing.** No western stock in the East area	2		

Other Robustness trials:

1) Probabilistic movement changes
2) Step-changes in catchability.
3) Split Med Larval index

"Second round" issues

The following aspects of uncertainty are suggested to be postponed at this time for consideration rather in a "second round":

1) More than two stocks in some OMs

2) Model only a single stock in some OMs
3) Allow for CMPs that set TACs for the whole Atlantic (note that this will require specification of OM components that allocate such catches between West and East areas each year)
4) Use of CAL data in a CMP
5) TACs allocated on a spatially more complex basis than the traditional west and East+Med
6) CMP Changes in technical measures affecting selectivity
7) Changes in stock distributions in the future
8) Future changes in proportional allocation of TACs amongst fleets

10 PERFORMANCE MEASURES/STATISTICS

Projections under CMPs will be for 100 years (unless this leads to computational difficulties) commencing in 2020. Prior to that, for projecting for years between the last year of the condition and 2020, the catches will be set equal to the TACs already set, with abundance index data (and any further monitoring data such as catch-at-length) not yet available for those years being generated as specified under Section 7. Note that considering a period as lengthy as 100 years is not to imply high reliability for projections for such a long time, but to be able take account of transient effects that persist for some time for a long-lived species.

Summary measures/statistics

All depletion metrics below are calculated as the spawning stock biomass (SSB) relative to dynamic SSB0. Dynamic SSB0 (MacCall et al. 1985) is the spawning biomass that would have occurred if zero catches had been taken historically and in the future, and is therefore impacted by shifts in recruitment expectations. The dynamic SSB0 is calculated using year-specific estimates of unfished recruitment (depending on the R0 phase in which the model is in each year) assuming that there was zero fishing, i.e. it lags shifts in productivity. Dynamic SSBMSY is calculated using a fixed fraction of SSB0, taken from the most recent estimates of SSBMSY relative to unfished (i.e. using the steepness parameter assumed for 2016). Since in some operating models R0 is changing over time, the maximum achievable level of stock biomass is also changing and keeping track of dynamic SSB0 and dynamic SSBMSY provides a realistic yardstick for evaluating management performance.

MSY quantities were calculated for each stock individually (i.e. not a global aggregate MSY) using the standard approach of Botsford (1981) and Walters and Martell (2004) (Box 3.2 of that book) which efficiently calculates equilibrium yields for an age-structured population dynamics model using growth, the stock recruitment relationship and a fishery selectivity at age vector. Since the operating model has multiple fleets model with time varying exploitation rates among fleets, the aggregate selectivity (across all fleets) in the final year of the historical period (2017) is used in these MSY calculations.

Table 10.1. Performance statistics calculated as part of the MSE outputs for each OM and CMP

AvC30	Mean catches over first 30 projected years
C10	Mean catches over the first 10 projected years

C20	Mean catches over projected years 11-20
C30	Mean catches over projected years 21-30
D10	Depletion (spawning biomass relative to dynamic B0) after the first 10 projected years
D20	Depletion (spawning biomass relative to dynamic B0) after projection year 20
D30	Depletion (spawning biomass relative to dynamic B0) after projection year 30
LD	Lowest depletion (spawning biomass relative to dynamic B0) over the 30 years for which the MP is applied.
DNC	Depletion (by stock) after 30 years, but calculated relative to the trajectory that would have occurred had no catches been taken over the full period for which CMP application is being considered.
LDNC	The lowest depletion (by stock) over the 30 years for which the CMP is applied, but calculated relative to the zero catch trajectory specified in d (LDNC).
POS	Probability of Over-Fished status (B<BMSY) after 30 projected years.
AAVC	Average annual variation in catches (AAV) (note that except where the resource is heavily depleted so that catches become limited by maximum allowed fishing mortalities, catches will be identical to TACs) defined by: $$AAV = \frac{1}{30}\sum_{y=2022}^{2051}\left\|C_y - C_{y-1}\right\|/C_{y-1} \qquad (13.1)$$
Br30	Depletion (spawning biomass relative to dynamic BMSY) after projection year 30

For each of these distributions, 5%-, 50%- and 95%iles are to be reported from 200 replicates. Note the reason for measures/statistics c) and e) is to compensate for regime changes. The choice of these percentiles may need further exploration with stakeholders.

Further stakeholder orientated measures may need to be included. These must be scientifically based, easily understood by stakeholders and such that managers may readily request the evaluation of any changes in options.

Summary plots

Catch and spawning biomass trajectories plotted as:

a) Annual medians with 5%- and 95%-ile envelopes
b) 10 worm plots of individual realisations

Note that repetitions for different options for selectivity may be needed.

Level of reporting

<u>Base Case</u>

a) Catch-related measures/statistics by traditional West and East+Med regions.
b) Spawning biomass depletions measures/statistics by separate stocks

<u>Alternative options</u>

Many can be conceived, likely related primarily to catch and depletion by some combination of stock and/or spatial stratum. However, these might be left for a "second round", as they would become more pertinent in the face of greater model complexities possibly introduced at that time, such as changing spatial distributions of stocks and/or catches (resulting from changed proportional allocations to different fleets).

A possible additional metric could be AAVC but for downward adjustments only.

It may be necessary to characterize stock trajectory to further differentiate among CMPs with similar statistics relating to biomass.

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11 Appendix 1 – year indexing in the OM fitting and ABTMSE R packages

Table App.2.1. The year indexing for the M3 model fitting and R package

Calendar year	ABTMSE indexing (dset)	Historical year	Conditioning year	Projected Year	MP implementation year
1864		1			
1865		2			
1866		3			
…		…			
1963		100			
1964		101			
1965	1		1		
1966	2		2		
…	…		…		
2008	44		44		
2009	45		45		
2010	46		46		
2011	47		47		
2012	48		48		
2013	49		49		
2014	50		50		
2015	51		51		

2016	52	52		
2017	53		1	
2018	54		2	
2019	55		3	
2020	56		4	
2021	57		5	1
2022	58		6	2
…	…		…	
2069	105		53	49
2070	106		54	50