Using multi-species food-web and assessment models to evaluate climate change impacts on fisheries

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Collaborators:
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- Al Hermann
- Liz Moffitt
- André Punt

www.bsierp.nprb.org
ML Pinsky et al. Marine Taxa Track Local Climate Velocities. 
Science, 13 September 2013: 1239-1242 
DOI:10.1126/science.1239352

A framework for modelling fish and shellfish responses to future climate change

Anne Babcock Hollowed, Nicholas A. Bond, Thomas K. Wilderbuer, William T. Stockhausen, Z. Teresa A’mar, Richard J. Beamish, James E. Overland, and Michael J. Schirripa


Weighted ensemble mean of IPCC forecasts of SST under A1B emissions scenario.

2 °C increase by 2050
4 °C increase by 2099
Projected Seasonal – Sea Ice Extent Over Bering Sea

Red – Observed
Black – Ensemble means under A1B scenario
Pink – Ensemble mean under A2 scenario
Gray curvy – one realization of one model

Wang, Overland and Stabeno 2012 DSR II 65-70: 46-57
Climate Change

SST

Bottom T
Conceptual Model of Carbon/Energy flow in the eastern Bering Sea (modified from Coyle et al. 2011)

‘Warm’ Year

- Small Pplktn
- Large Pplktn
- Micro. ZP
- Crust. ZP
- Age-0 Pollock
- Large Fish

‘Cold’ Year

- Small Pplktn
- Large Pplktn
- Ice Algae
- Micro. ZP
- Crust. ZP
- Age-0 Pollock
- Large Fish
What is the range of effects of climate change on biomass, production, & recommended harvest rates?

Are current assessment models robust to climate driven changes? (if not, why not)?
What is the range of effects of climate change on biomass, production, & recommended harvest rates?

Are current assessment models robust to climate driven changes? (if not, why not)?
Measured Ocean Conditions (SST, bottom temp, wind, surveyed predators)

- Correlations with single species recruitment from assessment
  - Forecast with correlates + error “measured” from IPCC climate models

- Correlations with recruitment from multispecies assessment
  - Forecast with correlates + error from ROMS-NPZ driven by IPCC climate models

- ROMS – NPZ high resolution 3D oceanography

- FEAST mechanistic fish model with feedback to plankton
  - FEAST model driven by IPCC climate models
Approaches

Measured Ocean Conditions
(SST, bottom temp, wind, surveyed predators)

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**Approaches**

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MSM Approach

1. HINDCAST
   - Fit to data from 1979-2012

2. REGRESSION
   - GAMs for $W_{age}$, R, foraging, etc.~$f(\text{zoop, tempC, cold pool})$

3. PROJECTION
   - Downscale IPCC / Run NPZ model
   - Project MSMo forward using ROMS/NPZ drivers with & without stochastic error
   - Harvest with current ABC / OFL from assessment models

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<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>Recruitment</td>
<td>( N_{y,1} = R_t = R_0 e^{\tau_y} )</td>
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<tr>
<td>Catch</td>
<td>( C_{y,a} = \frac{F_{y,a}}{Z_{y,a}} (1 - e^{-Z_{y,a}}) N_{y,a} w_{y,a} )</td>
</tr>
<tr>
<td>Numbers at age</td>
<td>( N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} )</td>
</tr>
<tr>
<td></td>
<td>( N_{y+1,A} = N_{y,A-1} e^{-Z_{y,A-1}} + N_{y,A} e^{-Z_{y,A}} )</td>
</tr>
<tr>
<td>Spawning biomass</td>
<td>( S_t = \sum_{a=1}^{A} w_{y,a} \phi_a N_{y,a} )</td>
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<tr>
<td>Total catch (yield)</td>
<td>( C_t = \sum_{a=1}^{A} w_{y,a} C_{y,a} )</td>
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<tr>
<td>Fishery age selectivity</td>
<td>( s_{f,a} = \frac{C_t}{C_{y,a}} )</td>
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<tr>
<td>Fishing mortality</td>
<td>( F_{y,a} = \frac{s_{f,a}}{1 - s_{f,a}} )</td>
</tr>
<tr>
<td>Natural mortality</td>
<td>( M_{y,a} = \frac{C_{y,a}}{1 - s_{f,a}} + F_{y,a} )</td>
</tr>
<tr>
<td>Total mortality</td>
<td>( Z_{y,a} = M_{y,a} + F_{y,a} )</td>
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**Residual Natural Mortality**

**Predation Natural Mortality**
### Predation Mortality

**Size-specific predation mortality**

\[ M_{2,y,k_i} = \frac{E_{y,k_i}}{B_{y,k}} \]

**Biomass consumed** \((g \cdot yr^{-1})\)

\[ E_{y,k_i} = \sum_{y=1}^{\infty} \sum_{i=1}^{\infty} (\psi_{y,p_j,k_i} \cdot N_{y,p_j} \cdot U_{y,p_j,k_i}) \]

