



+ TMB

The Woods Hole Assessment Model  
**WHAM:**

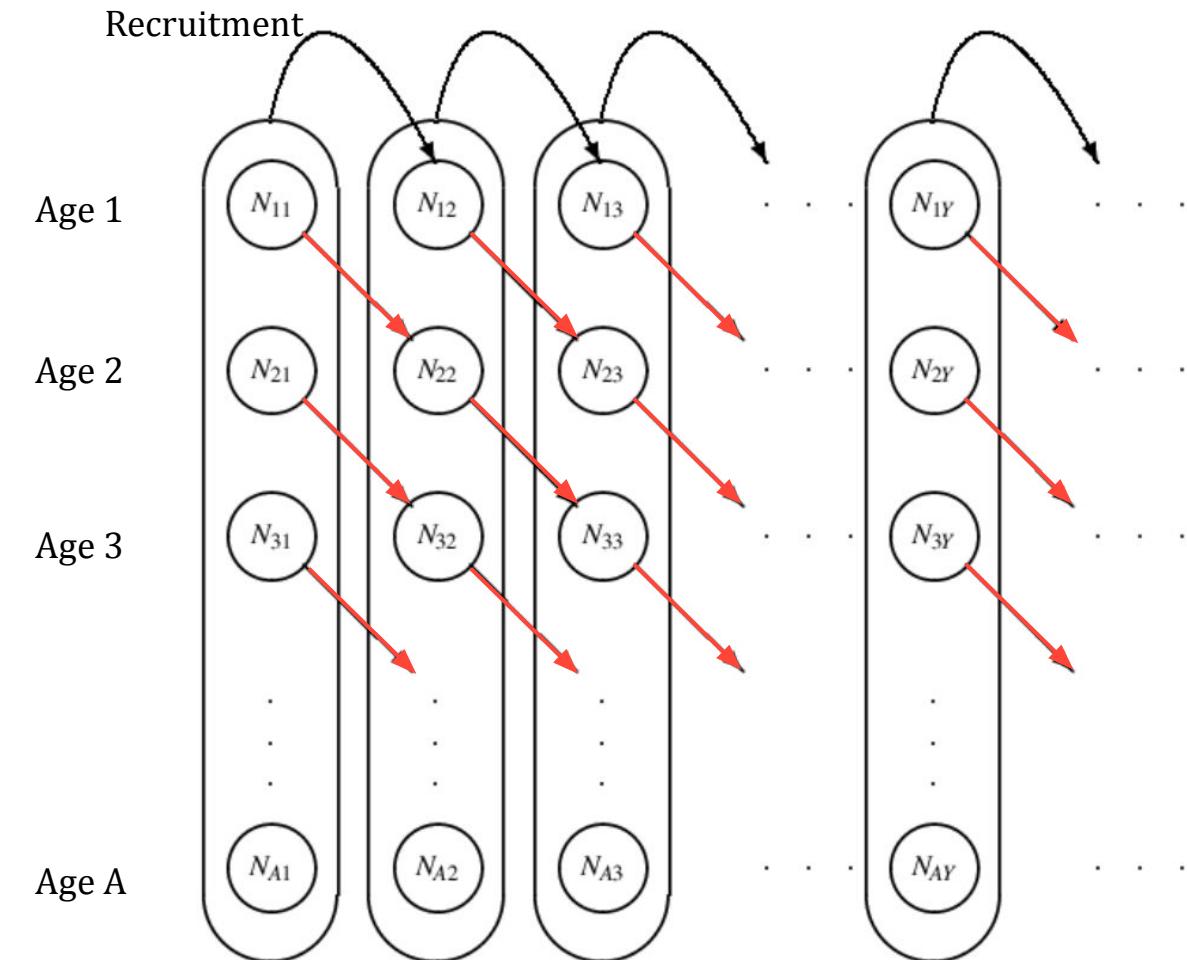
An open-source state-space  
assessment framework

Tim Miller  
Northeast Fisheries Science Center



**NOAA**  
**FISHERIES**

# What is a “state-space” model?



Statistical catch-at-age

$$\log N_{a,y} = f(\log N_{a-1,y-1})$$

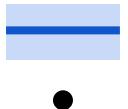
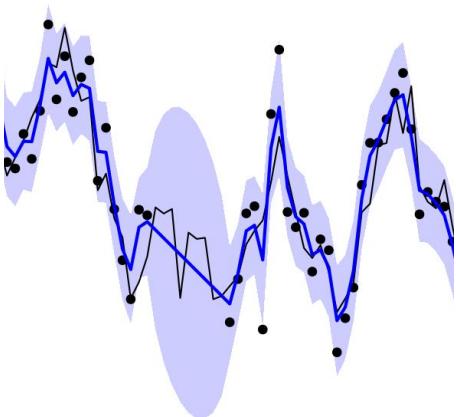
Statistical catch-at-age, random recruitment

$$\log N_{1,y} = \log(f(\text{SSB}_{y-1})) + \varepsilon_{1,y}$$

“Full state-space”

$$\log N_{a,y} = \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \varepsilon_{a,y}$$

# What is a “state-space” model?



$x_t$  **Process**  
 $y_t$  **Observations**

Statistical catch-at-age

$$\log N_{a,y} = f(\log N_{a-1,y-1})$$

Statistical catch-at-age, random recruitment

$$\log N_{1,y} = \log(f(\text{SSB}_{y-1})) + \varepsilon_{1,y}$$

“Full state-space”

$$\log N_{a,y} = \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \varepsilon_{a,y}$$

# WHAM: A research and management tool designed for:

Required

**Single-species** stock assessment

**Age-structured** population data

Optional

Unexplained temporal variation in some stock attributes (**random effects**)

Clear, **mechanistic hypothesis** that an environmental variable(s) drives a demographic and observational process(es) + **Environmental data**

Traditional assessments

WHAM/State-space

# Data components

All observations have error (whether to sampling or model-derived)

- Aggregate catch (fleet-specific)
- Catch age composition (fleet-specific)
- Aggregate indices (biomass or numbers)
- Index age composition (biomass or numbers)
- **Optional:** Environmental/Climate observations

# Random effects

Options for alternative covariance structures (AR1, iid, etc)

- Recruitment (year)
- Interannual transitions in abundance at age (“survival”) (year, age)
- Natural mortality (year, age)
- Selectivity (fishery or index) (year, age)
- Catchability (year)
- Hidden (imperfectly observed) environmental/climate variables (year)

