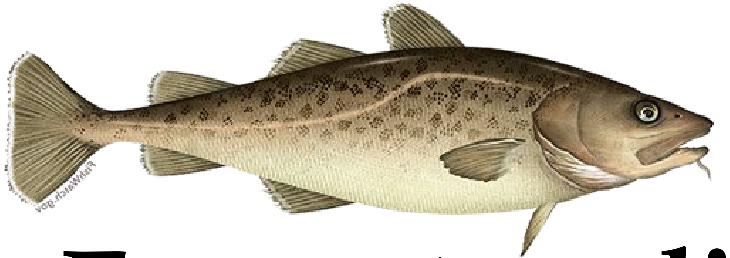


Ecosystem-linked assessment model for Gulf of Alaska Pacific cod to assess climate change driven changes in productivity

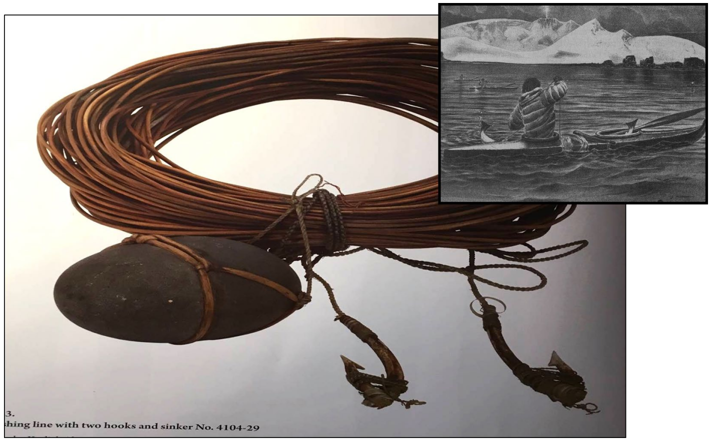
Steven J Barbeaux

2023 Western Groundfish Conference

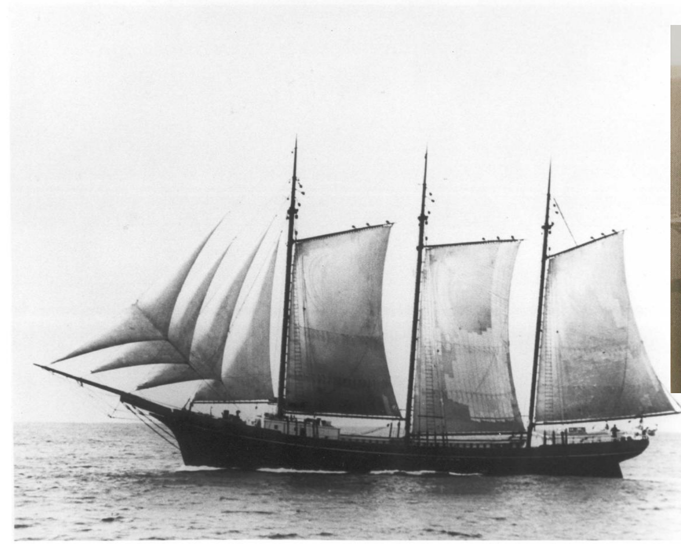
Juneau, Alaska

April 25, 2023

West, C.F., Etnier, M.A., Barbeaux, S., Partlow, M.A. and Orlov, A.M., Size distribution of Pacific cod (*Gadus macrocephalus*) in the North Pacific Ocean over 6 millennia. *Quaternary Research*, pp.1-21.



More than 6,000 years as an important resource to Alaskan coastal communities



Salt cod dory fishery 1863-1940's

Pacific cod is an historically important resource to Alaskan coastal communities

- **Atxidax̂** – Unangan for the fish that stops
- The reason for the 1940's collapse is unknown, they just stopped…

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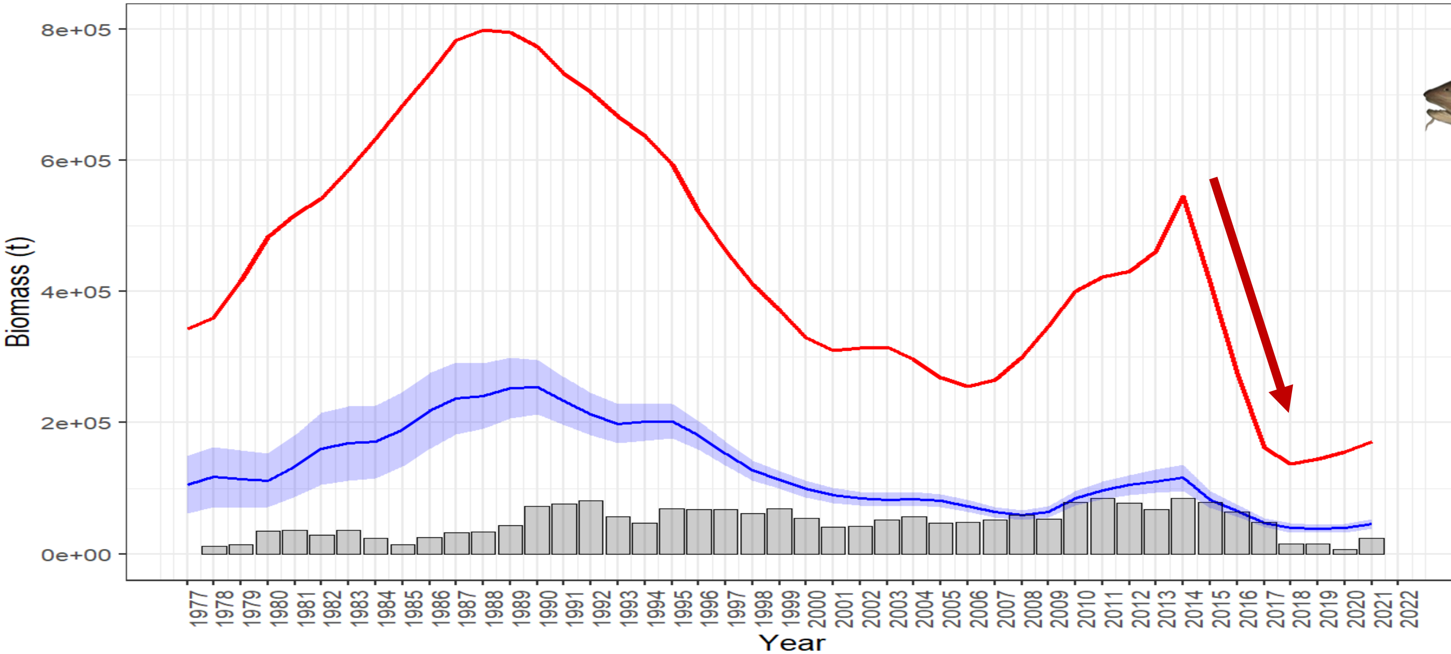
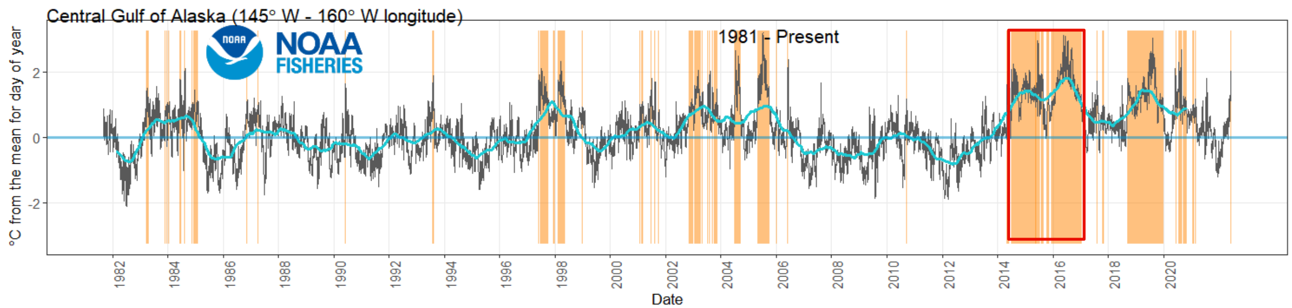




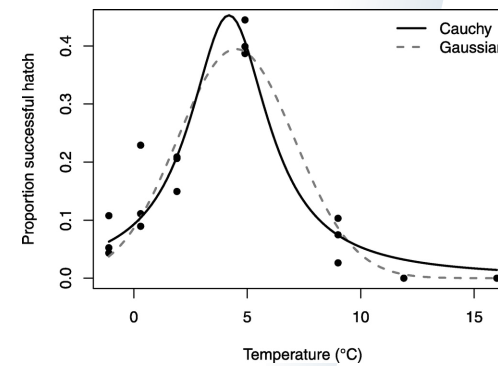
Modern fishery 1977-Present

- Gadid outburst in the 1980's
- Expansion of the fishery in the 1980-1990's
- Sudden collapse in 2016-2018 following severe marine heatwave

SST data: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html

- Bio-energetics hypothesis for adult collapse (Barbeaux et al. 2020)
  - Warmer temperatures were throughout the year and water column
  - Higher metabolism in warmer temps lead to higher forage requirements
  - Indications of lower forage amounts in 2015-2016
  - Combination likely lead to higher Pacific cod **natural mortality** for heatwave years.