**Annual ration** \((g \cdot pred^{-1} \cdot yr^{-1})\)

\[ \psi_{y,p_j} = \delta_p \cdot f(T_y) \cdot C_{max,p_j} \cdot D_p \]

**Maximum consumption** \((g \cdot pred^{-1} \cdot d^{-1})\)

\[ C_{max,p_j} = \alpha_p^c \cdot w_{p_j}^{(1+\beta_p^c)} \]

**Temperature scaling function**

\[ f(T_y) = V_x \cdot \rho(X \cdot (1-V)) \]

\[ X = (Z^2 \cdot (1 + (1 + 40/Y)^{0.5})^2) / 400 \]

\[ Z = \ln(Q_p^c) \cdot (T_{cm} - T_{co}) \]

\[ Y = \ln(Q_p^c) \cdot (T_{cm} - T_{pc} + 2) \]

### Bioenergetics Model

**Size specific prey selectivity**

\[ U_{y,p_j,k_i} = K_{p_j,k} \cdot \frac{\alpha_{p_k}^U \cdot (\sum_{\eta_{p_j,k_i}}) \beta_{p_k}^U}{1 + \alpha_{p_k}^U \cdot (\sum_{\eta_{p_j,k_i}}) \beta_{p_k}^U} \]

**Vulnerable prey**

\[ \eta_{p_j,k_i} = \sum N_{k_i} \phi_{p_j,k_i} \]

**Prey vulnerability switch**

\[ \phi_{p_j,k_i} = \max \left\{ 0, \left( \frac{l_{k_i} - \ell_{p_k} \cdot H_{p_j}}{\ell_{p_k}} \right) \right\} \]

**Predator gape limit (mm)**

\[ H_{p_j} = \alpha_p^H + \beta_p^H \cdot l_{p_j} \]
Bioenergetics models

How much is eaten?
Foraging models

What is eaten?
<table>
<thead>
<tr>
<th>Size-specific respiration rate</th>
<th>$M_{2y,i} = \frac{E_{y,i}}{B_{y,i}}$</th>
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<tbody>
<tr>
<td>Biomass conversion factor</td>
<td>$L_{p} \sum_{i=1}^{N_{sp}} \psi_{y,i} \cdot N_{y,i} \cdot U_{y,i}$</td>
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<tr>
<td>Annual ration $(g \cdot pred^{-1} \cdot yr^{-1})$</td>
<td>$\psi_{y,p} = \delta_{p} \cdot f(T_{y}) \cdot C_{max} \cdot D_{p}$</td>
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<tr>
<td>Maximum consumption $(g \cdot pred^{-1} \cdot d^{-1})$</td>
<td>$C_{max}\psi_{p} = \alpha_{p}^{c} \cdot w_{p}^{(1+\beta_{p})}$</td>
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<td>Temperature scaling function</td>
<td>$f(T_{y}) = V^{X} \cdot e^{(X \cdot (1-V))}$</td>
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<tr>
<td>V = $(T_{p}^{cm} - T_{y})/(T_{p}^{cm} - T_{p}^{co})$</td>
<td></td>
</tr>
<tr>
<td>X = $(Z^{2} \cdot (1 + (1 + 40/Y)^{0.5})^{2})/400$</td>
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<tr>
<td>Z = $\ln(Q_{p}) \cdot (T_{p}^{cm} - T_{p}^{co})$</td>
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<td>Vulnerability</td>
<td>$\phi_{p,i} = \max \left{ 0, \left( \frac{l_{k,i} - l_{p} \cdot H_{p,j}}{l_{p}^k} \right) \right}$</td>
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MSM HINDCAST

(a) Pollock
- MSM
- Single

(b) P. Cod

(c) Arrowtooth
- SS (MSM)
- MSM

Fits to survey biomass

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MSM HINDCAST

Fits to catch biomass

a) Pollock
b) P. Cod
C) Arrowtooth

kirstin.holsman@noaa.gov
a) Pollock  

b) P. Cod  

C) Arrowtooth
### Projections

#### Equations

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<td>( N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} ) ( 1 &lt; y \leq Y ) ( 1 &lt; a &lt; A ) ( \frac{N_{y,A}}{N_{y+1,A}} = N_{y,A-1} e^{-Z_{y,A-1}} ) ( 1 \leq y \leq Y ) ( a \geq A )</td>
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#### Future recruitment

\[
\log(R_{p,v}^{fut}) = \log(\alpha_{R,p} \cdot SSB_{p,v-1}) - \beta_{R,p} \cdot SSB_{p,v-1} + \beta_{Z,p} \cdot Z_{v}^{spr} - \beta_{Z,p}^{fall} \\
\delta_{p1,v}^{fut} \left( \frac{\delta_{p1,v}^{fall}}{Z_{v}^{fall}} \right)
\]

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Projections

- Walleye Pollock
  - Observed Weight
  - VonE
  - Mean Obs Weight
  - VonE w/ d{\sim}1(y)
  - VonE w/ d{\sim}1(\sqrt{y})

- Pacific Cod

- Arrowtooth (Males)

