+ TMB

The Woods Hole Assessment Model: WHAM:

An open-source state-space assessment framework

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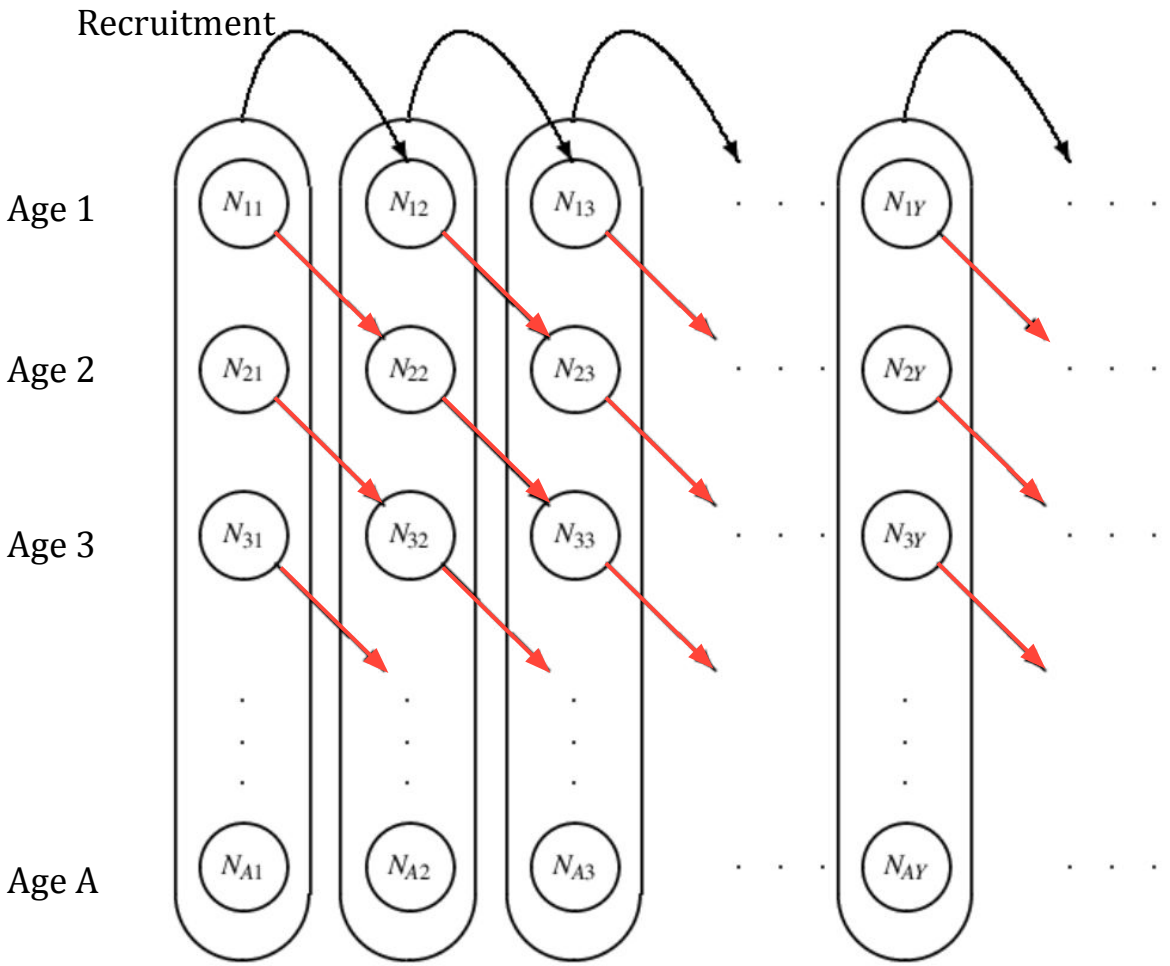
NOAA FISHERIES

What is a “state-space” model?



Statistical catch-at-age

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

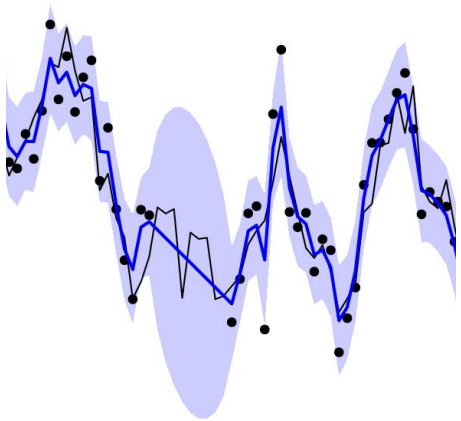
Statistical catch-at-age, random recruitment

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

“Full state-space”

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

What is a “state-space” model?



x_t **Process**

y_t **Observations**

Statistical catch-at-age

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Statistical catch-at-age, random recruitment

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“Full state-space”

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

WHAM: A research and management tool designed for:

Required

Single-species stock assessment

Age-structured population data

Traditional assessments

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**

WHAM/State-space

Data components

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

- Aggregate catch (fleet-specfic)
- Catch age composition (fleet-specfic)
- 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	σ^2
`"ar1"`	autoregressive-1 (correlated across ages/parameters)	σ^2, ρ_a
`"ar1_y"`	autoregressive-1 (correlated across years)	σ^2, ρ_y
`"2dar1"`	2D AR1 (correlated across both years and ages/parameters)	σ^2, ρ_a, ρ_y