# Time- and age-varying processes

## Random effects models

```
NAA_re = list(sigma="rec+1", cor="iid"))
```

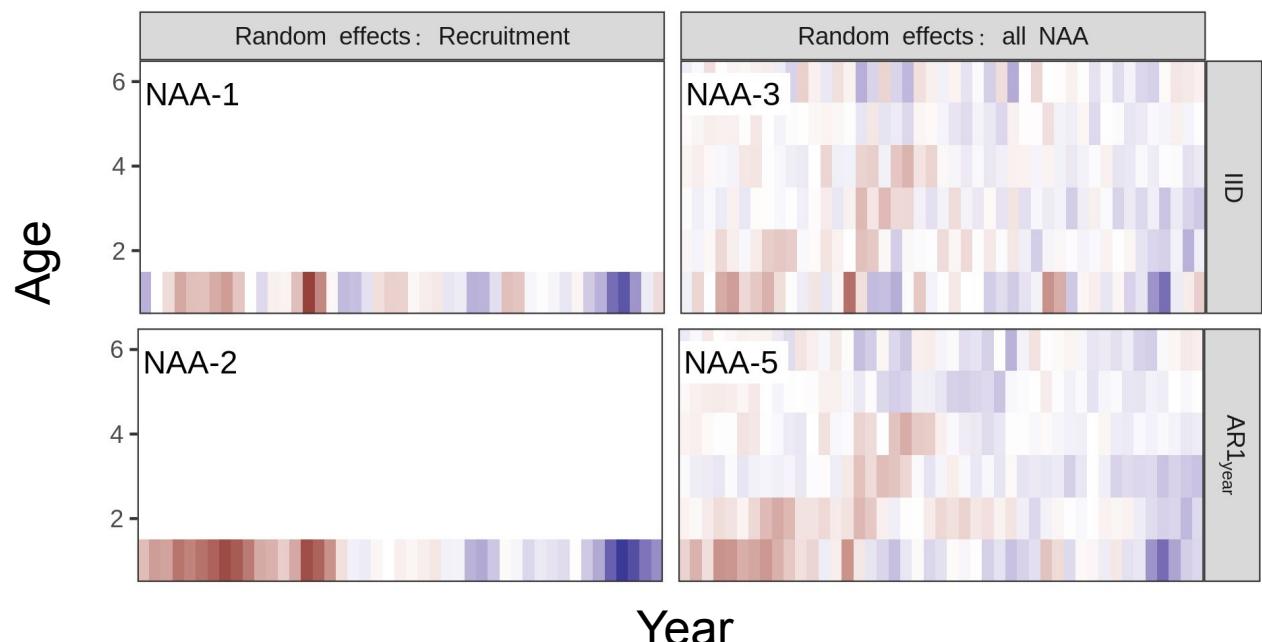
Code	Description	Parameters
"none"	time-constant (no deviation)	
"iid"	independent, identically-distributed	$\sigma^2$
"ar1"	autoregressive-1 (correlated across ages/parameters)	$\sigma^2, \rho_a$
"ar1_y"	autoregressive-1 (correlated across years)	$\sigma^2, \rho_y$
"2dar1"	2D AR1 (correlated across both years and ages/parameters)	$\sigma^2, \rho_a, \rho_y$

$$\text{Cov}(\varepsilon_{a,y}, \varepsilon_{\tilde{a},\tilde{y}}) = \frac{\sigma_a \sigma_{\tilde{a}} \rho_a^{|a-\tilde{a}|} \rho_y^{|y-\tilde{y}|}}{(1 - \rho_a^2)(1 - \rho_y^2)}$$

# Time- and age-varying processes

Biological processes are often  
**correlated by year and age**

- Recruitment
- Inter-annual transitions (“Survival”)
- Natural mortality
- Selectivity
- Catchability



$$\log N_{a,y} = \begin{cases} \log(f(\text{SSB}_{y-1})) + \varepsilon_{1,y}, & \text{if } a = 1 \\ \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \varepsilon_{a,y}, & \text{if } 1 < a < A \\ \log(N_{A-1,y-1} e^{-Z_{A-1,y-1}} + N_{A,y-1} e^{-Z_{A,y-1}}) + \varepsilon_{A,y}, & \text{if } a = A \end{cases}$$

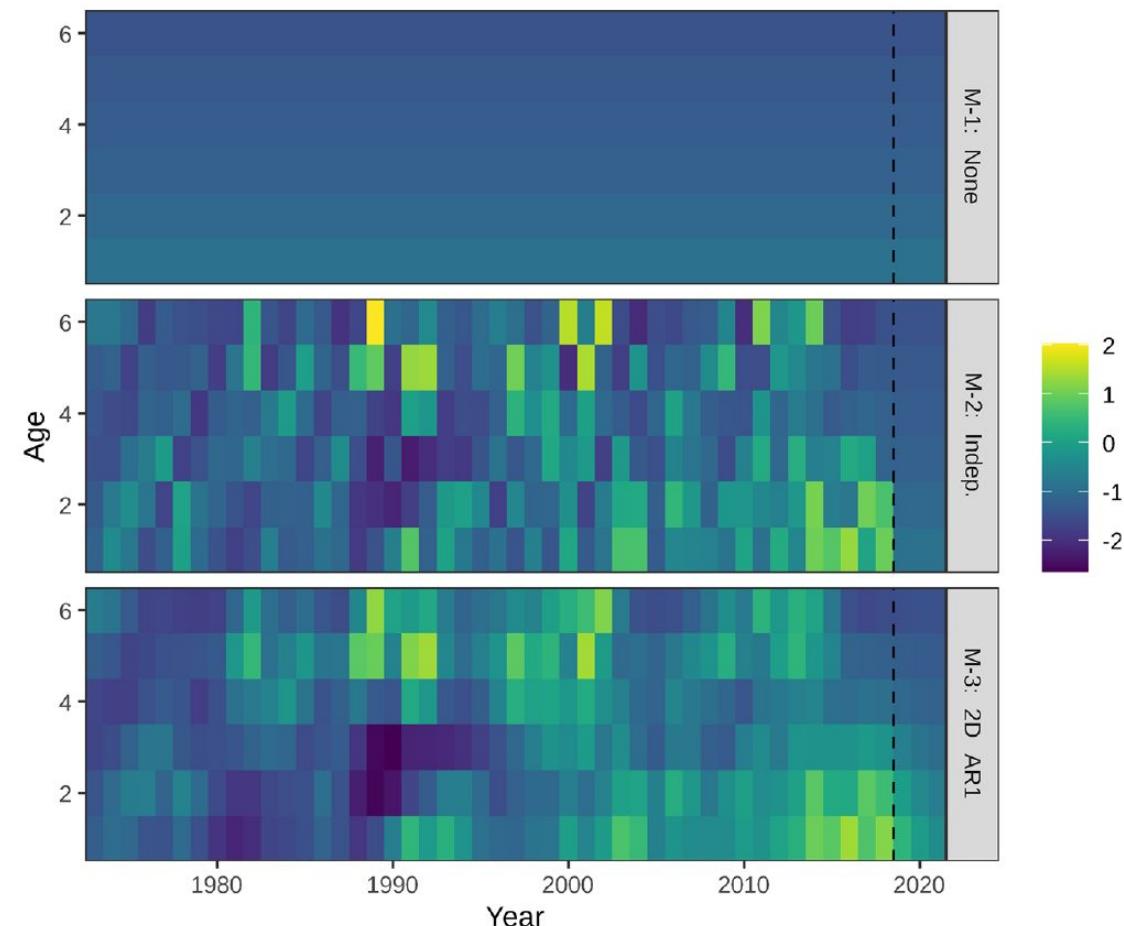
# Time- and age-varying processes

Biological processes are often **correlated by year and age**

- Recruitment
- Inter-annual transitions (“Survival”)
- **Natural mortality**
- Selectivity
- Catchability