- Low egg hatch and larval survival (Laurel and Rogers 2020)
  - Laboratory studies indicate increased temperature results in lower egg survival and fewer larvae
  - Poor spawning habitat during winter heatwaves
  - Leading to decreased **recruitment** for heatwave years



- Barbeaux, S.J., Holsman, K. and Zador, S., 2020. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific Cod Fishery. Frontiers in Marine Science, 7, p.703.
- Laurel, B.J. and Rogers, L.A., 2020. Loss of spawning habitat and pre-recruits of Pacific cod during a Gulf of Alaska heatwave. Canadian Journal of Fisheries and Aquatic Sciences, 77(4), pp.644-650.

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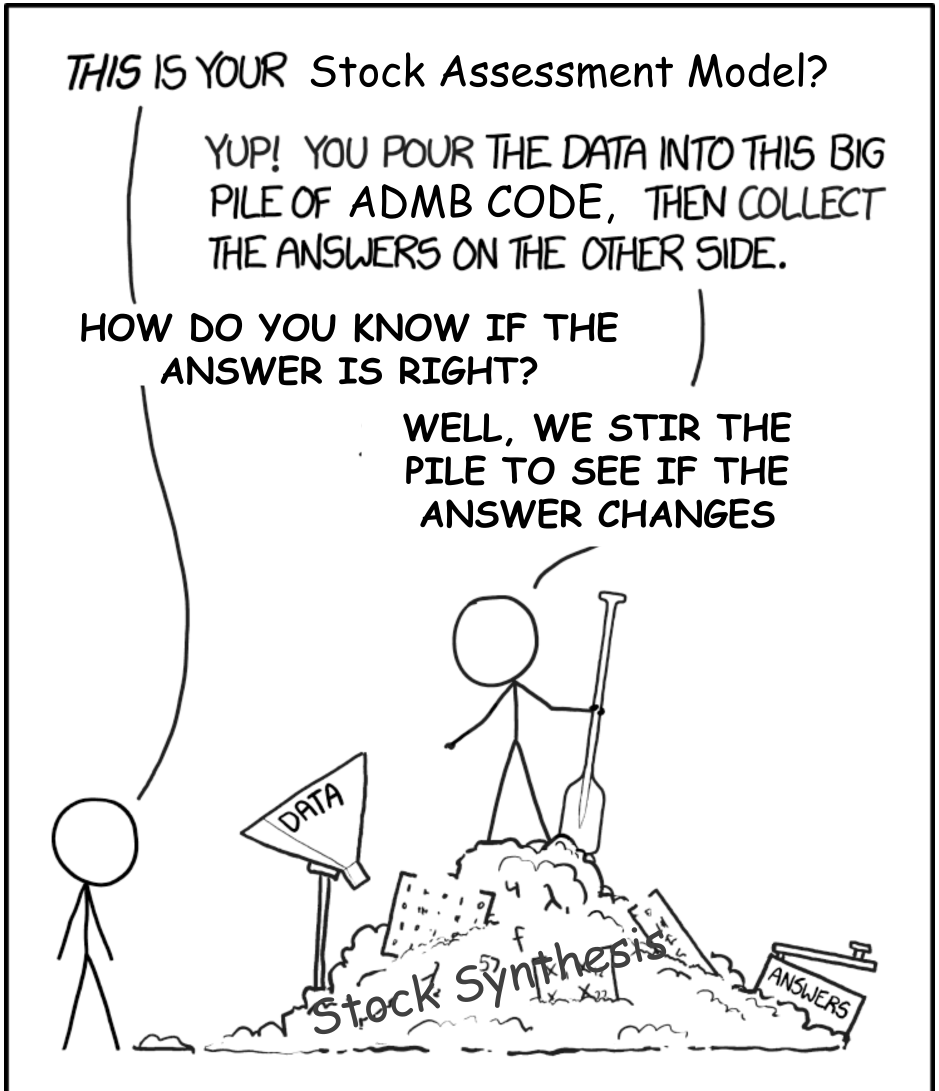
Gulf of Alaska Pacific cod model



https://xkcd.com/1838/

- Single species age-structured assessment model in Stock Synthesis
- Base model with no environmental links for projection
- Assumes static M, average growth, and average recruitment (1977-present) for projections
- Uncertainty in projections based on past variability in recruitment and growth

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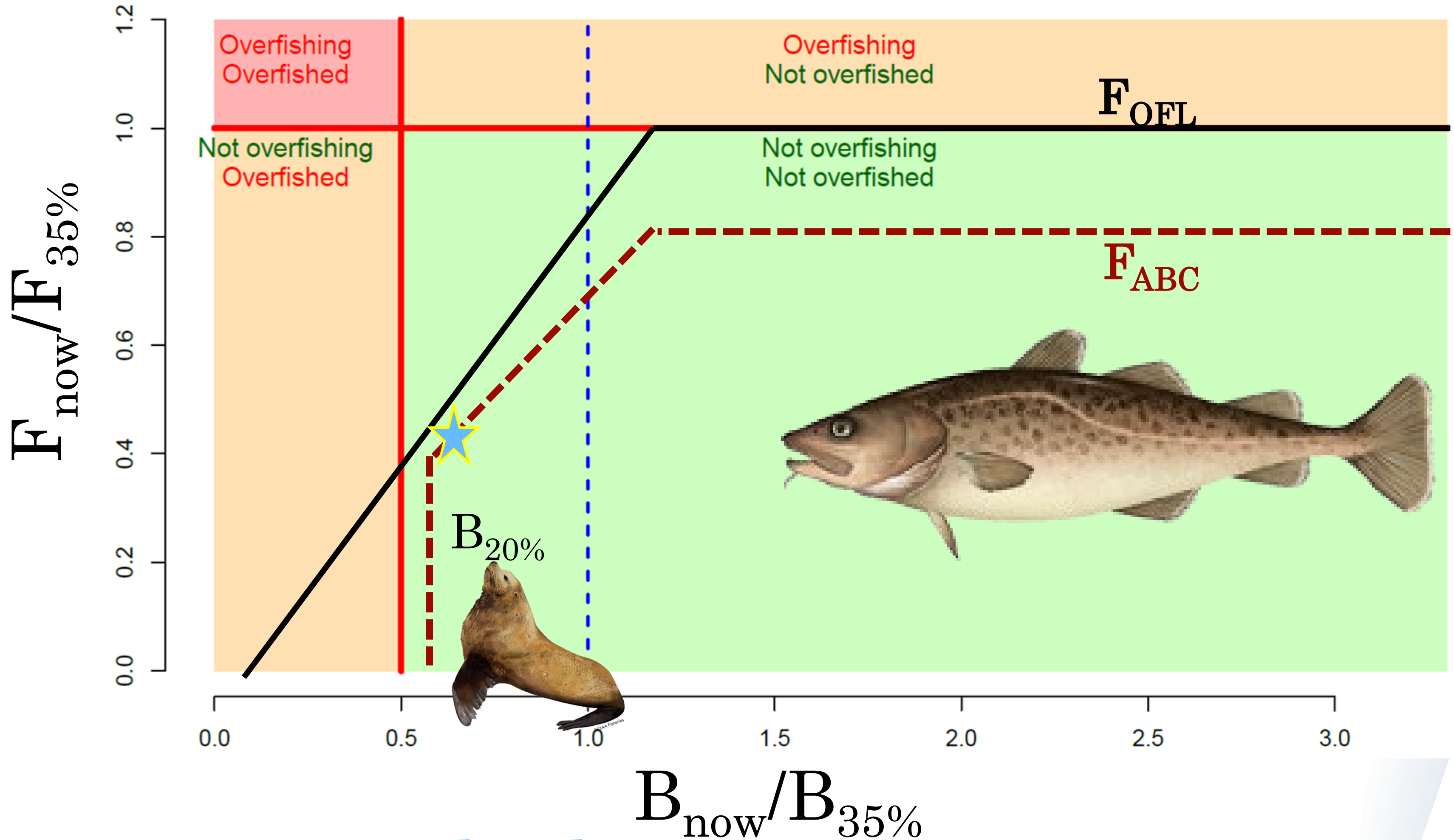

Harvest control rule

$B_{35\%}$ is proxy for B_{MSY}

- Based on female spawning biomass ($B_{\%}$)
- Sloping control rule with reduced F below $B_{40\%}$
- Overfished at $B_{17.5\%}$ or projected continue to be below $B_{35\%}$ after 10 years
- Steller sea lion rules with closure of federal fishery below $B_{20\%}$