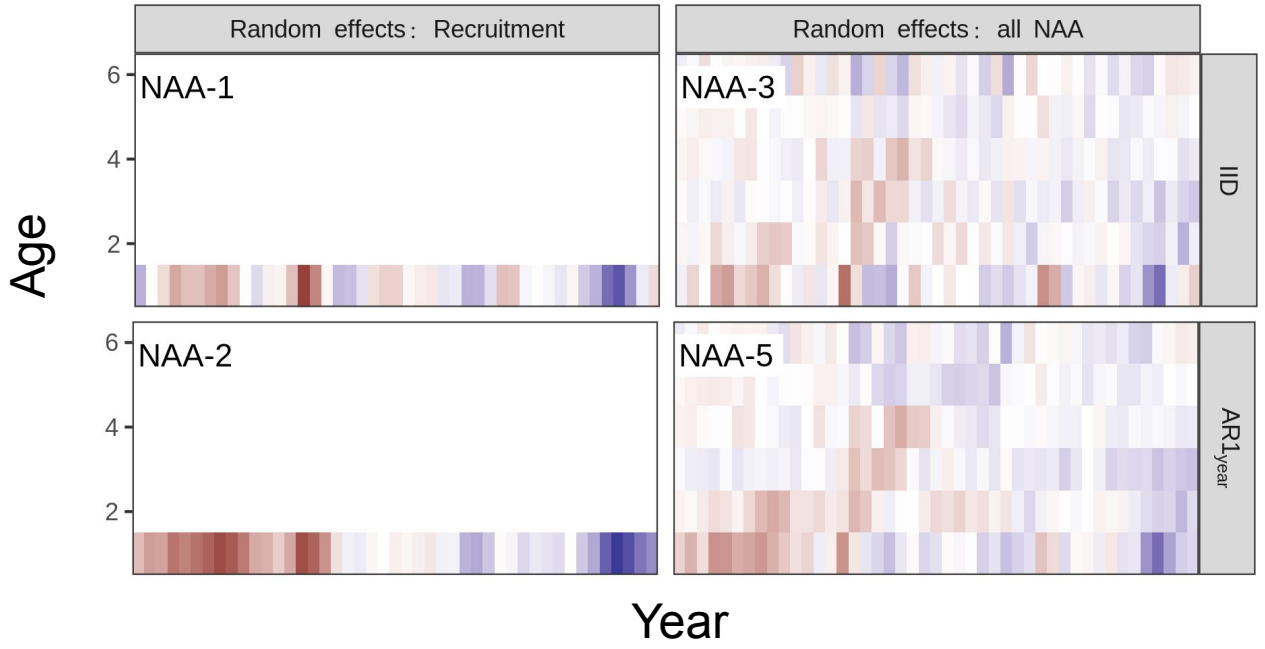
$$\mathrm{Cov}\left(\varepsilon_{a,y}, \varepsilon_{\tilde{a},\tilde{y}}\right) = \frac{\sigma_a \sigma_{\tilde{a}} \rho_a^{|a-\tilde{a}|} \rho_y^{|y-\tilde{y}|}}{\left(1-\rho_a^2\right)\left(1-\rho_y^2\right)}$$

Time- and age-varying processes

Biological processes are often

correlated by year and age

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



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

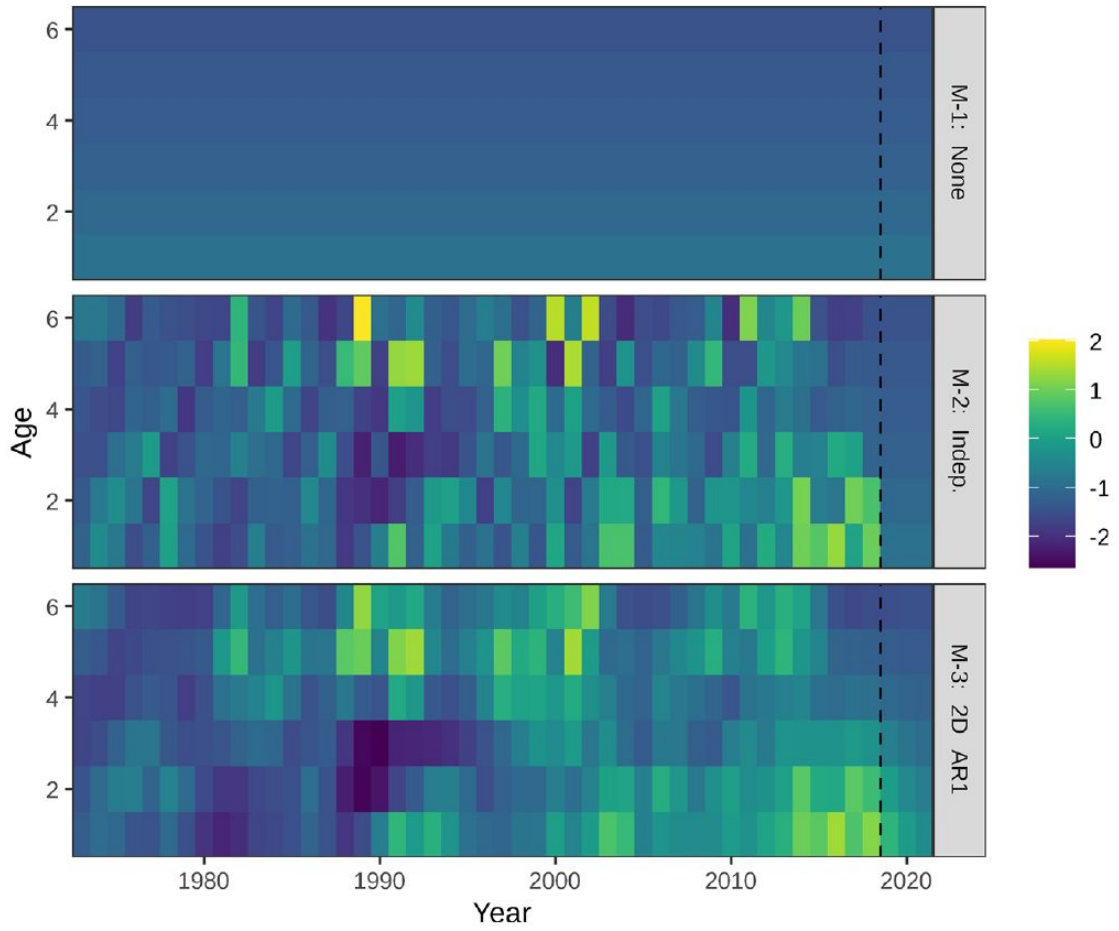
Time- and age-varying processes

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

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

Estimate or fix mean M parameters:

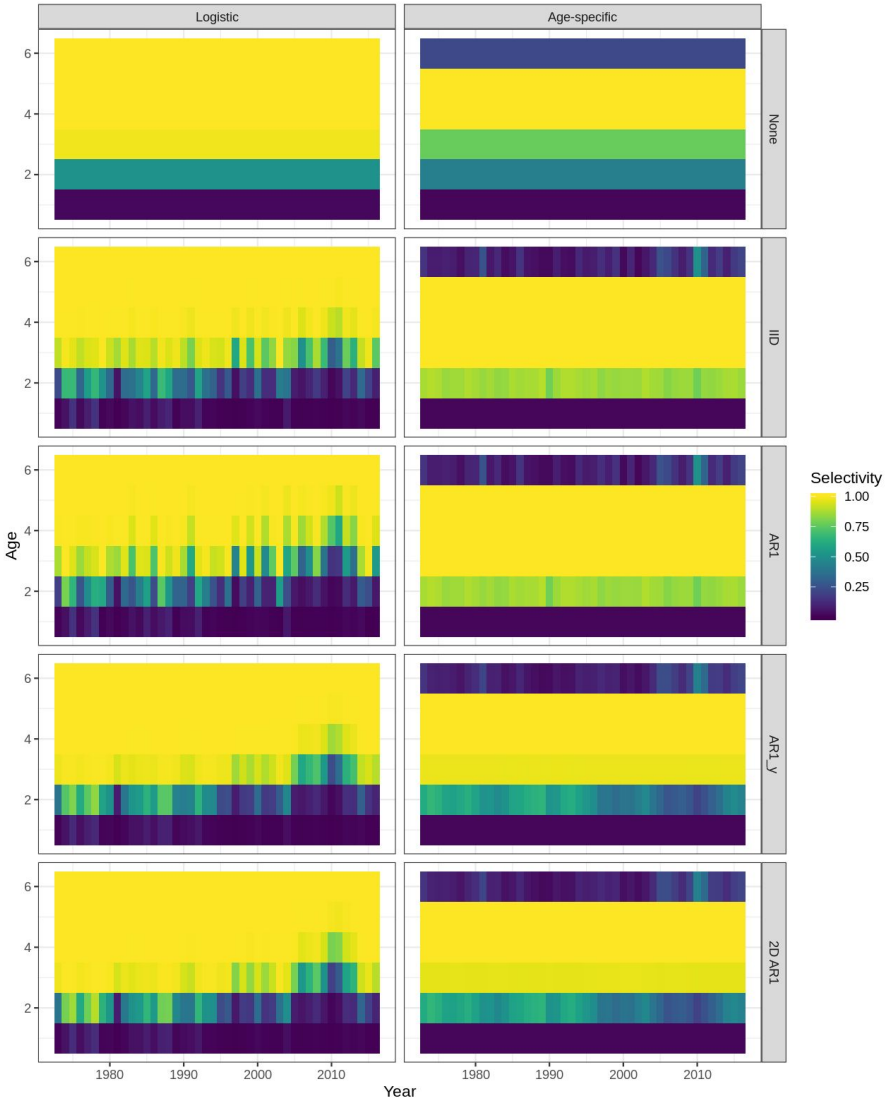
- constant across ages
- age-specific
- function of weight-at-age



Time- and age-varying processes

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

“blocks” indexed to particular years of indic
- logistic (increasing or decreasing), doubl
- constant, iid, or 1D or 2D AR1 processes f



Time- and age-varying processes

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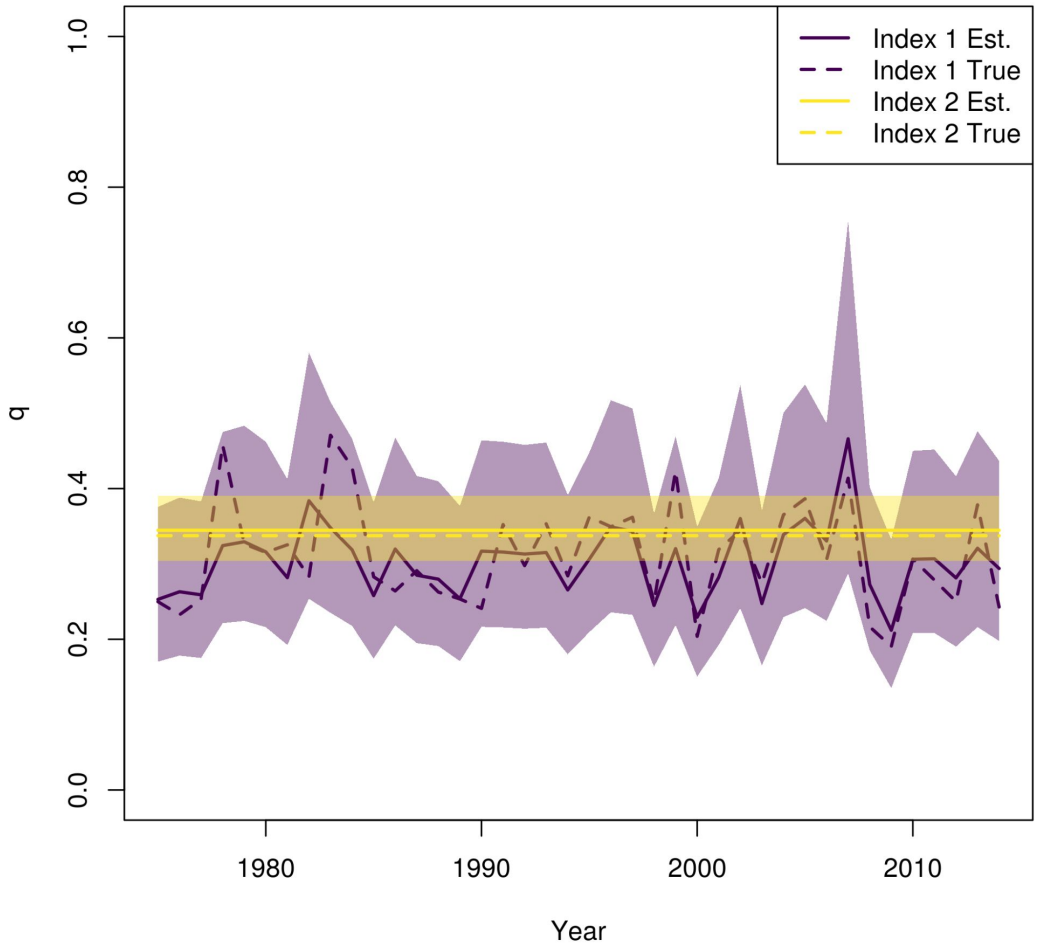
- constant, iid, or AR1 processes



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

$$\begin{aligned} \boldsymbol{\theta} &= (x_1, \sigma_x^2, \sigma_y^2) \\ \boxed{x_t} &= x_{t-1} + \mathcal{N}(0, \sigma_x^2) \\ y_t &= x_t + \mathcal{N}(0, \sigma_y^2) \end{aligned}$$

2. AR1

$-1 < \phi < 1$

$$\begin{aligned} \boldsymbol{\theta} &= (\mu, \sigma_x^2, \sigma_y^2, \phi) \\ \boxed{x_t} &= \mu + \phi x_{t-1} + \mathcal{N}(0, \sigma_x^2) \\ y_t &= x_t + \mathcal{N}(0, \sigma_y^2) \end{aligned}$$

Environmental effects on…

Recruitment models:

1. Random walk
2. Random about mean
3. Beverton-Holt
4. Ricker

$$\hat{R}_t = R_{t-1} \quad e^{\gamma x} R_0 \quad \frac{\alpha S e^{\gamma x}}{1+\beta S} \quad \frac{\alpha S}{1+\beta S e^{\gamma x}} \quad \frac{\alpha S}{e^{\gamma x}+\beta S} \quad \alpha S e^{-\beta S+\gamma x} \quad \alpha S e^{-\beta S(1+\gamma x)}$$