Estimate or fix mean M parameters:

- constant across ages
- age-specific
- function of weight-at-age

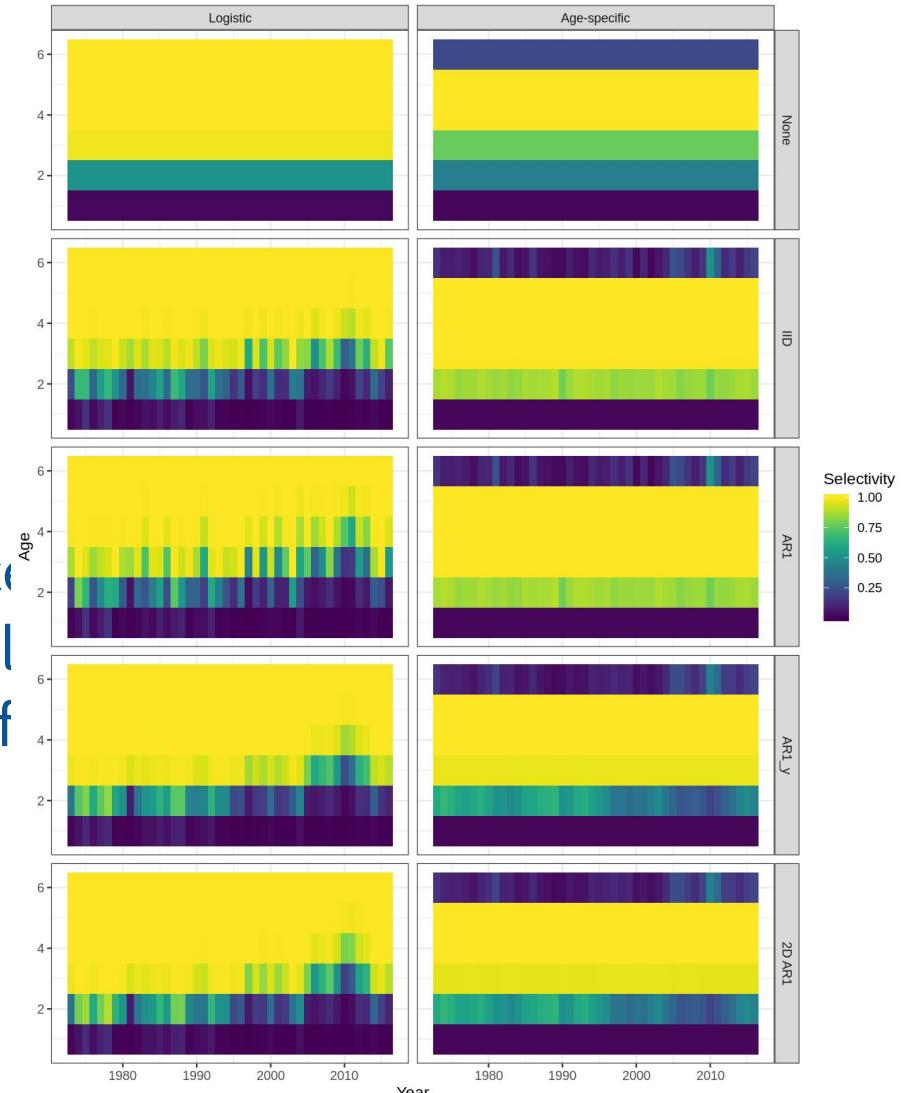


# Time- and age-varying processes

- Recruitment
- Inter-annual transitions (“Survival”)
- Natural mortality
- Selectivity
- Catchability

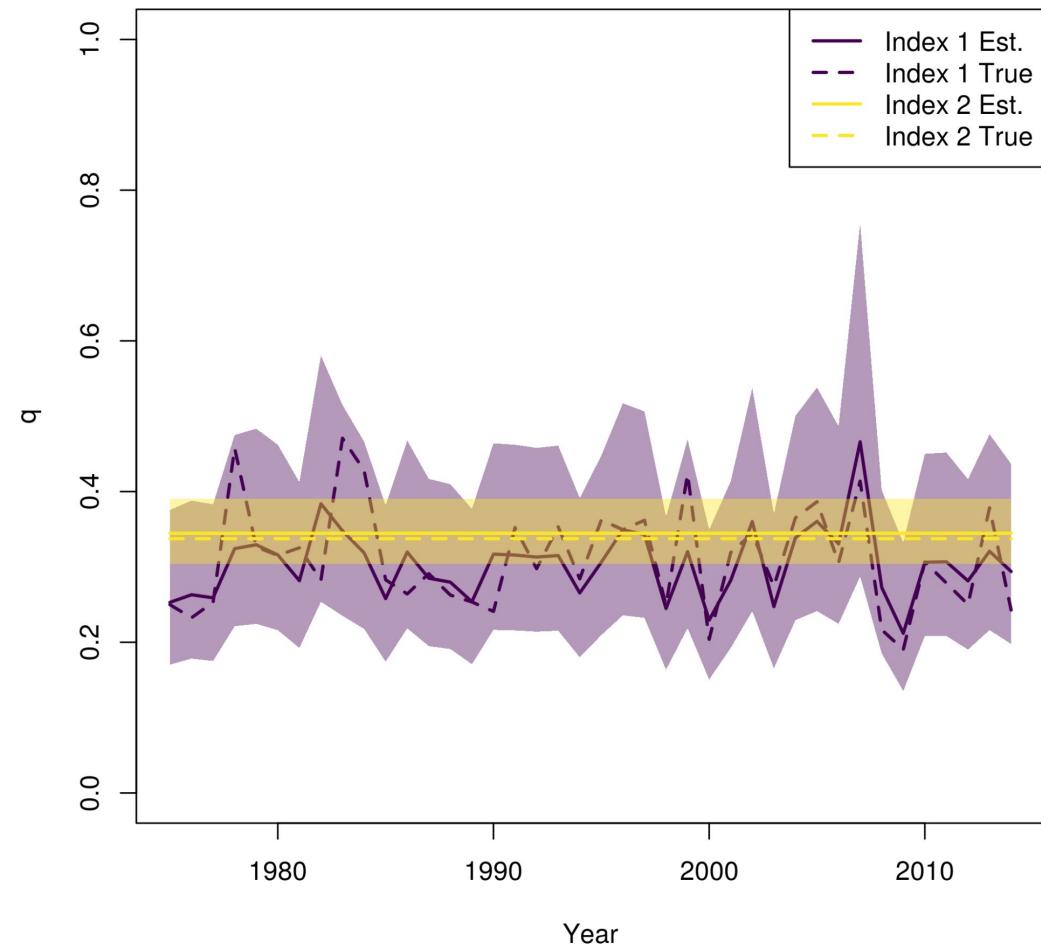
“blocks” indexed to particular years of indicator