- Arrowtooth (Females)
Projections

\[
\log(R_{p,v}^{fut}) = \log(\alpha_{R,p} \cdot SSB_{p,v-1}) - \beta_{R,p} \cdot SSB_{p,v-1} + \beta_{Z,p}^{spr} \cdot Z_{v}^{spr} - \beta_{Z,p}^{fall} + \delta_{p1,v}^{fut} \cdot \left(\frac{Z_{v}^{fall}}{Z_{v}}\right)
\]

Future recruitment
Projections

\[
\log(R_{p,w}^{\text{fut}}) = \log(a_{i,R} \cdot SSB_{p,w-1}) - \beta_{R,w} \cdot SSB_{p,w-1} + \beta_{z,w} \cdot Z_{p,w} - \beta_{z,p} \cdot Z_{p,w} \cdot \left(\frac{\delta_{p,w}^{\text{fut}}}{Z_{f,\text{fut}}}\right)
\]

Future recruitment

Mean R/S + Food

Mean R/S

Mean R/S + Food - Competition

W. pollock

Recruitment

P. cod

arrowtooth

SSB
Projections

\[ \log(R_{p,v}^{fut}) = \log(\beta_{R,p} \cdot SSB_{p,v-1}) - \delta_{p,v} \cdot Z_{p}^{spr} \cdot Z_{p}^{fut} - \beta_{p,v}^{fut} \]

Future recruitment
Projections

Temperature (°C)

- SST
- Bottom T

Year


Observed
Avg Forecast
a) walleye pollock

- Spawning Biomass (x 100,000 mT)
- Years

- 1.1
- SSB unfished
- B40%

- B_0
  - No fishing, all three
- 40% B_0
SPAWNING BIOMASS

a) walleye pollock

- Spawning Biomass (x 100,000 mT)
- Years

- 1.1
- SSB unfished
- B40%

- B₀: No fishing, all three
- 40% B₀
a) walleye pollock

SPAWNING BIOMASS

Spawning Biomass (x 100,000 mT)

Years


1.1  SSB unfished  B40%
a) walleye pollock

Mean Rec

Spawning Biomass (x 100,000 mT)

Years

SPAWNING BIOMASS

a) walleye pollock

1.1  SSB unfished

B40%

Spawning Biomass (x 100,000 mT)

Years


Mean Rec
R~f(B)
SPAWNING BIOMASS

a) walleye pollock

Mean Rec

R~f(B)

R~f(B,Z)

R~f(B,Z,T)

Spawning Biomass (x100,000 t)


Years

B_0

B_{msy}
SPAWNING BIOMASS

a) walleye pollock

- 1.1
- SSB unfished
- B40%

Spawning Biomass (x 100,000 mT)

Years

SPAWNING BIOMASS

a) walleye pollock

- 1.1
- SSB unfished
- B40%

Spawning Biomass (x 100,000 mT)

Years

SPAWNING BIOMASS

a) walleye pollock

> 35% SSB

Years


Spawning Biomass (x 100,000 mT)
SPAWNING BIOMASS

a) walleye pollock

Set $B_0$ after predators are fished to $B_{40\%}$

- $> 35\%$ SSB

- $1.1$ - SSB unfished
- $1.2$ - $B_{40\%}$
- $1.3$

Spawning Biomass ($\times 100,000$ mT)

Years

SPAWNING BIOMASS

a) walleye pollock

Solve for $40\%$ of $\text{sum}(B_0)$

Set $B_0$ after predators are fished to $B_{40\%}$

$>35\%$ SSB
SPAWNING BIOMASS

a) walleye pollock

recMode = 4

SSB unfished
B40%

2013 ABC

Catch (x100,000 t)

1.1
1.2
1.3
1.4
3.1
3.3

Years

SPAWNING BIOMASS

a) walleye pollock

recMode = 4

SSB unfished
B40%

2013 ABC

Years

Catch (x100,000 t)
0 5 10 15 20 25 30

1.1 1.2 1.3 1.4 3.1 3.3
SPAWNING BIOMASS

a) walleye pollock

recMode = 4

SSB unfished
B40%

2013 ABC

Years

Catch (x100,000 t)
b) Pacific cod

recMode = 4

2013 ABC
c) arrowtooth flounder

recMode = 4

2013 ABC
SPAWNING BIOMASS

a) walleye pollock

Temperature

W_{age} M_{2} Rec.

ABC (million t)

Control Rules

2013 ABC
CONCLUSIONS

- MSM provides annual estimates of natural mortality
- Can project MSM models to derive multi-species BRPs
- BRPs are highly variable & depend on control rules
- Climatic variability introduces some differences but they are less than that introduced by control rules (4 pollock)
- For species with low predation – MSM ~ SS models
THANKS!

Collaborators
Kerim Aydin, Bruce Miller, Elizabeth Moffitt

Colleagues
Brain Knoth, Troy Buckley, Matt Baker, William Stockhausen, Sarah Gaichas, P. Sean McDonald, Ivonne Ortiz, Stephanie Zador

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BEST-BSIERP  Bering Sea Project