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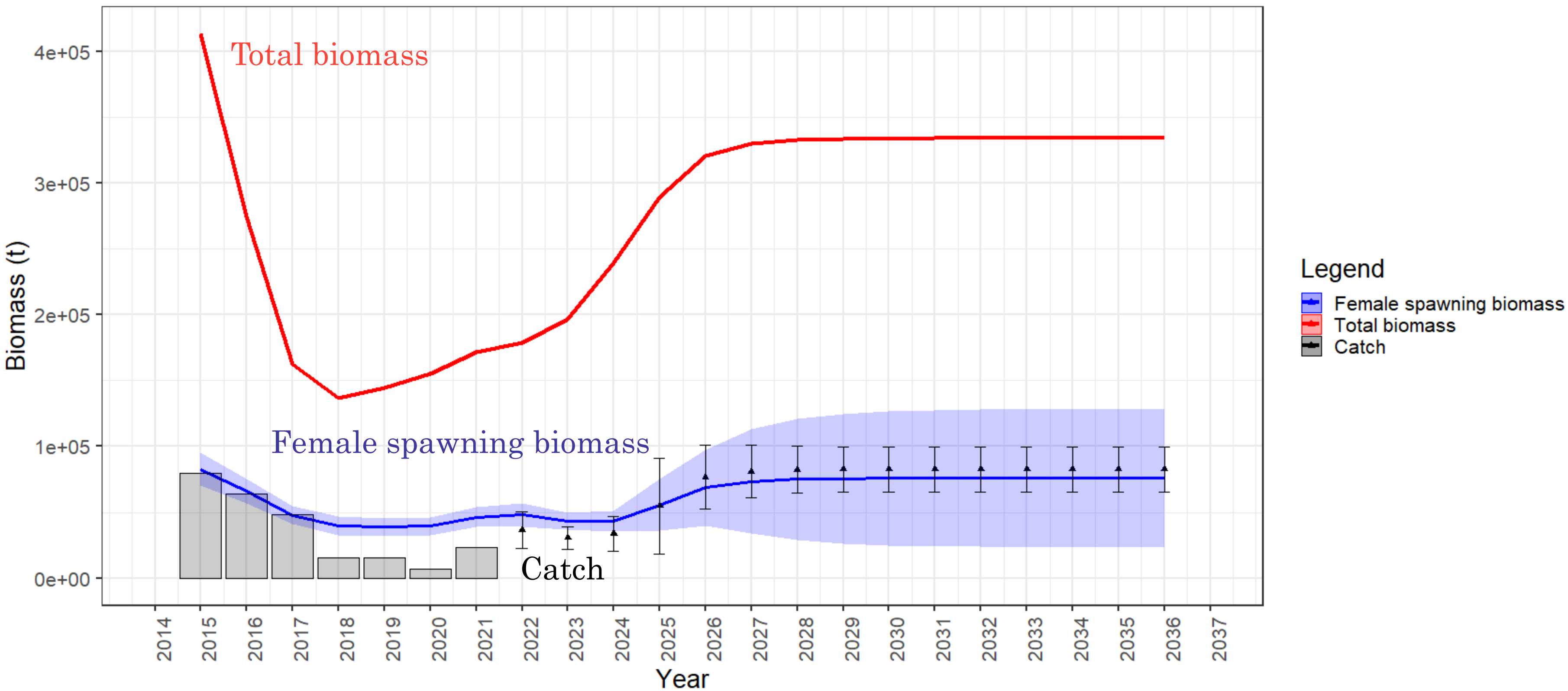
Current management for Gulf of Alaska Pacific cod assumes stationarity in population production, **but we know that likely won't be true.**



Can we do better?

- Base model with no environmental links for projection
- Assumes static M, average growth, and average recruitment (1977-present)
- Uncertainty based on past variability in recruitment and growth

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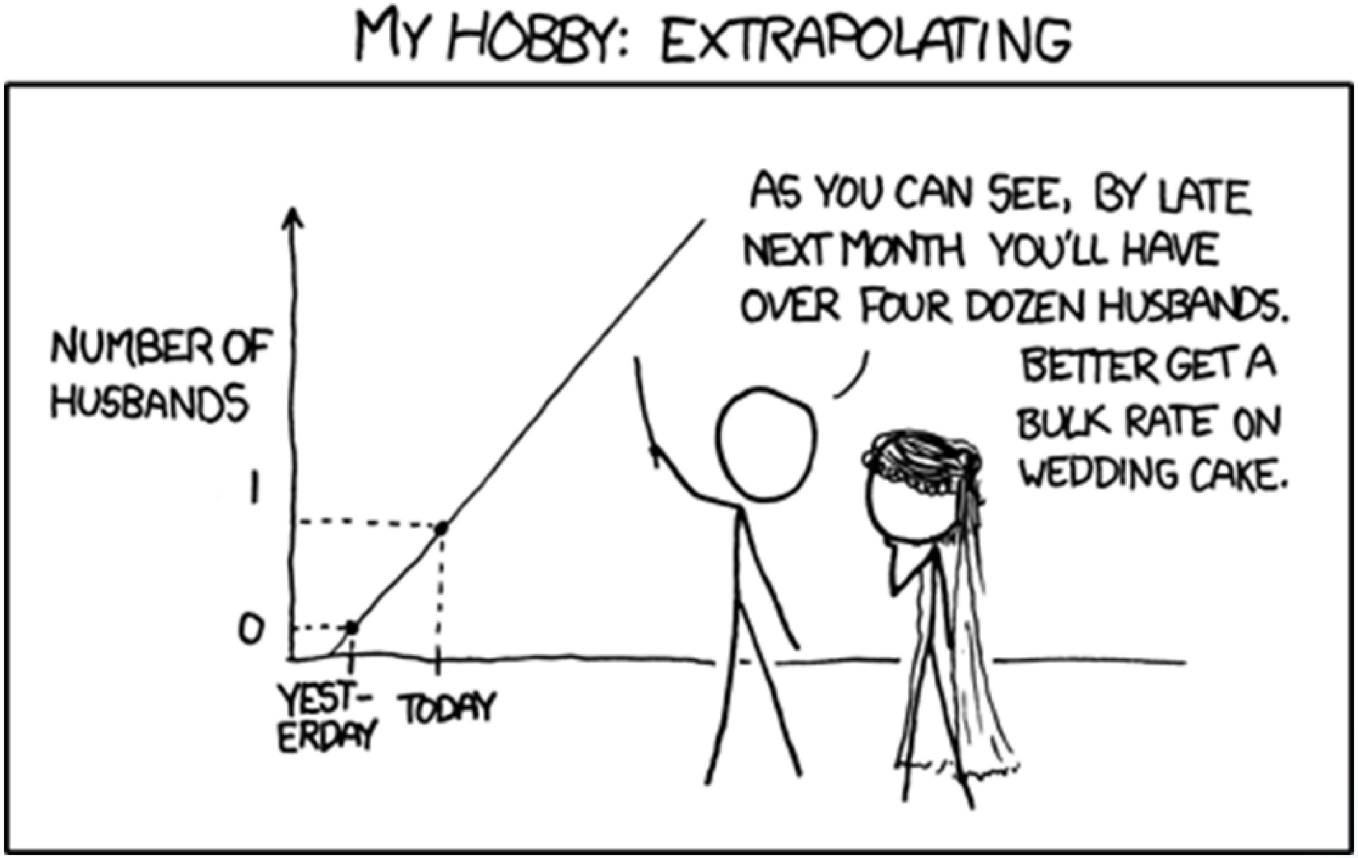
Environmentally-linked models: Applying lessons from the heatwave



https://xkcd.com/605/

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Mean recruitment

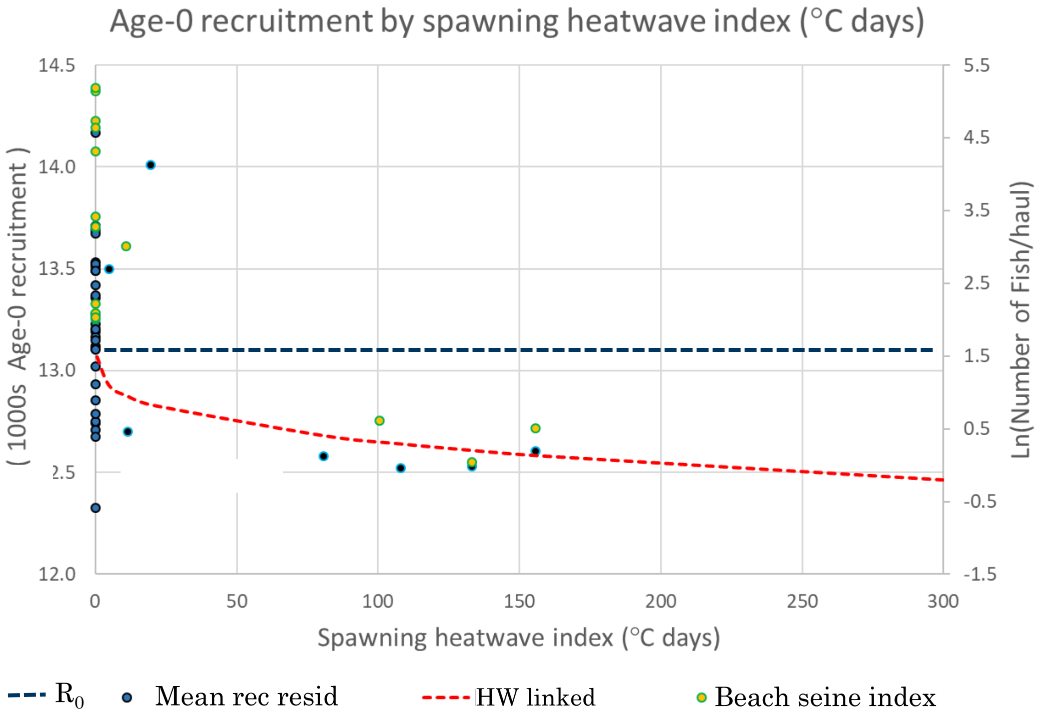
$$R_y = \left(R_0 e^{\vartheta}\right) e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}$$

Base model with mean recruitment R_0
For 1977-2019

Heatwave index linked mean recruitment

$$R_y = e^{\vartheta + \ln\left(R_0 e^{\omega I_{Sy}^{\frac{1}{3}}}\right)} e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}$$

Heatwave index linked Beverton-Holt with steepness h = 1 and $\sigma_R = 0.44$



- Lower recruitment with increased temperature but only when above heatwave conditions.