- logistic (increasing or decreasing), double exponential
- constant, iid, or 1D or 2D AR1 processes for selectivity



# Time- and age-varying processes

- Recruitment
- Inter-annual transitions (“Survival”)
- Natural mortality
- Selectivity
- Catchability
- constant, iid, or AR1 processes



# Environmental Covariates

## Linkages:

- Recruitment
- Natural Mortality
- Catchability
- Lag is user-specified
- Non-linear (orthogonal polynomial) options for effects
- Multiple effects (Recruitment, M, catchability) (devel branch)

## Covariate state-space models:

### 1. Random walk

$$\theta = (x_1, \sigma_x^2, \sigma_y^2)$$

$$x_t = x_{t-1} + \mathcal{N}(0, \sigma_x^2)$$
$$y_t = x_t + \mathcal{N}(0, \sigma_y^2)$$

### 2. AR1

$$-1 < \phi < 1$$

$$\theta = (\mu, \sigma_x^2, \sigma_y^2, \phi)$$

$$x_t = \mu + \phi x_{t-1} + \mathcal{N}(0, \sigma_x^2)$$
$$y_t = x_t + \mathcal{N}(0, \sigma_y^2)$$

# Environmental effects on...

Recruitment models:

1. Random walk

$$\hat{R}_t =$$

$$R_{t-1}$$

2. Random about mean

$$e^{\gamma x} R_0$$

3. Beverton-Holt

$$\frac{\alpha S e^{\gamma x}}{1 + \beta S} \quad \left| \begin{array}{c} \alpha S \\ 1 + \beta S e^{\gamma x} \end{array} \right| \quad \left| \begin{array}{c} \alpha S \\ e^{\gamma x} + \beta S \end{array} \right|$$

4. Ricker

$$\alpha S e^{-\beta S + \gamma x} \quad \left| \begin{array}{c} \alpha S e^{-\beta S(1+\gamma x)} \end{array} \right|$$

Iles & Beverton (1998)

M models:

linear (in log-space),  $M_{y,a} = e^{\log \mu_M + \beta_1 E_y}$

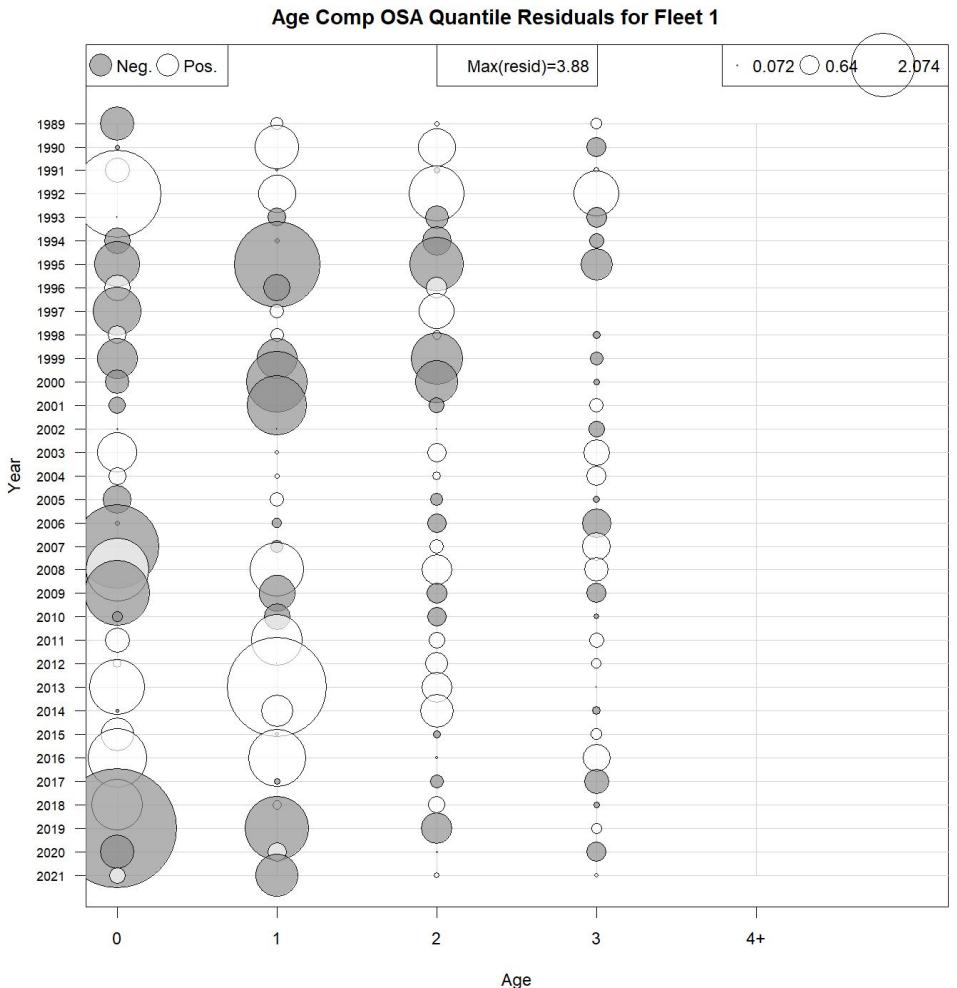
$$M_{y,a} = e^{\log \mu_M + b W_{y,a} + \beta_1 E_y + \beta_2 E_y^2 + \delta_{y,a}}$$

Catchability models: see M.