Iles & Beverton (1998)

M models:

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

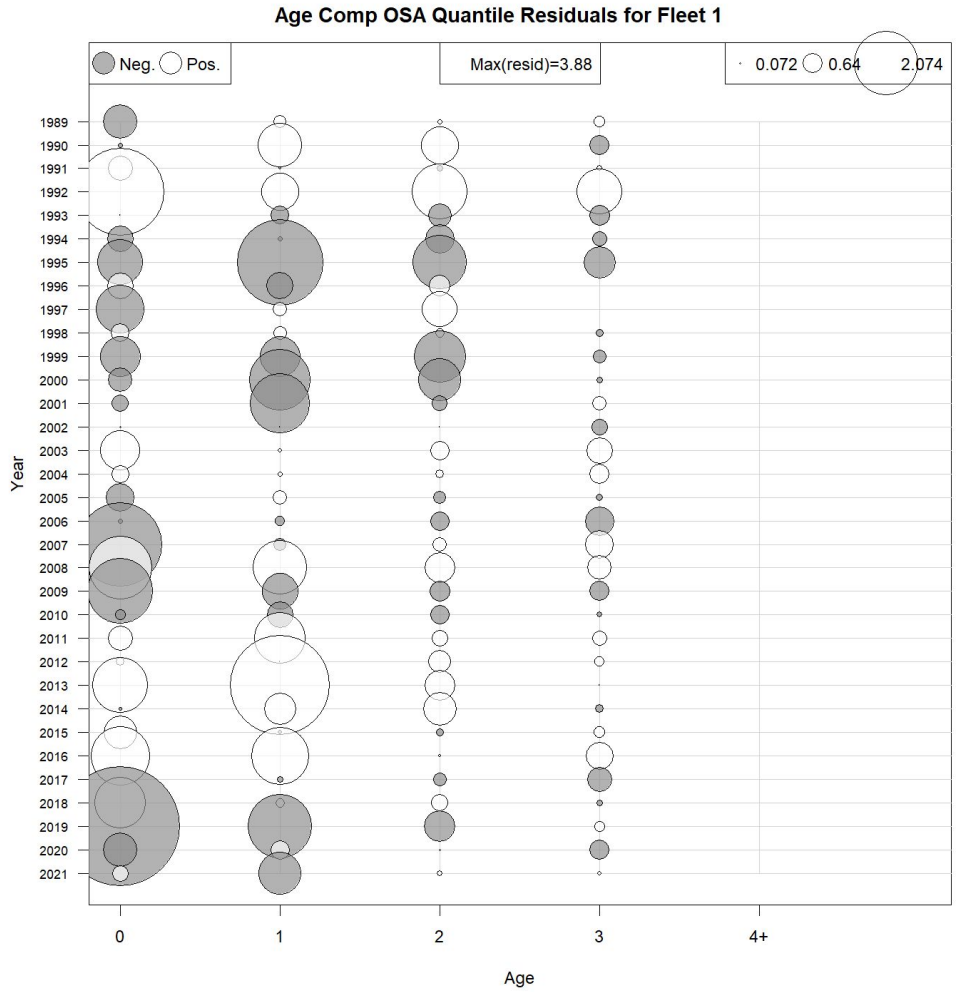
$$M_{y,a} = e^{\log\mu_M + bW_{y,a} + \beta_1 E_y + \beta_2 E_y^2 + \delta_{y,a}}$$

Catchability models: see M.

WHAM: Other useful features

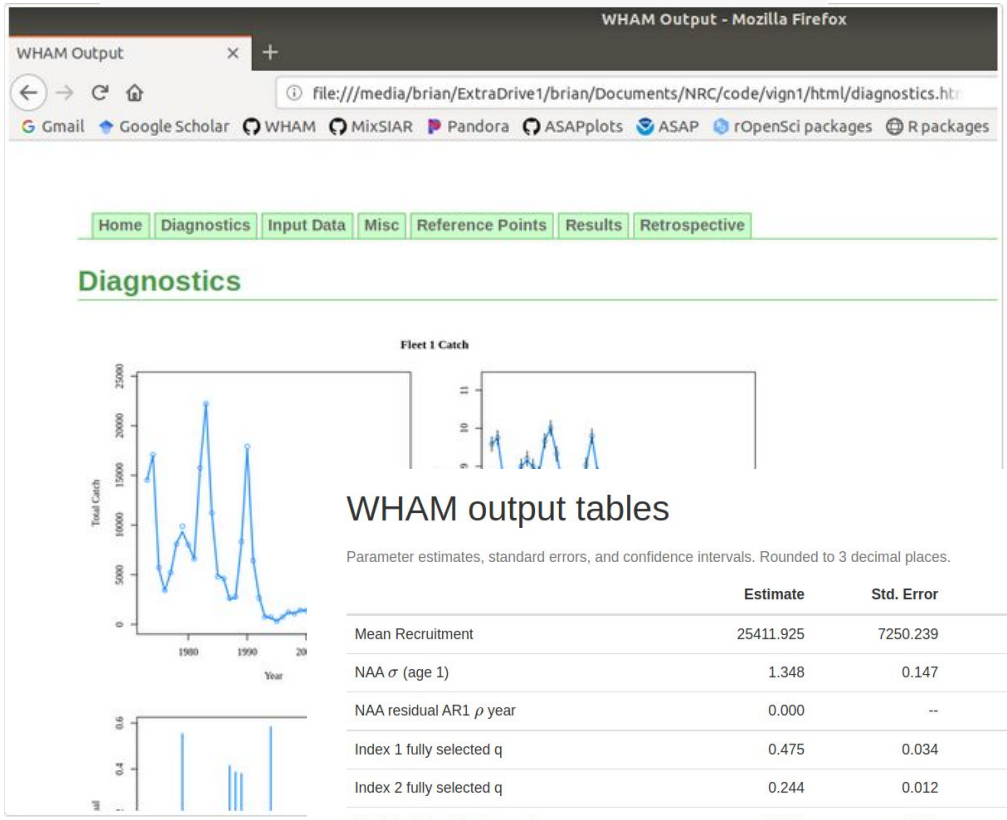
Alternative age composition models

- Multinomial
- Dirichlet
- Dirichlet-multinomial
- Logistic normal



WHAM: Other useful features

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



WHAM output tables

Parameter estimates, standard errors, and confidence intervals. Rounded to 3 decimal places.