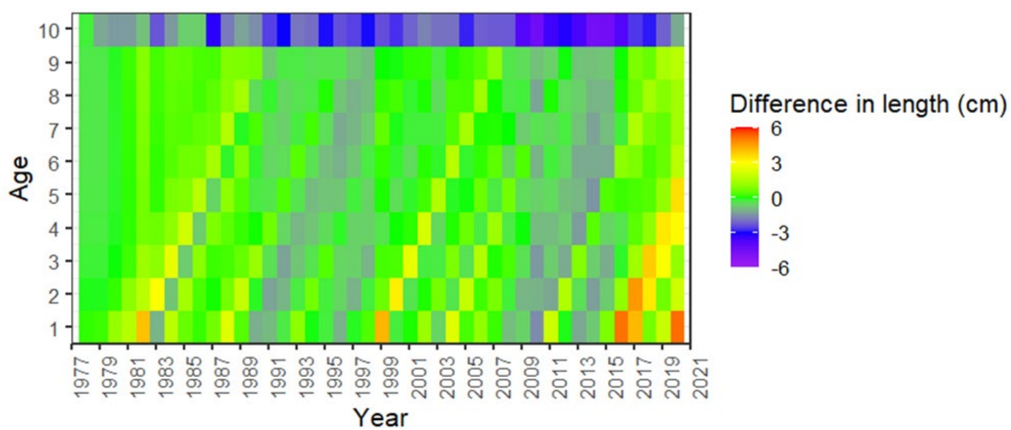
Temperature dependent von Bertalanffy growth

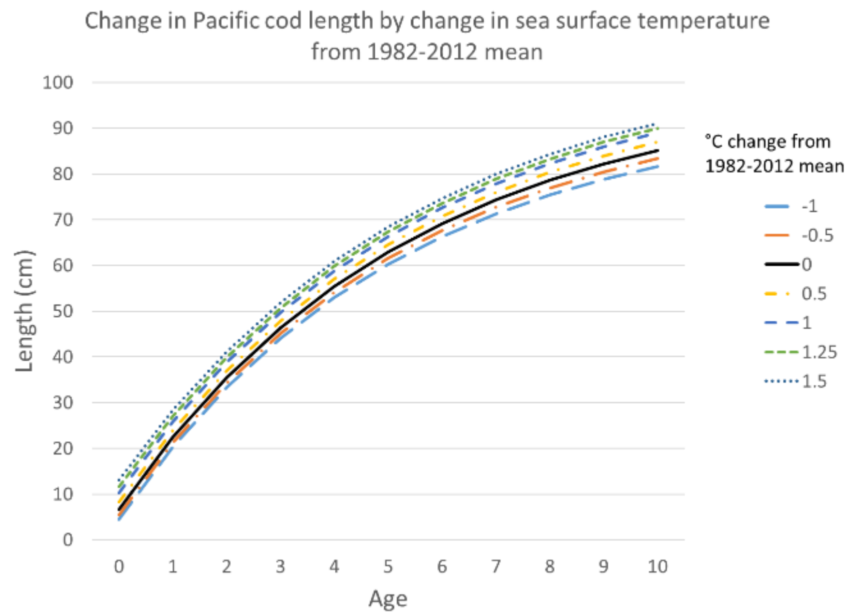
$$L_{ay} = L_{2y} - (L_{2a} - L_{1a})e^{-ak\left(e^{-\varphi f_{jy}}\right)}$$

$$L_{1a} = \bar{L}_1\left(\gamma \frac{e^{\left(0.2494+0.3216\left(\bar{t}+f_{jy}\right)-0.0069\left(\bar{t}+f_{jy}\right)^2-0.0004\left(\bar{t}+f_{jy}\right)^3\right)}}{e^{(0.2494+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3)}}\right)$$

$$L_{2y} = \overline{L_2}e^{\nu f_{jy}}$$

Static growth vs Temp. Dependent





Temperature dependent growth

- L_{1a} based on Laurel et al. (2015) larval growth rate by June mean sea surface temperature
- Apparent cohort effect in model results, with high growth for heatwave cohorts.

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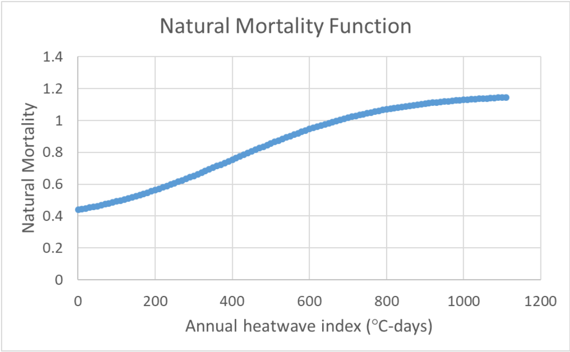
Heatwave linked natural mortality with asymptote

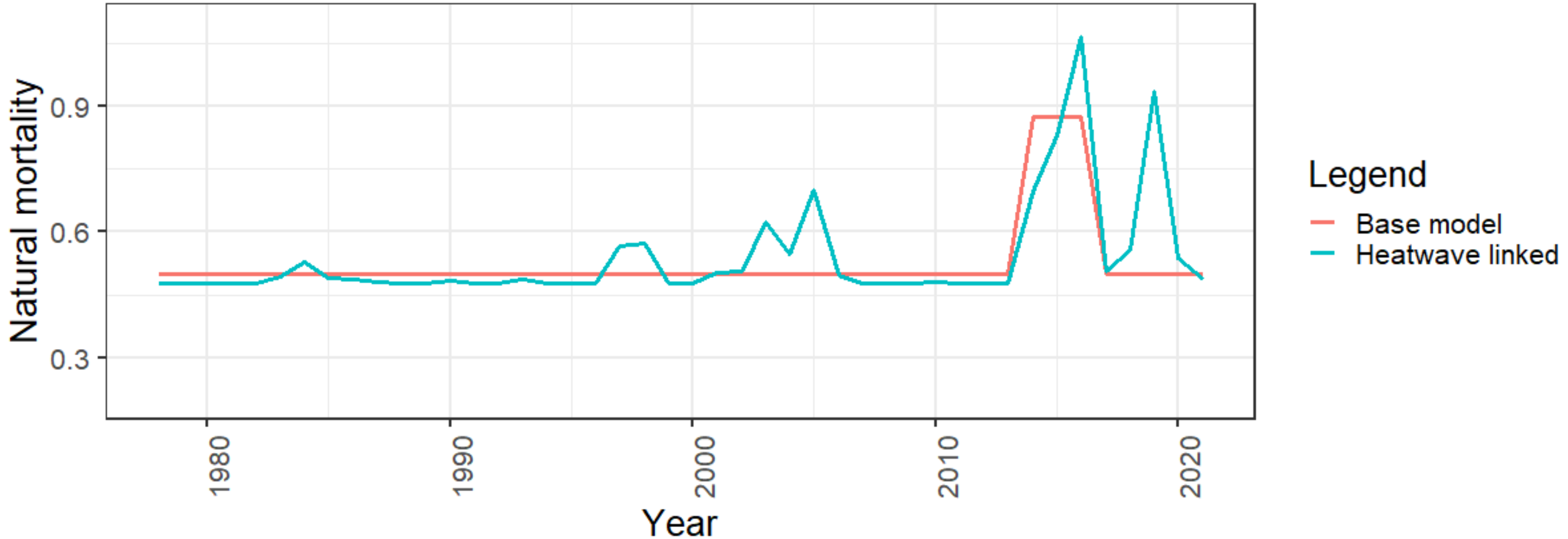
$$M_y = \widehat{M} + \eta l_y$$

$$l_y = \lambda \Big/ \left(1 + e^{-\varsigma(I_{Ay} - \psi)}\right)$$

Logistic function fit iteratively

- $\lambda = 0.65$
- $\varsigma = 0.05$
- $\psi = 400$





Heatwave linked natural mortality

- Higher natural mortality with increased temperature and higher probability of heatwave conditions.