# WHAM: Other useful features

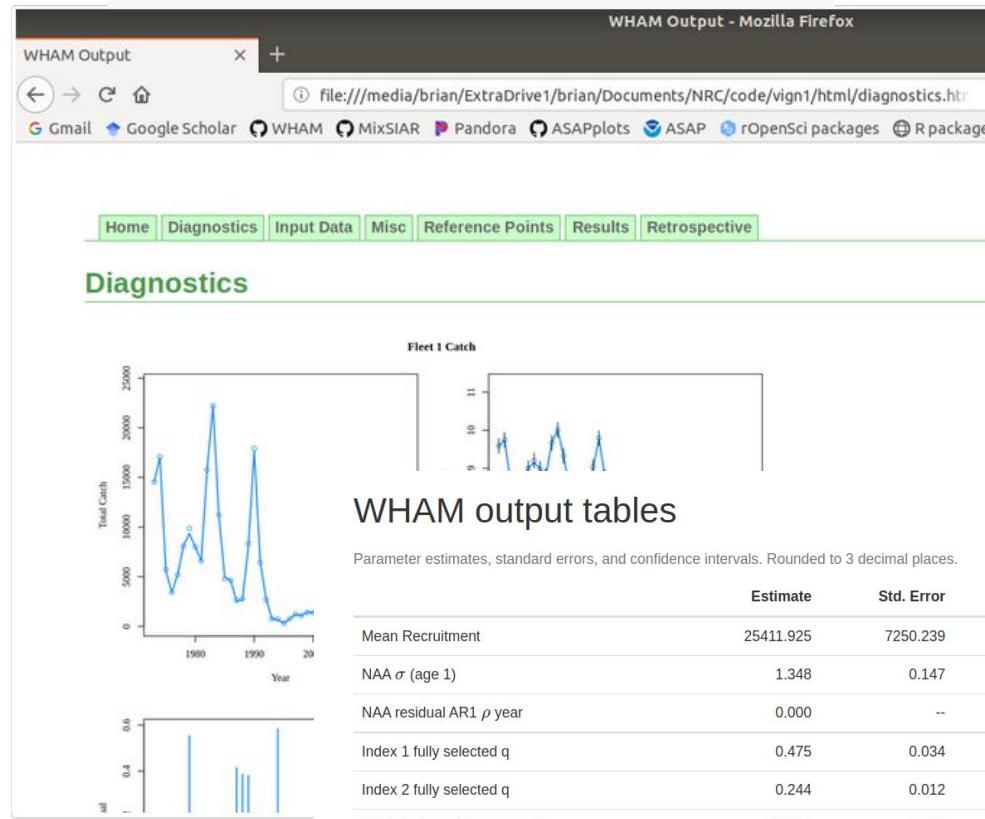
## Alternative age composition models

- Multinomial
- Dirichlet
- Dirichlet-multinomial
- Logistic normal



# WHAM: Other useful features

```
plot_wham_output(mod=m4, out.type='html')
```



```
check_convergence(m1)
```

```
#> stats:nlminb thinks the model has converged: mod$opt$converged
#> Maximum gradient component: 1.01e-07
#> Max gradient parameter: log_F1
#> TMB:sdreport() was performed successfully for this model
```

```
res <- compare_wham_models(mods, fname=
```

```
#>          AIC rho_R rho_SSB rho_Fbar
#> m4 -1466.9 0.3610 0.0091 -0.0106
#> m2 -1172.7 3.1589 -0.0735 -0.0167
#> m3 4107.1 0.1287 0.0304 -0.0162
#> m1 4846.5 0.8207 0.1905 -0.2322
```

Thanks  
to r4ss and  
ASAPplots!

# WHAM: Other useful features

## One step ahead (OSA) residuals

- provides independent residuals for correlated observations
- available for aggregate catch and indices
- available for age composition

Environ Ecol Stat (2017) 24:317–339  
DOI 10.1007/s10651-017-0372-4

## Validation of ecological state space models using the Laplace approximation

Uffe Høgsbro Thygesen<sup>1</sup> · Christoffer Moesgaard Albertsen<sup>1</sup> ·  
Casper Willestofte Berg<sup>1</sup> · Kasper Kristensen<sup>1</sup> · Anders Nielsen<sup>1</sup>

Fisheries Research 257 (2023) 106487

Contents lists available at ScienceDirect

Fisheries Research

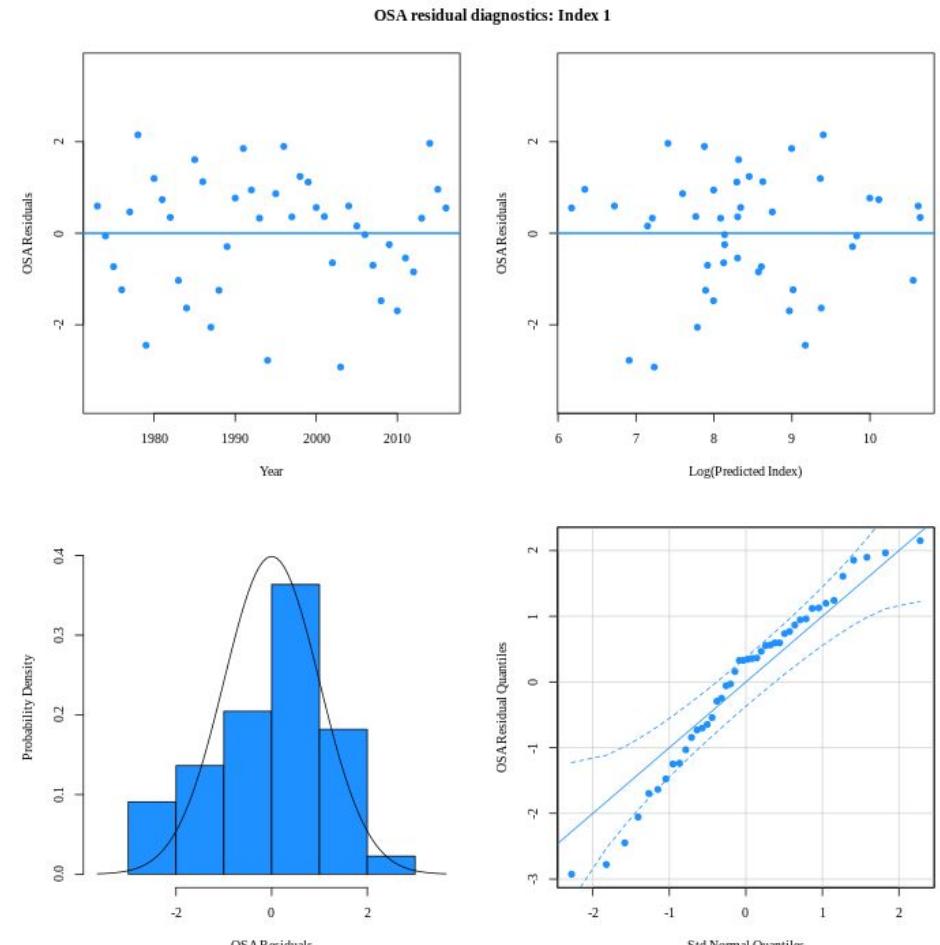
Journal homepage: [www.elsevier.com/locate/fishres](http://www.elsevier.com/locate/fishres)

Model validation for compositional data in stock assessment models:  
Calculating residuals with correct properties

Vanessa Trijoulet <sup>a,\*</sup>, Christoffer Moesgaard Albertsen <sup>a</sup>, Kasper Kristensen <sup>a</sup>,  
Christopher M. Legault <sup>b</sup>, Timothy J. Miller <sup>b</sup>, Anders Nielsen <sup>a</sup>

<sup>a</sup> National Institute of Aquatic Resources, Technical University of Denmark, Kemitorvet 201, DK-2800 Kgs. Lyngby, Denmark