	Estimate	Std. Error	95% CI lower	95% CI upper
Mean Recruitment	25411.925	7250.239	14527.220	44452.134
NAA σ (age 1)	1.348	0.147	1.088	1.669
NAA residual AR1 ρ year	0.000	--	--	--
Index 1 fully selected q	0.475	0.034	0.412	0.548
Index 2 fully selected q	0.244	0.012	0.222	0.268
Block 1: Selectivity for age 1	0.036	0.003	0.031	0.042
Block 1: Selectivity for age 2	0.352	0.018	0.317	0.387
Block 1: Selectivity for age 3	0.821	0.038	0.734	0.884
Block 1: Selectivity for age 4	1.000	--	--	--
Block 1: Selectivity for age 5	1.000	--	--	--
Block 1: Selectivity for age 6+	0.154	0.019	0.119	0.196
Block 2: Selectivity for age 1	0.027	0.003	0.022	0.035

Thanks to r4ss and ASAPplots!

```
check_convergence(m1)
```

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

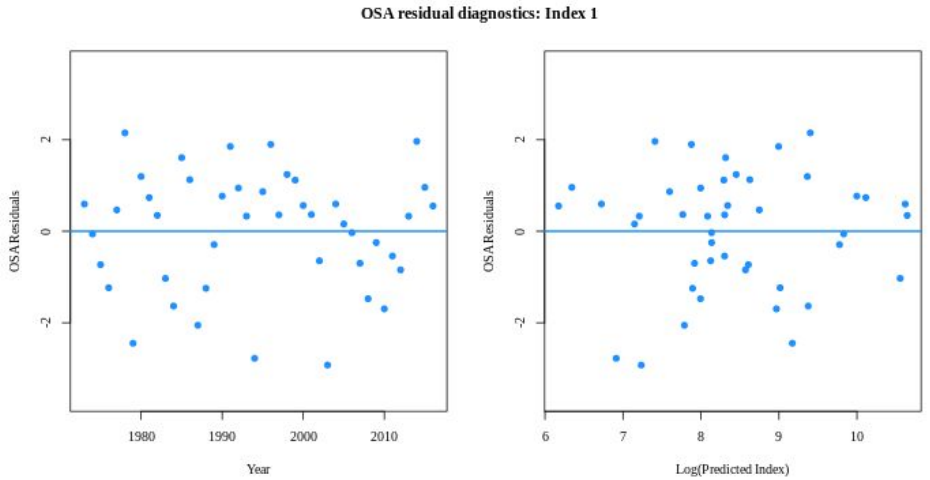
```
res <- compare_wham_models(mods, fname=
```

```
#>        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
```

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



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Validation of ecological state space models using the Laplace approximation

Uffe Høgsbro Thygesen[1] · Christoffer Moesgaard Albertsen[1] · Casper Willestofte Berg[1] · Kasper Kristensen[1] · Anders Nielsen[1]

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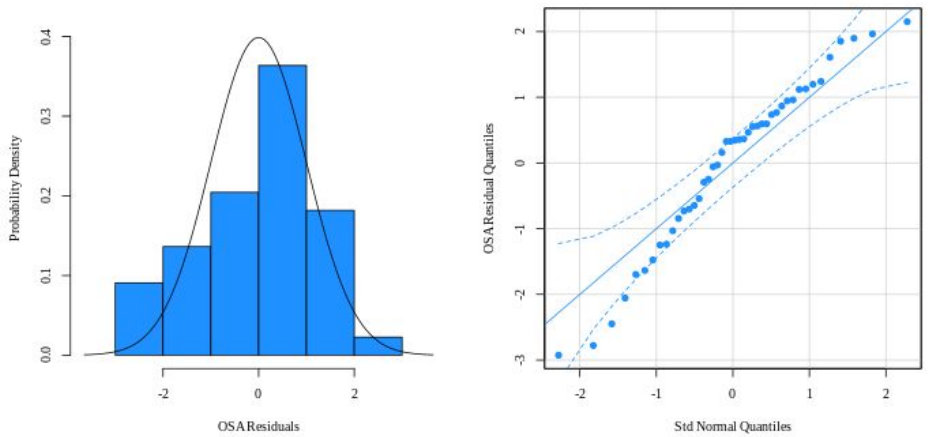

Model validation for compositional data in stock assessment models: Calculating residuals with correct properties

Vanessa Trijoulet[a,*], Christoffer Moesgaard Albertsen[a], Kasper Kristensen[a], Christopher M. Legault[b], Timothy J. Miller[b], Anders Nielsen[a]

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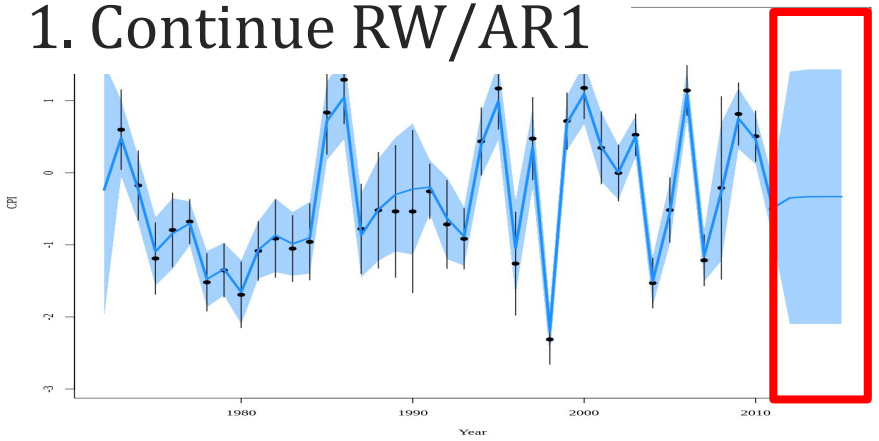
[b] Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA 02543, USA