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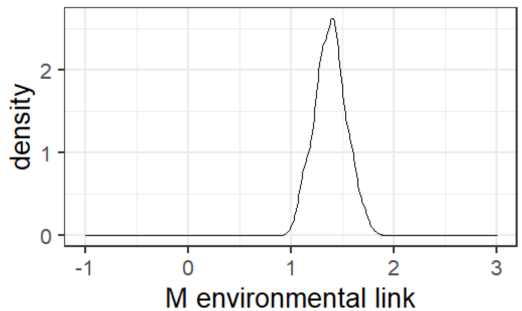
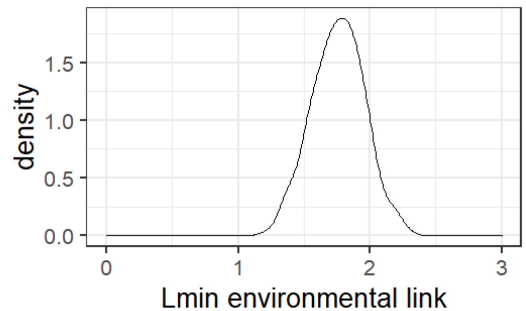
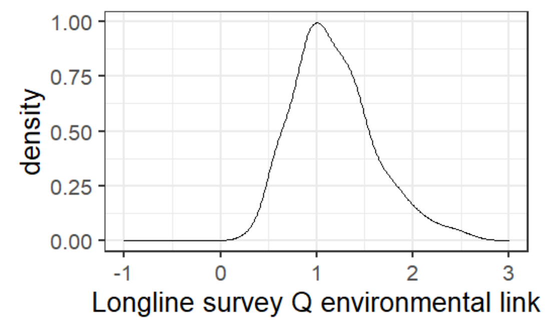
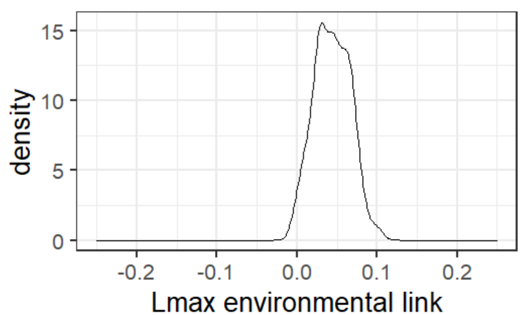
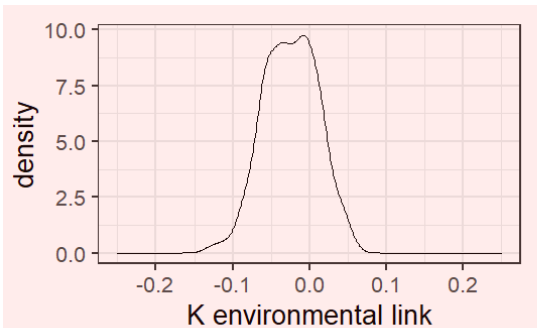
		MCMC link posterior percentile				Link MLE		
Parameter	Link	2.50%	50%	97.50%	p	Value	σ	Gradient
M	η	1.0974	1.3865	1.7005	< 0.002	1.4098	0.14725	-3.91E-06
L_1	γ	1.3676	1.7659	2.1559	< 0.002	1.8003	0.20917	5.98E-07
L_2	ν	0.0023	0.0434	0.0854	0.02	0.0476	0.02208	2.68E-06
K	**ϕ**	**-0.0893**	**-0.0235**	**0.0423**	**0.25**	**-0.0299**	**0.03510**	**1.32E-06**
R_0	ω	-0.0141	-0.0076	-0.0015	0.002	-0.0072	0.00351	-2.66E-06
Q_{BT}	τ	0.5235	1.1259	2.2078	< 0.002	1.3188	0.56170	9.55E-0.8











Model 21.2 Environmental links

- Link parameters fit with uninformative priors
- Inverse Hessian and MCMC results agree
- ϕ link to K not significantly different from 0

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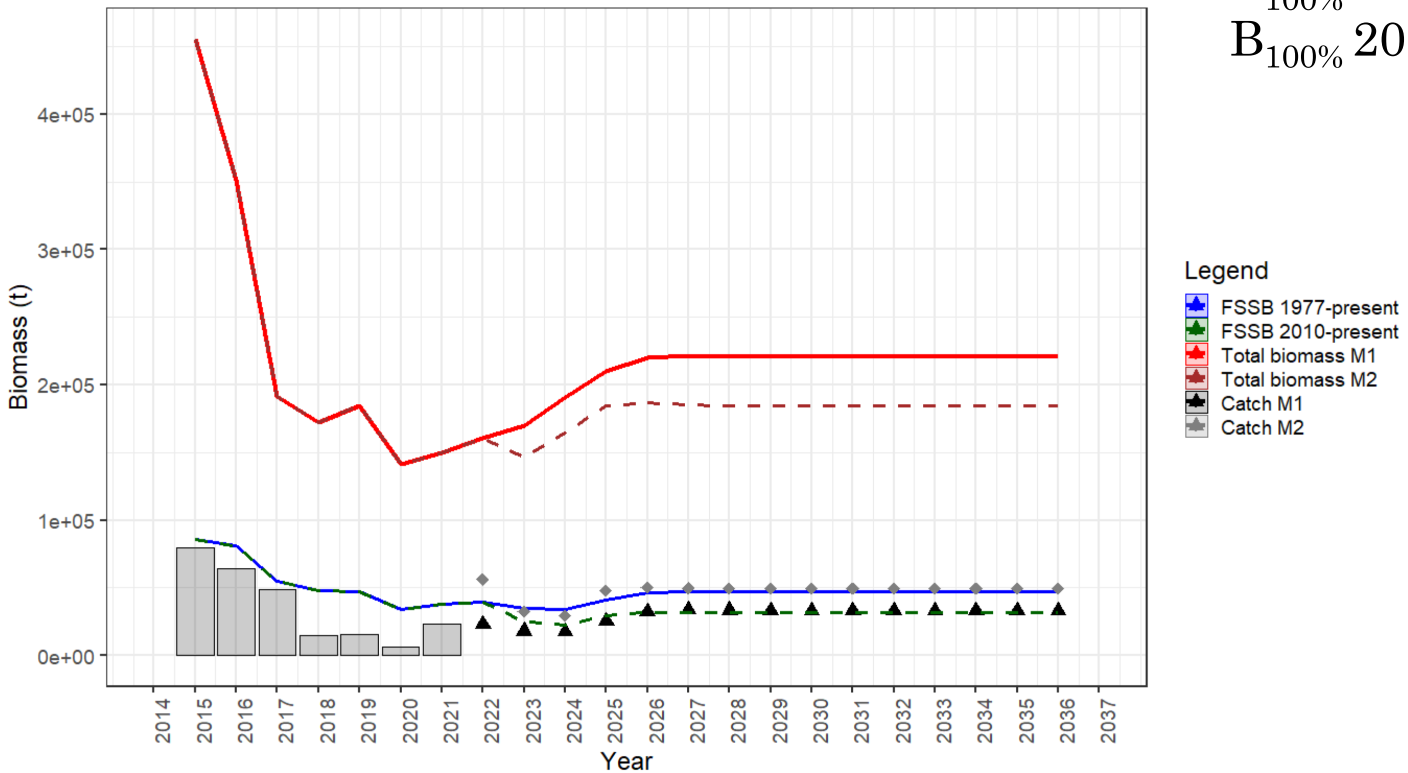
What if the previous 10 years are the norm going forward for the next 15?

$B_{100\%}$ 1977-Present = 162 Kt
$B_{100\%}$ 2010-Present = 71 Kt



Redefine reference points?

- Still assumes static M, average growth, and average recruitment but different baselines
- Status quo leaves us at $B_{29\%}$, overfished by our definitions.
- Changing our baseline to the previous 10 years allows us to not be ‘overfished’, but at a lower overall biomass in the ecosystem.

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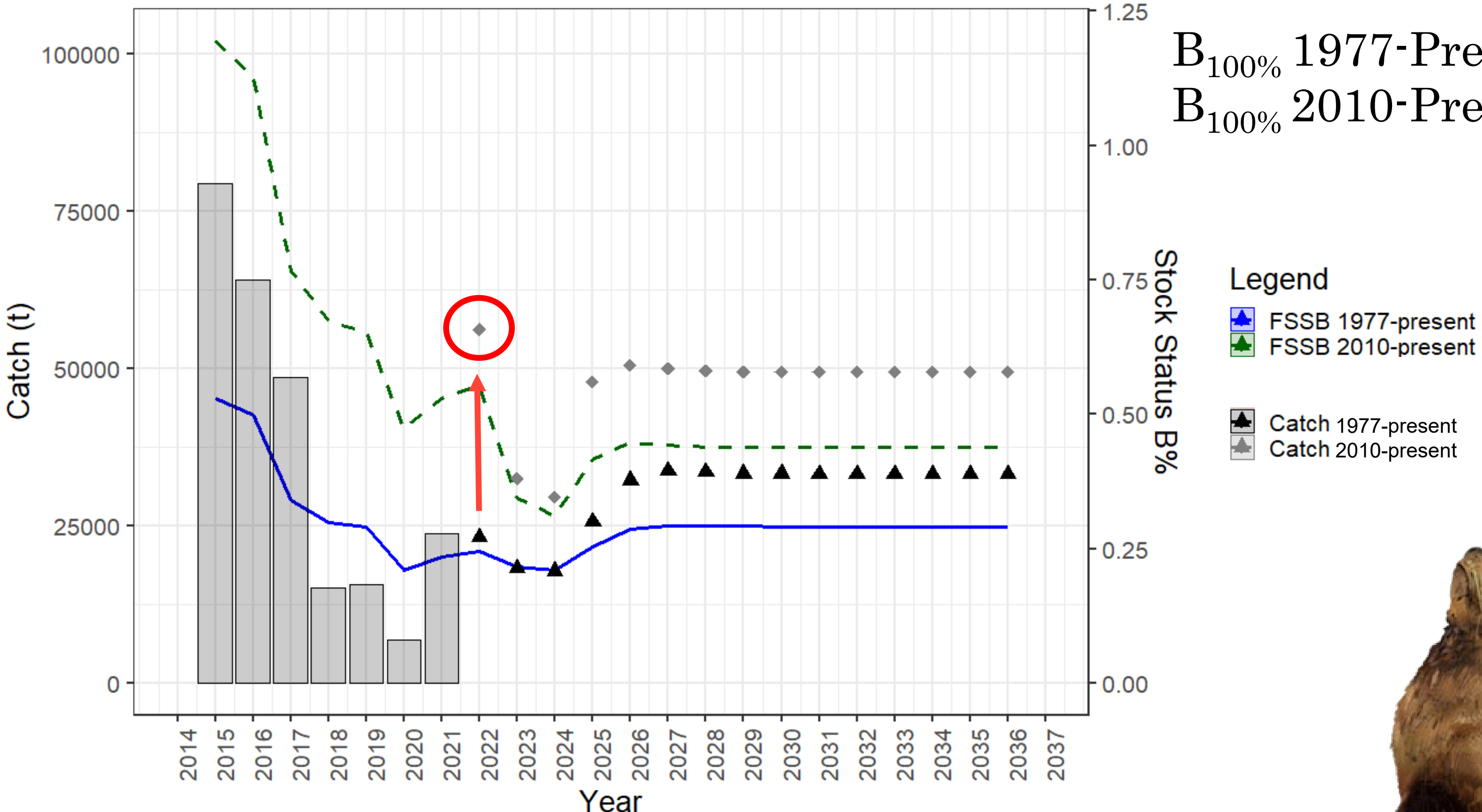