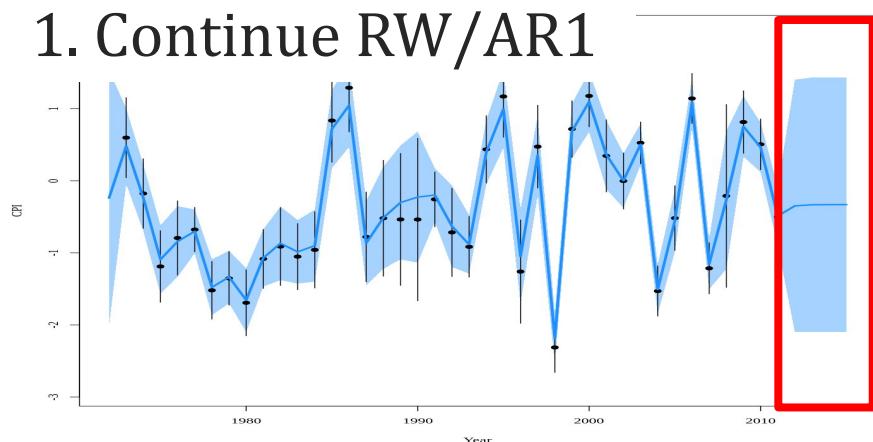
<sup>b</sup> Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA 02543, USA