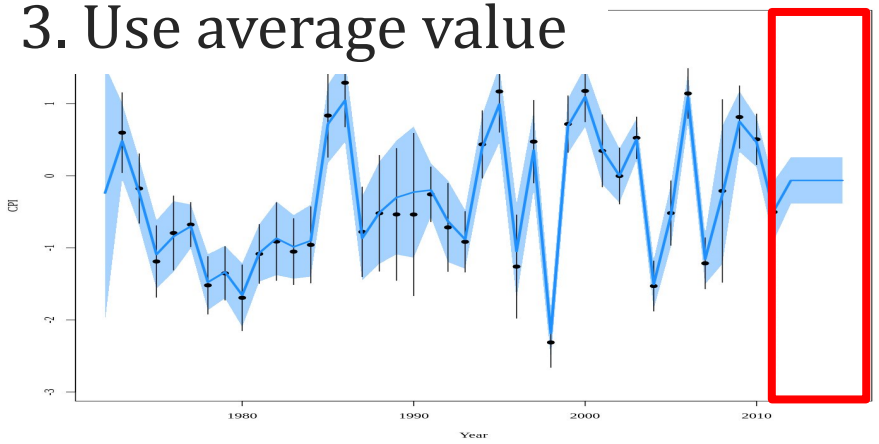
WHAM: other useful features

Environmental covariate options in projections

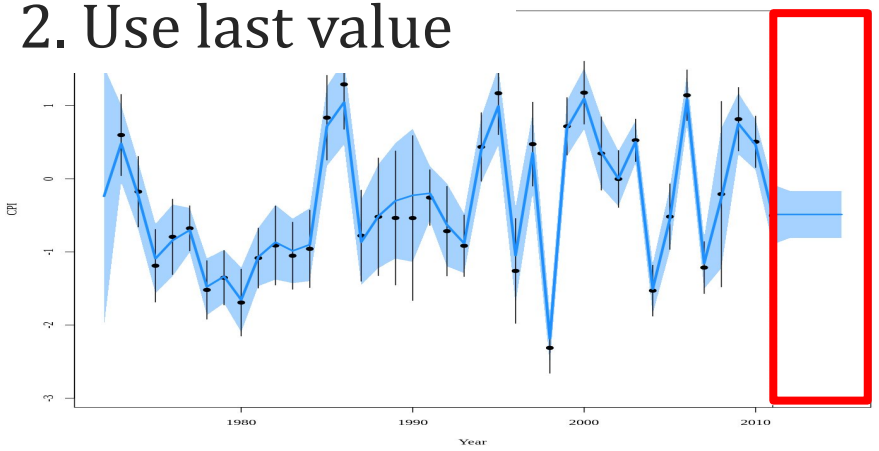
1. Continue RW/AR1



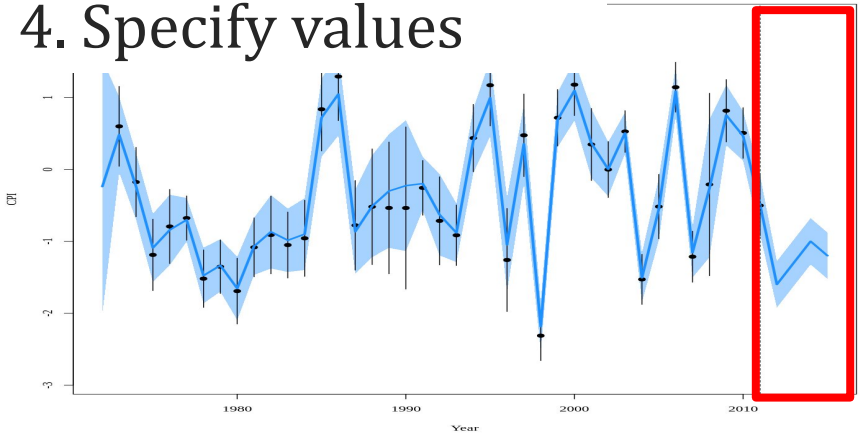
3. Use average value



2. Use last value

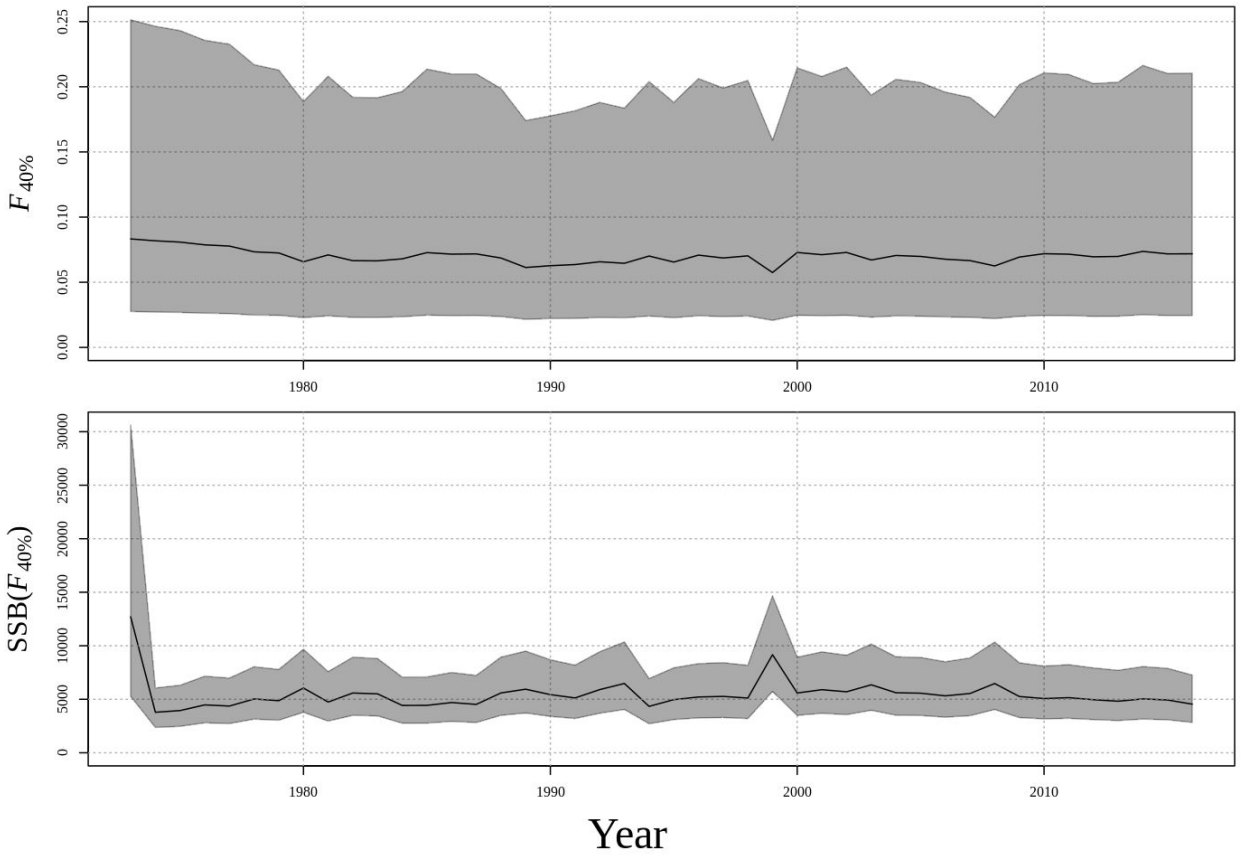