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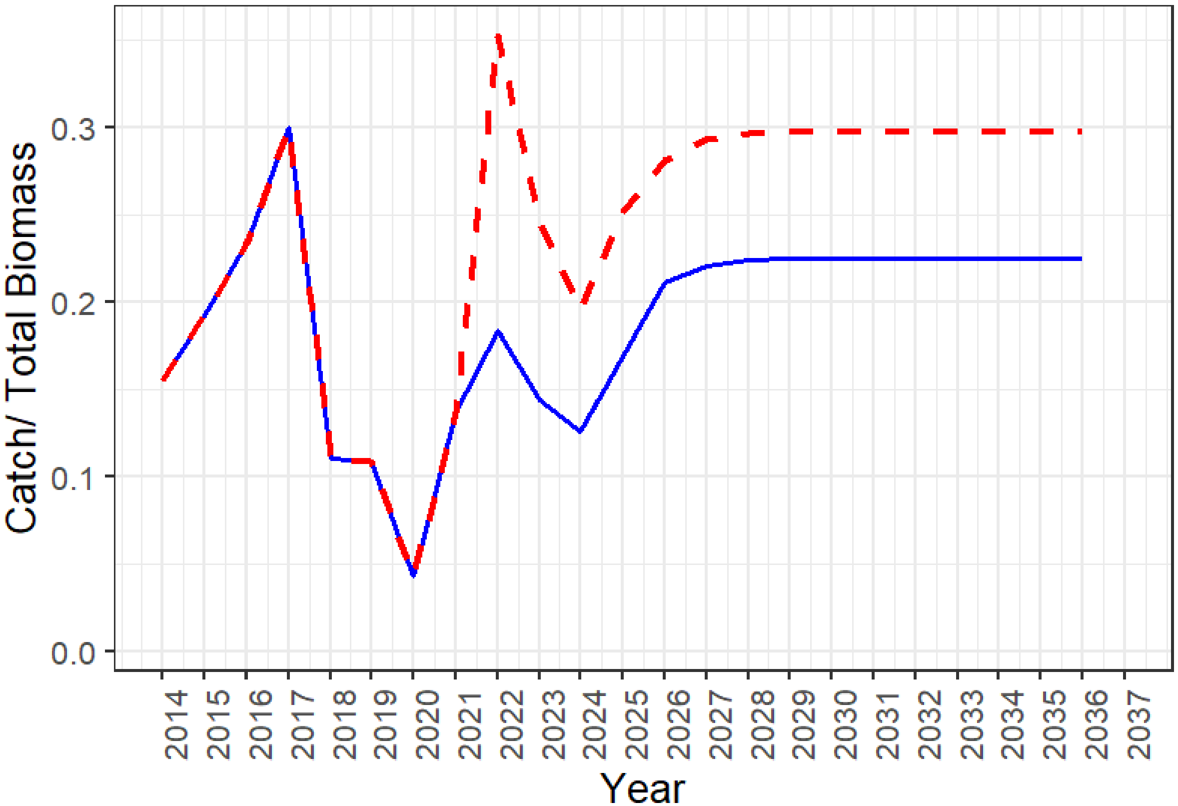

<u>Should</u> we adjust expectations of future productivity given assumptions on changes in species population dynamics in response to climate change?

- Doing so may result in short-term increase in allowable catch, but leads to quicker drop in standing biomass.
- Not doing so leads to short-term loss of revenue while potentially maintaining higher standing biomass for a longer term

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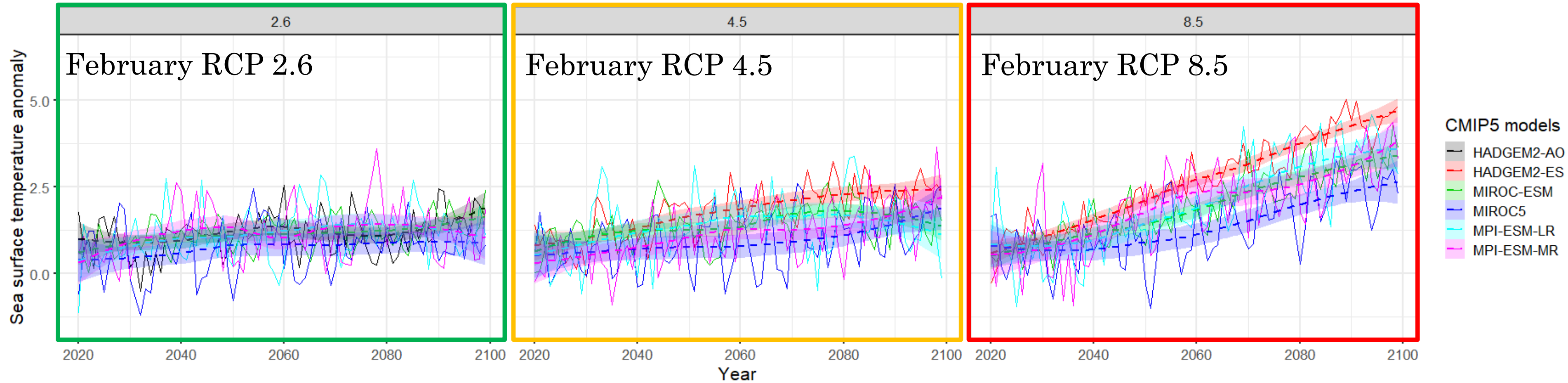
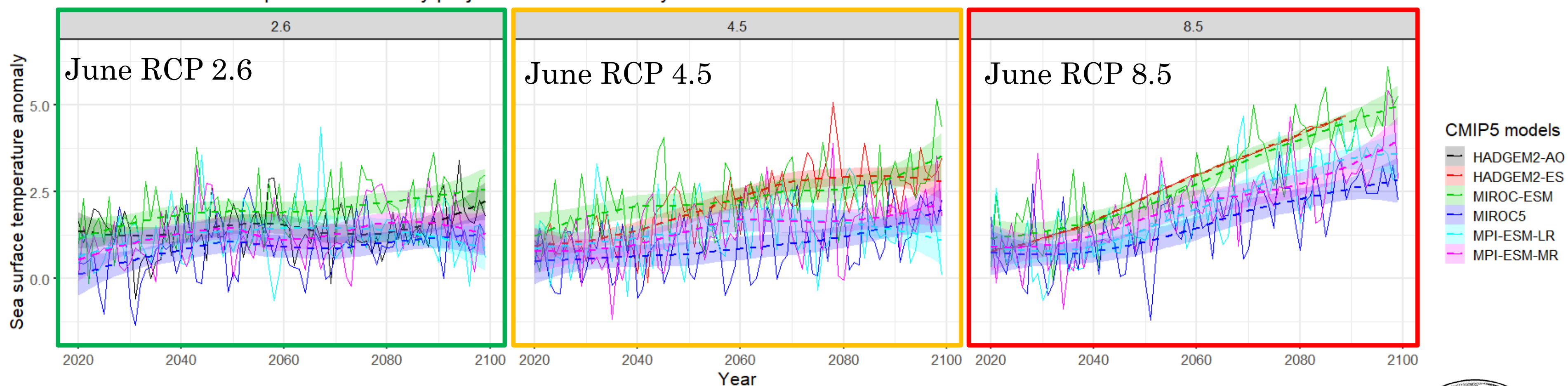
February sea surface temperature anomaly projections for CMIP5 by RCP for the Gulf of Alaska from 1982-2012 baseline



June sea surface temperature anomaly projections for CMIP5 by RCP for the Gulf of Alaska from 1982-2012 baseline