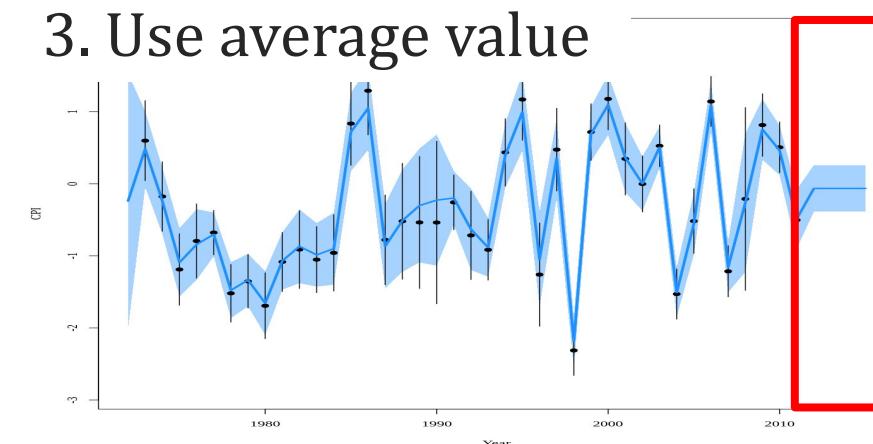
# WHAM: other useful features

Environmental covariate options in projections

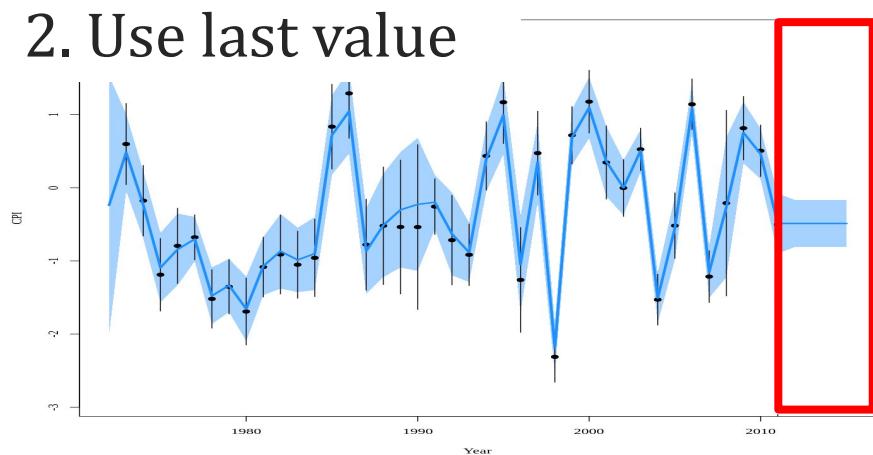
1. Continue RW/AR1



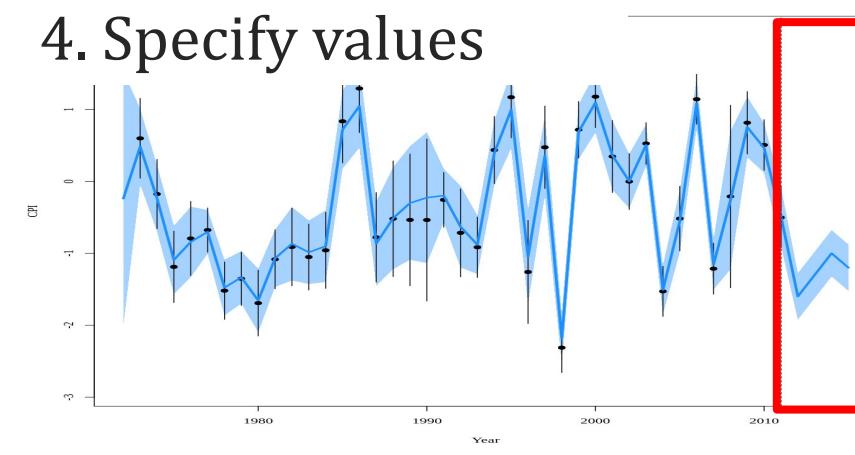
3. Use average value



2. Use last value

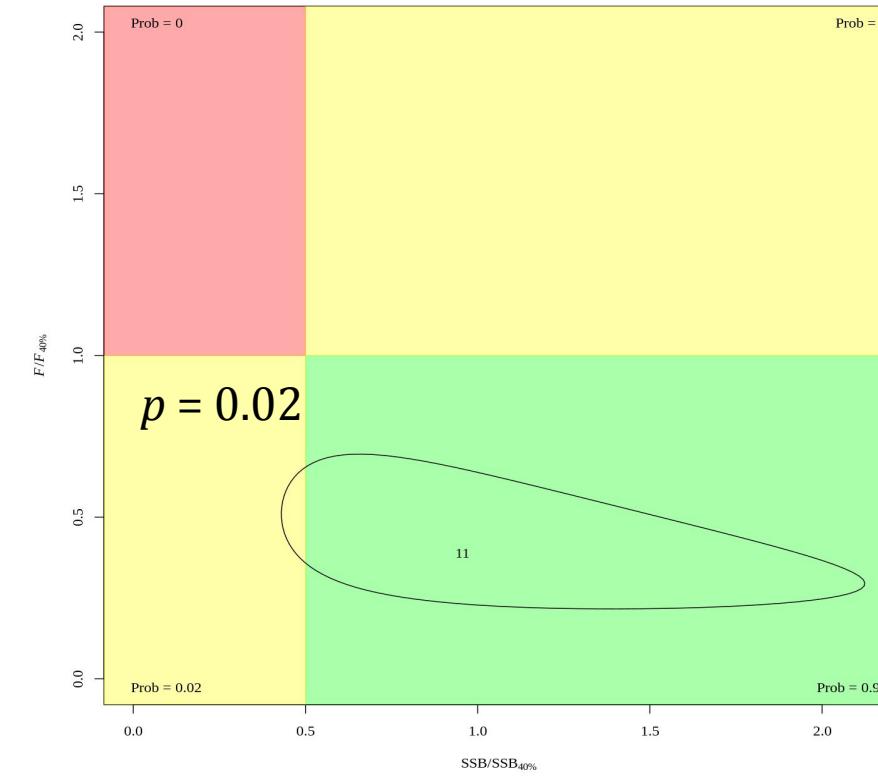
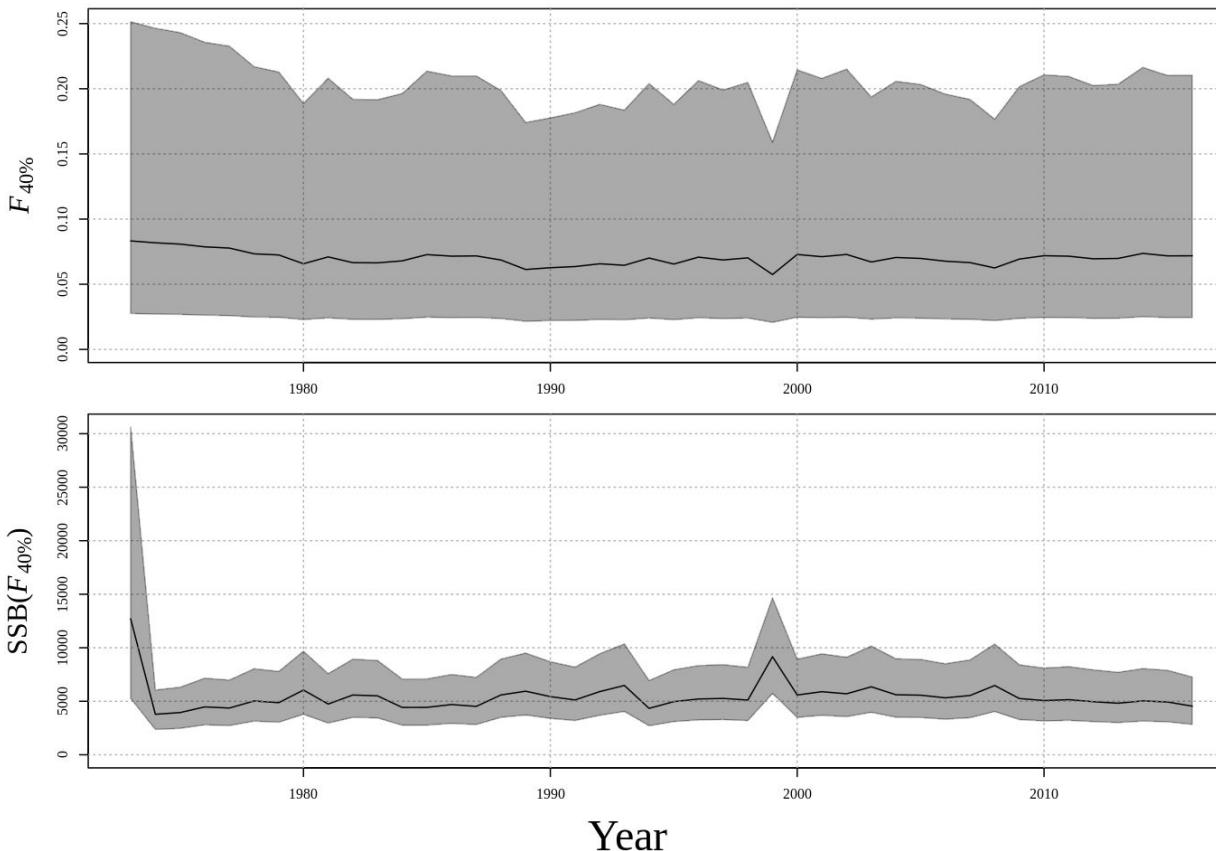


4. Specify values



# WHAM: Other useful features

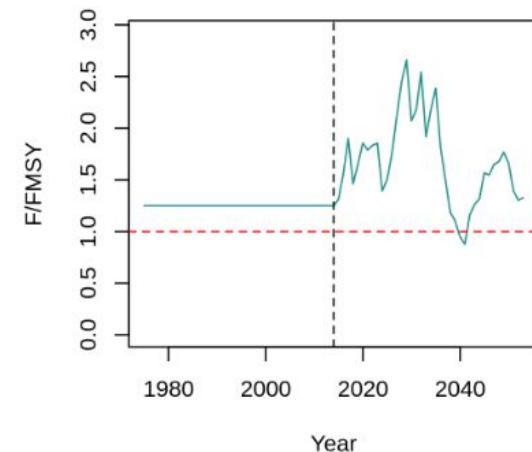
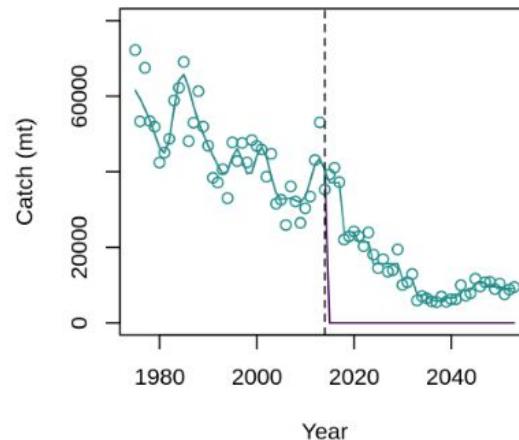
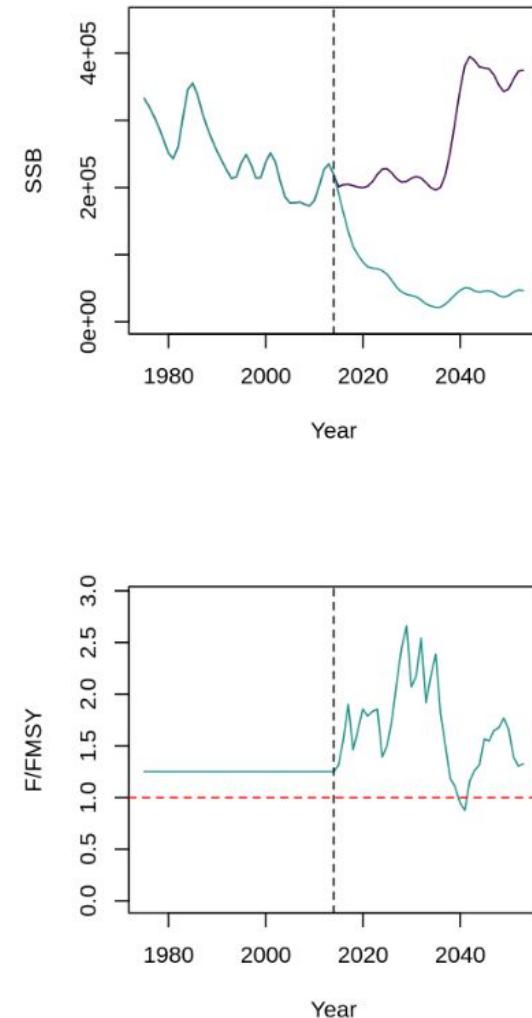
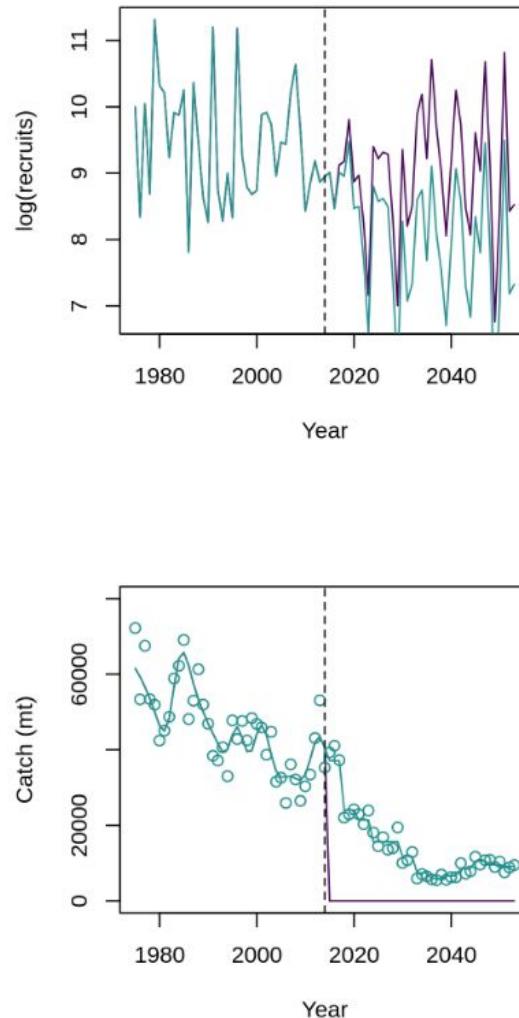
Internal estimation of reference points and status