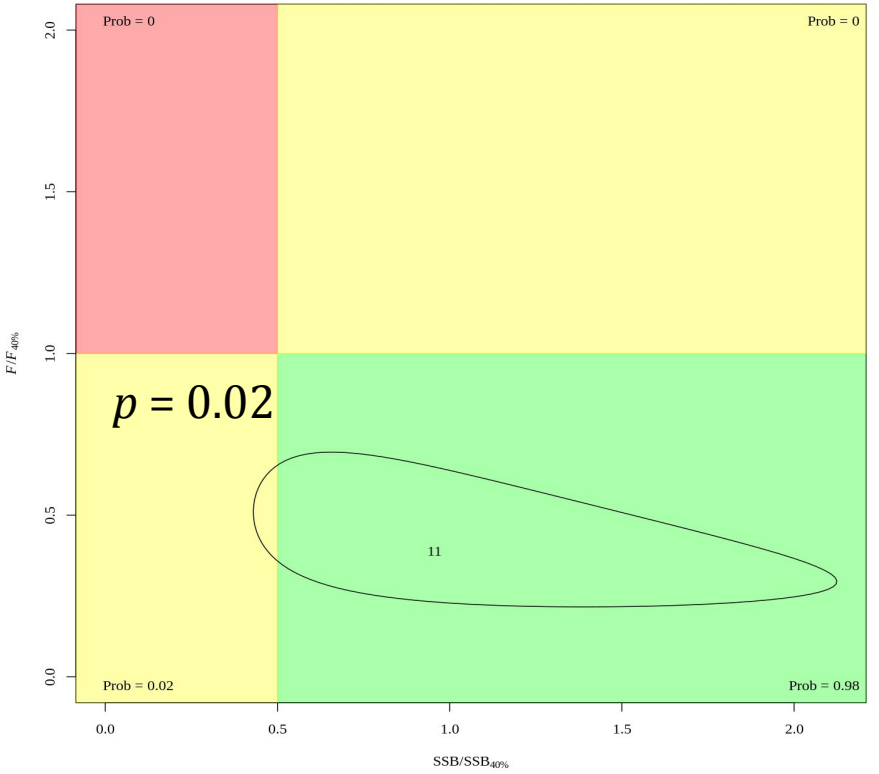
4. Specify values



WHAM: Other useful features

Internal estimation of reference points and status

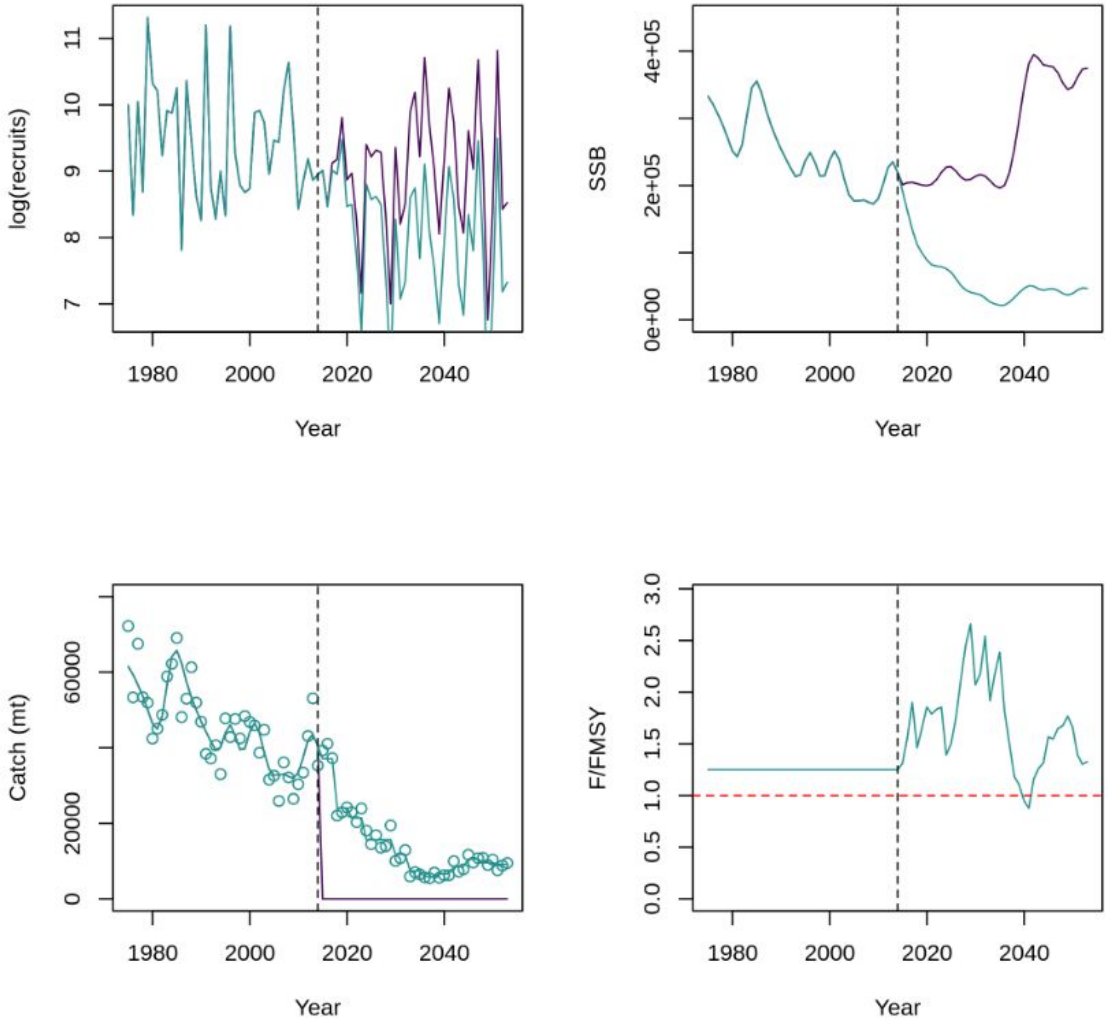




WHAM: Other useful features

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.