CMIP5 RCP projections 2020 to 2099

- Sea surface anomaly projections from CMIP5 by RCP for central Gulf of Alaska from 1982-2012 baseline
- Available: https://psl.noaa.gov/ipcc/ocn/timeseries.html

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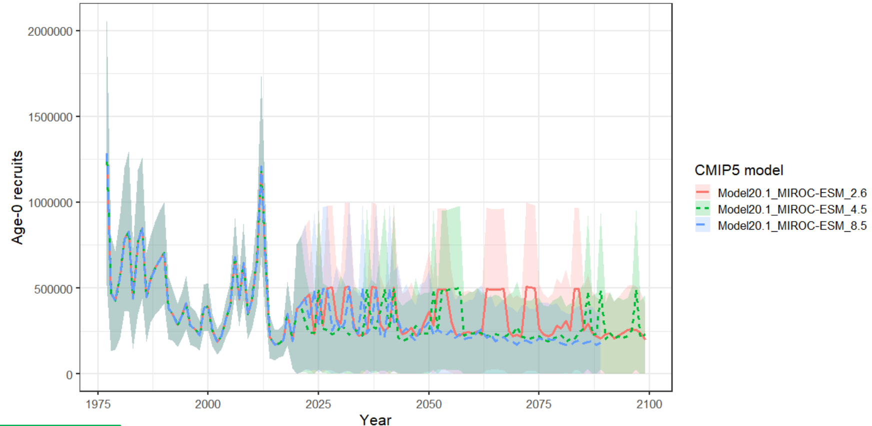

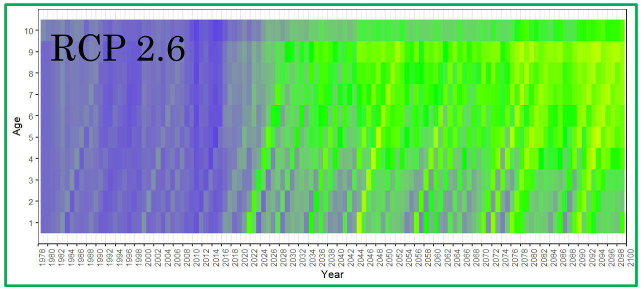

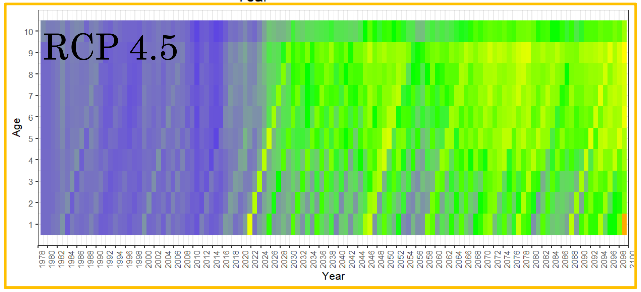

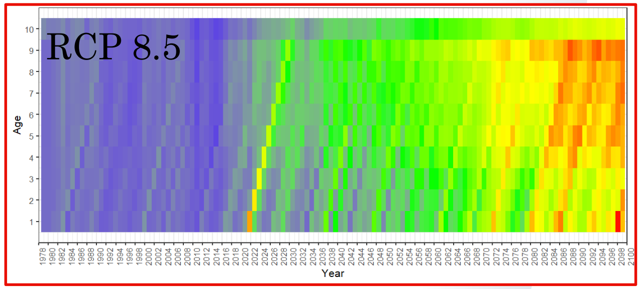

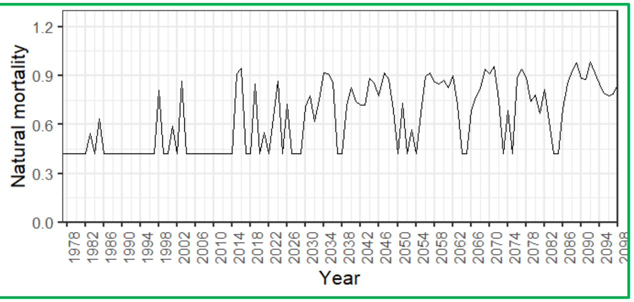

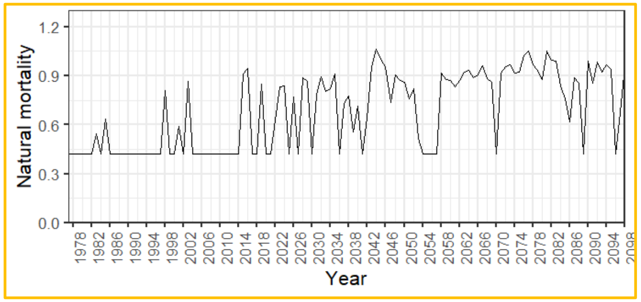

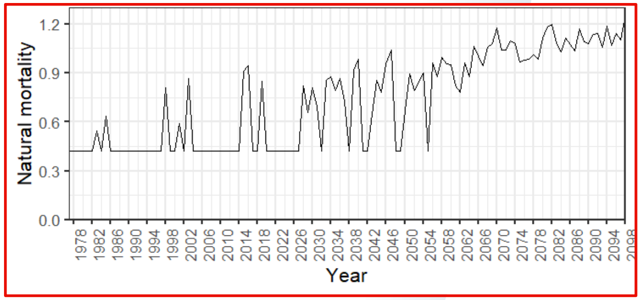

Projected recruitment, growth, and natural mortality

- Similar trends until 2040 in all RCPs however after 2040:
  - Lower overall recruitment with increasing RCP
  - Greater growth at higher temps in the higher RCPs
  - Increase in natural mortality in higher RCPs

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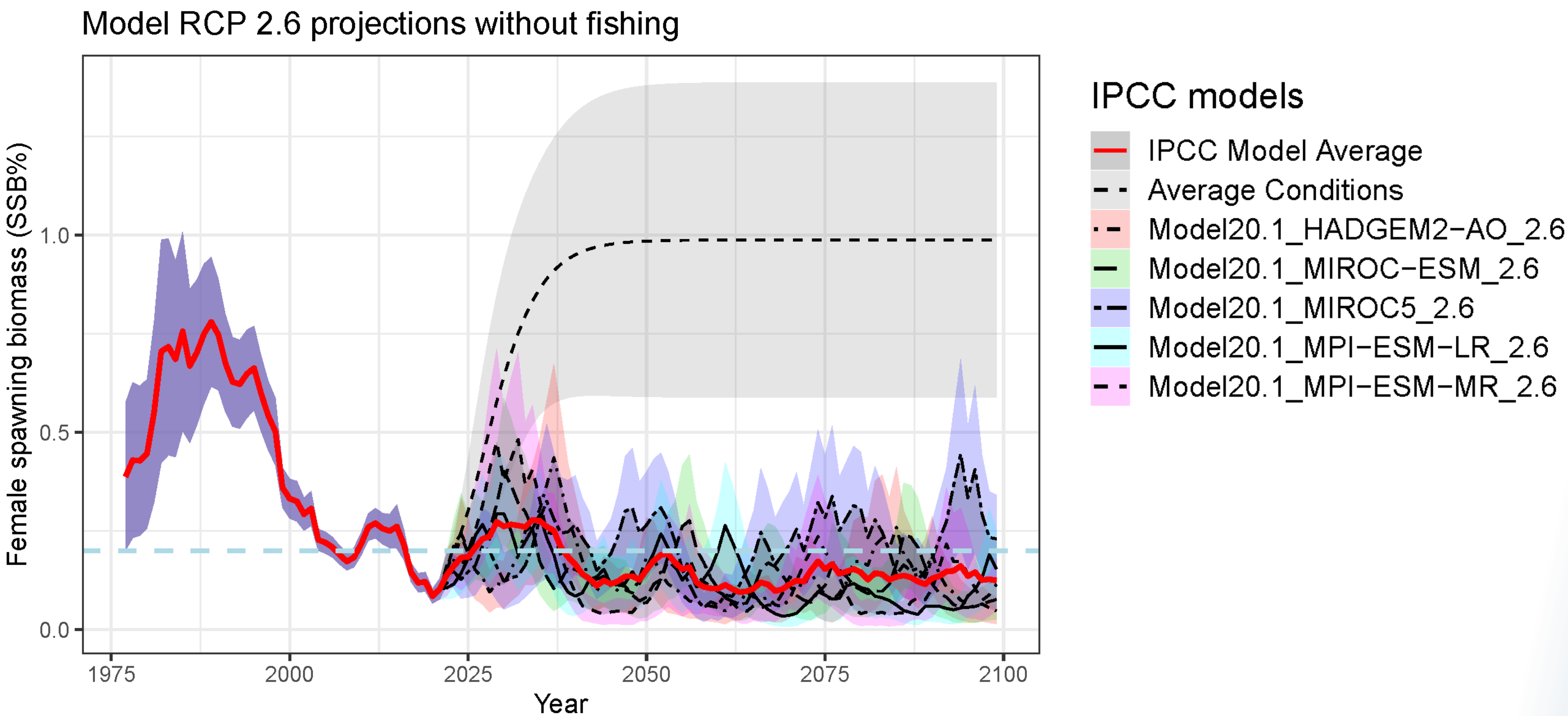
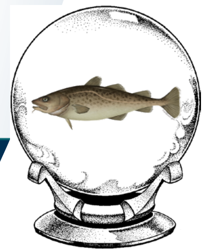


Projections without fishing to estimate future productivity potential of the stock without assumptions of stationarity

Long-term projections?