# WHAM: Other useful features

## Operating model/MSE usage

- can be used for simulating populations and data as well as estimation
- Used this way in Index-based Methods Research Track and in state-space Research Track
- Used for testing reliability of models in stock-specific research tracks.



# WHAM: Other useful features

## Continual development

- 7 versions have been released to date
  - development history is saved
  - previous versions can be accessed/used
- next version is planned to
  - allow multiple stocks and areas
  - allow environmental effects on migration
  - be used for black sea bass research track

# <https://timjmiller.github.io/wham>

wham 1.0.6    Vignettes    Functions    Source code    News    Issues    Contact

## WHAM: a state-space age-structured assessment model

The Woods Hole Assessment Model (WHAM) is a general state-space age-structured stock assessment framework designed to include environmental effects on population processes. The state-space framework is attractive because it can estimate observation and process error, as well as naturally propagate random effect parameters in stock projections. WHAM can be configured to estimate a range of assessment models (see [Ex 1](#) and [Ex 6](#)):

- statistical catch-at-age (SCAA) model with recruitments as fixed effects,
- SCAA with recruitments as random effects
- 'full state-space model', abundance at all ages are random effects

WHAM advances fisheries assessment because it can estimate constrained random deviations, i.e. random effects, on parameters such as:

- recruitment / numbers-at-age ([Ex 2](#) and [Ex 6](#)),
- selectivity ([Ex 4](#)),
- natural mortality ([Ex 5](#)), and
- environmental effects on the above ([Ex 2](#) and [Ex 5](#))

A nice property of treating population and environmental processes as random effects is that their uncertainty is naturally propagated in projections/forecasts ([Ex 3](#)).

Overview of WHAM presentation (Jan 8 2021):



Links

- [Browse source code](#)
- [Report a bug](#)

License

- [GPL-3](#)

Community

- [Contributing guide](#)

Citation

- [Citing wham](#)

Developers

- Tim Miller  
Author, maintainer 
- Brian Stock  
Author 
- [More about authors...](#)

Dev status

repo status Active

## Basic use:

```
devtools::install_github("timjmiller/wham")
```

```
library(wham)
```

```
asap3 <- read_asap3_dat("ex1_SNEMAYT.dat")
```

```
input <- prepare_wham_input(asap3,
```

```
mod <- fit_wham(input, do.retro=TRUE, do.osa=TRUE)
```

Compiles .cpp

<https://timjmiller.github.io/wham>

The screenshot shows the homepage of the wham GitHub repository. At the top, there's a navigation bar with links for "wham 1.0.6", "Vignettes", "Functions", "Source code", and "News". Below the navigation bar, the main content area has a large title "WHAM: assessment made easy". A sidebar on the left contains text about WHAM's purpose and features, including a bulleted list of its advantages. The main content area features a "Vignettes" dropdown menu with 11 items, each with a blue link. The first item, "Ex 1: The basics", is currently selected. The text below the vignettes lists the purpose of WHAM and its advantages.

wham 1.0.6

Vignettes ▾

Functions

Source code

News

Contact

Overview

Ex 1: The basics

Ex 2: Recruitment linked to an environmental covariate (Cold Pool Index)

Ex 3: Projecting / forecasting random effects

Ex 4: Selectivity with time- and age-varying random effects

Ex 5: Time-varying natural mortality linked to the Gulf Stream Index

Ex 6: Numbers-at-age / survival deviations as random effects

Ex 7: Debugging WHAM models

Ex 8: Compare ASAP and WHAM model results

Ex 9: Retrospective predictions

Ex 10: Operating models and MSE

Ex 11: Catchability configurations

The Woods Hole Acoustic Trawl Survey (WHAM) is designed to include environmental covariates because it can estimate constrained random deviations in stock projections. V

- statistical catch at sea
- SCAA with recruitment
- “full state-space model”, abundance at all ages are random effects

WHAM advances fisheries assessment because it can estimate constrained random deviations, i.e. random effects, on parameters such as:

- recruitment / numbers-at-age ([Ex 2](#) and [Ex 6](#)),
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A nice property of treating population and environmental processes as random effects is that their uncertainty is naturally propagated in projections/forecasts ([Ex 3](#)).

<https://timjmiller.github.io/wham/articles/index.html>

# Other uses in management

- Atlantic butterfish
  - numbers at age residual random effects
- Georges Bank haddock
  - numbers at age residual random effects
  - time-varying fleet selectivity random effects
- Eastern Georges Bank haddock
  - time-varying fleet selectivity random effects

# Benefits of using state-space models

- Reduced retrospective patterns
- More realistic perception of uncertainty in assessment output
- Ability to better model temporal changes in productivity and fisheries
- Allows more statistical rigor in comparing alternative assessment models
- Short-term projections can be done consistently within the assessment model

# Tutorials on running WHAM

- Starting Simple:
  - run basic wham fits to SNEYT yellowtail data
  - using WHAM without an asap3 dat file
- Random effects on other parts of the assessment model
  - selectivity
  - catchability
  - M
- Environmental effects
  - including data and configuring models for latent process
  - Effects on recruitment
  - Effects on M