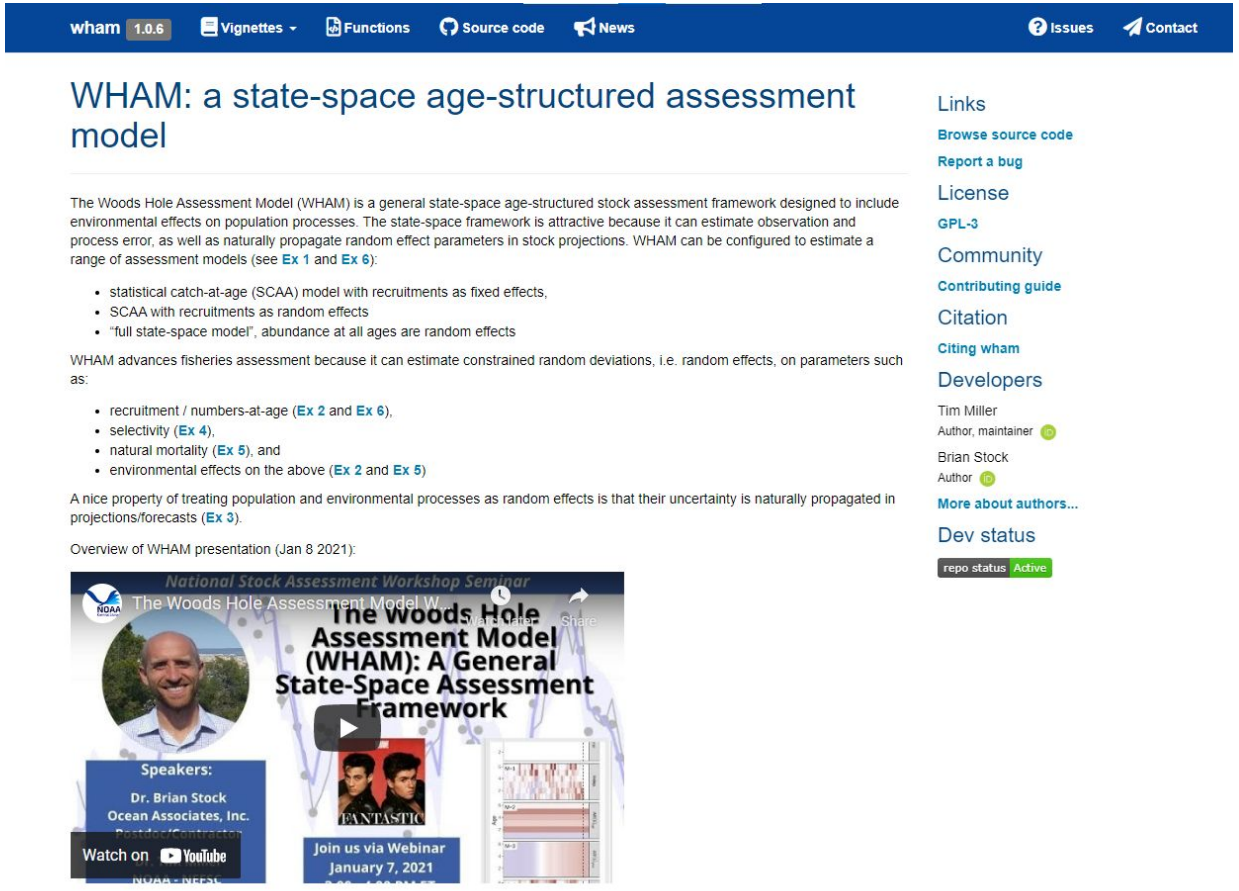


WHAM: Other useful features

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



Compiles .cpp

Basic use:

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

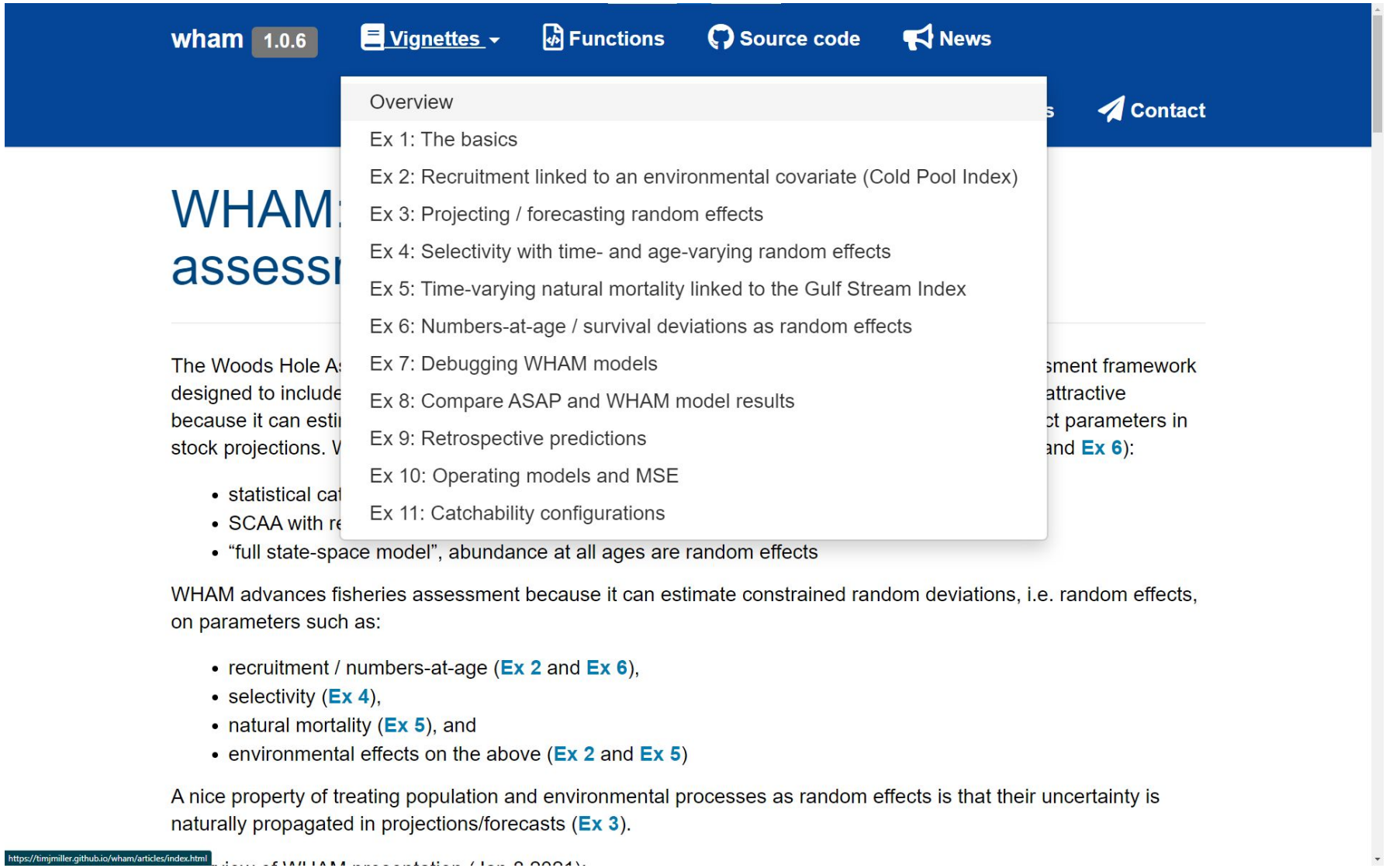
```
library(wham)
```

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

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

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

https://timjmiller.github.io/wham



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