- Potential to address uncertainty, stationarity in reference points by projecting forward and using management strategy evaluations.

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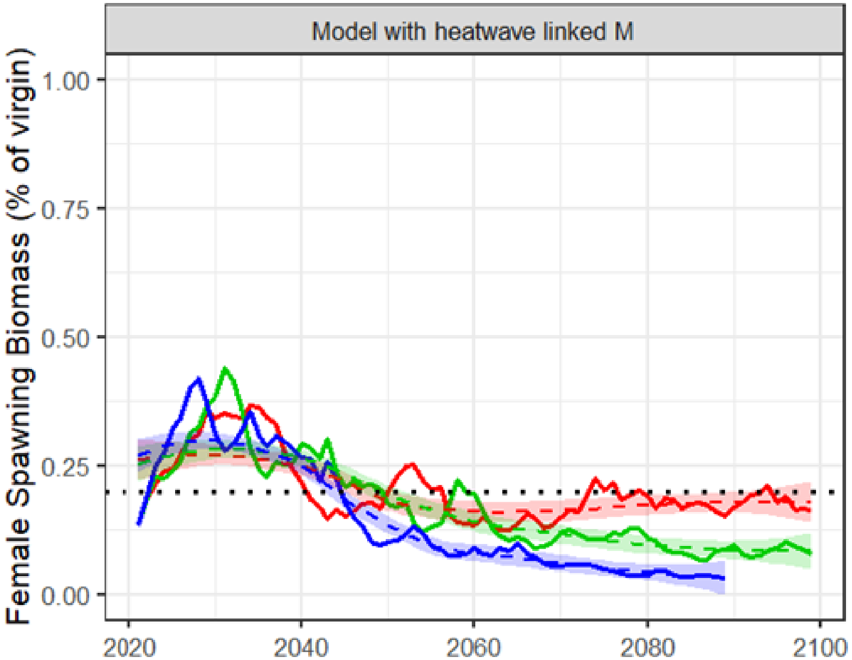
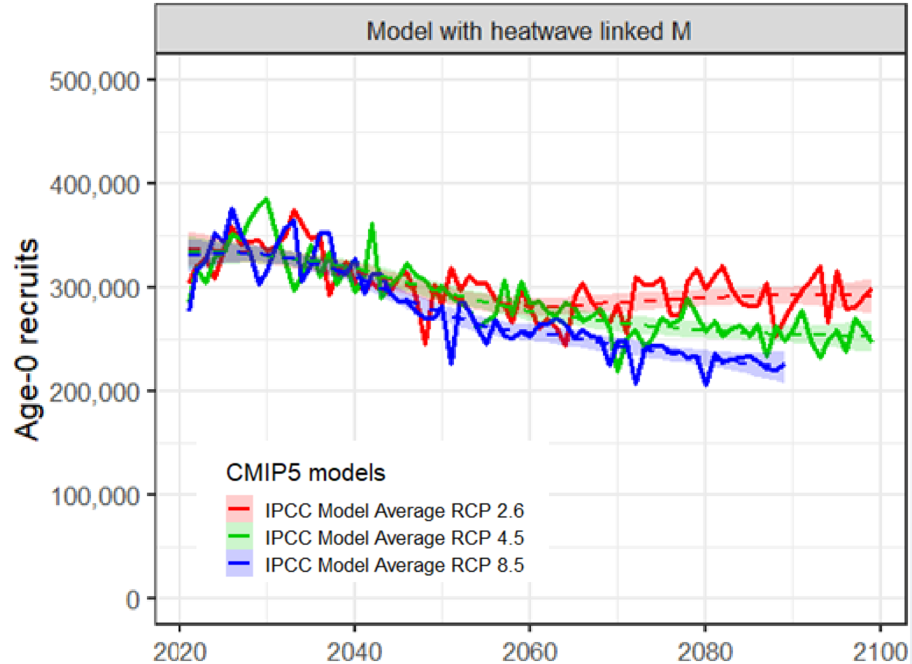
Model projections with no fishing to evaluate change in $B_{100\%}$

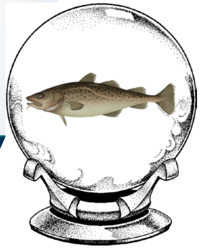




For this model set and projections there is a > 80% reduction in unfished spawning biomass by 2100

Strategic management?

- Projections **could** be used to adjust expectations of future productivity given assumptions on changes in species population dynamics in response to climate change



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More food for discussion

- Are our current control rules and adaptive tactical management process adequate to address non-stationarity in productivity due to climate change?
- If there was no uncertainty in our projections of future productivity for Pacific cod would we change our baseline? For everything including SSL rules?
- Can we be more strategic given our current level of uncertainty in the relationship between productivity and future climate?
- What are possible ways to reduce uncertainty in the assessment model projections? Other possible environmental links?
- Are there other alternatives, not based on assumed stationarity and theoretical equilibrium, for specifying harvest levels that may be explored?

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Thank you!

My many co-conspirators

Kerim Aydin

Ben Fissel

Kirstin Holsman

Ben Laurel

Wayne Palsson

Lauren Rogers

Stephani Zador

Kalei Shotwell

Muyin Wang

Qiong Yang

And XKCD.com for all the great cartoons…

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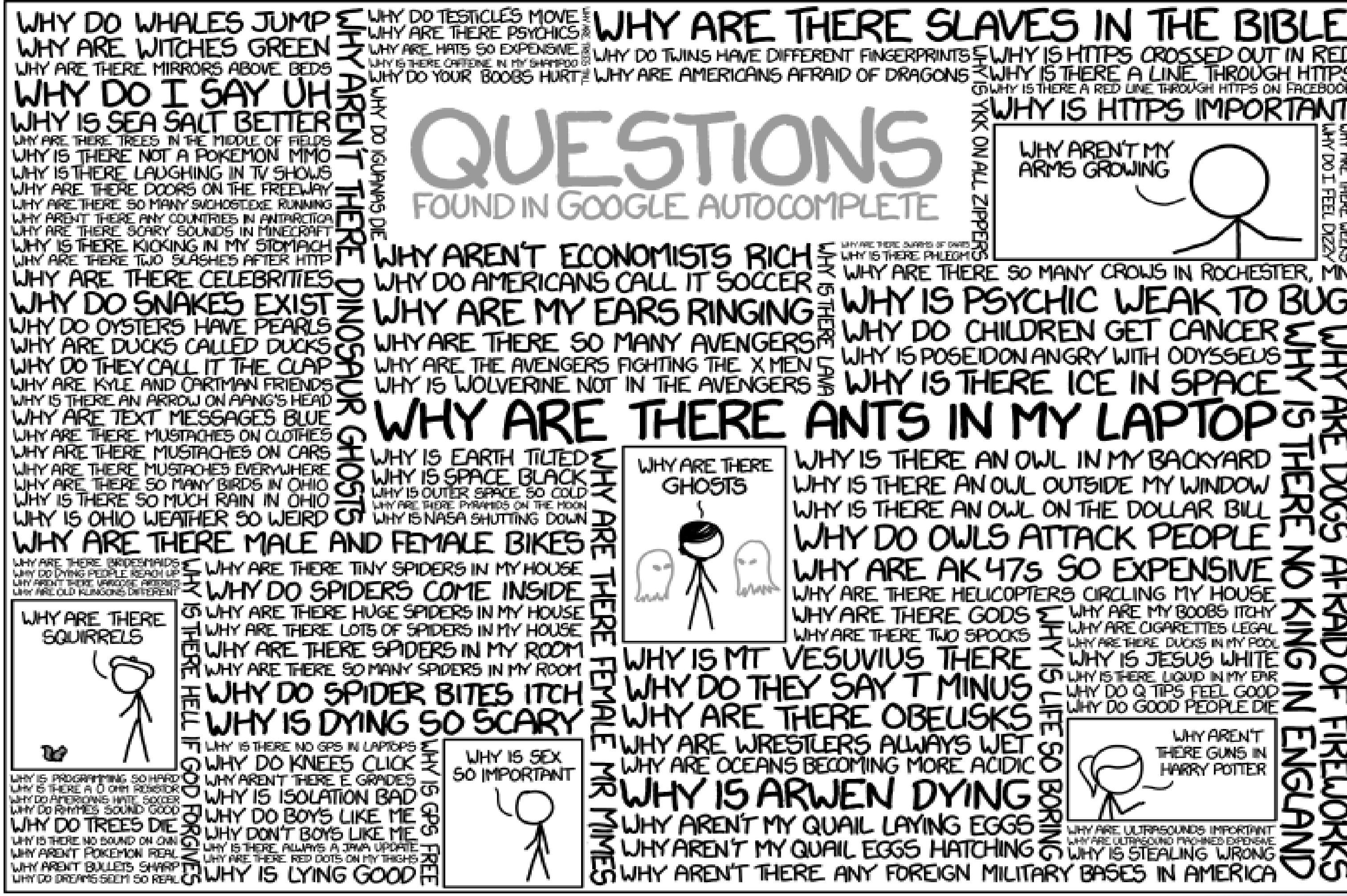

https://xkcd.com/1256/

Email: Steve.Barbeaux@noaa.gov

Phone: (206) 526-4211

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