Forecasting distribution shifts using oceanographic indices: the spatially varying effect of cold-pool extent in the Eastern Bering Sea

James Thorson

Spatially-varying effects

Question

How to identify the impact of oceanographic indices (e.g., PDO) on fish distribution

Approach

Develop model with “spatially varying coefficients”

- Represents localized impact of regional oceanographic index on local density
- Estimates “map” of response to regional conditions
Spatially-varying effects

Three interpretations of a spatially-varying coefficient model:

1. Varying slope model
2. Regression of spatio-temporal variation $\varepsilon(s, t)$ on covariate $X(s, t)$ for each location $s$
3. Map of “teleconnections” for nonlocal environmental conditions on local density
Spatially-varying effects

What is a spatially-varying coefficient model:

- Conventional linear model
  \[ Y(s) = \beta + \gamma X(s) + \varepsilon(s) \]

- Model with spatially varying slope \( \gamma(s) \) for covariate \( X(s) \) when predicting variable \( Y(s) \)
  \[ Y(s) = \beta + \gamma(s)X(s) + \varepsilon(s) \]

- Extension to spatio-temporal models
  \[ Y(s, t) = \beta(t) + \gamma(s)X(s, t) + \varepsilon(s, t) \]

- ... which can be used for effect of regional conditions
  \[ Y(s, t) = \beta(t) + \gamma(s)X(t) + \varepsilon(s, t) \]

Where
- \( Y(s) \) is response and \( X(s) \) predictor at location \( s \)
- \( \beta \) is intercept and \( \gamma(s) \) a slope term
- \( \varepsilon(s) \) is residual error
Spatially-varying effects

Case study methods:

- Fit to multispecies survey
  - 17 groundfish and crabs
  - Eastern Bering Sea
- Compare four models
  1. No covariates (“None”)
  2. Local temperature effect (“Temp”)
  3. Spatially-varying cold pool effect (“Cold pool”)
  4. Both temperature and cold pool (“Both”)

<table>
<thead>
<tr>
<th>Species</th>
<th>None</th>
<th>Temp</th>
<th>Cold Pool</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gadus chalcogrammus</td>
<td>239.4</td>
<td>68.2</td>
<td>138.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Gadus microcephalus</td>
<td>528.6</td>
<td>134.4</td>
<td>363.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Hippoglossoides elassodon</td>
<td>175.5</td>
<td>6.2</td>
<td>142.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Chionoecetes opilio</td>
<td>38.4</td>
<td>0.0</td>
<td>37.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Hippoglossus stenolepis</td>
<td>260.9</td>
<td>87.5</td>
<td>178.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Limanda aspera</td>
<td>79.8</td>
<td>6.4</td>
<td>67.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Pleuronectes quadrituberculatus</td>
<td>70.3</td>
<td>37.4</td>
<td>20.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Chionoecetes bairdi</td>
<td>0.8</td>
<td>6.5</td>
<td>0.0</td>
<td>5.8</td>
</tr>
<tr>
<td>Podothecus accipenserinus</td>
<td>212.3</td>
<td>7.4</td>
<td>157.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Atheresthes stomias</td>
<td>475.4</td>
<td>34.6</td>
<td>365.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Hyas coarctatus</td>
<td>31.5</td>
<td>11.0</td>
<td>17.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Myoxocephalus polyacanthocephalus</td>
<td>85.5</td>
<td>19.5</td>
<td>47.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Lycodes palearis</td>
<td>98.4</td>
<td>8.5</td>
<td>62.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Myoxocephalus jaok</td>
<td>104.5</td>
<td>26.4</td>
<td>70.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Hyas lyratus</td>
<td>0.0</td>
<td>4.3</td>
<td>2.2</td>
<td>6.7</td>
</tr>
<tr>
<td>Paralithodes camtschaticus</td>
<td>32.4</td>
<td>9.1</td>
<td>23.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Lycodes brevipes</td>
<td>8.1</td>
<td>0.0</td>
<td>11.2</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Spatially-varying effects

Case study results:

- Spatially varying effect of cold pool is different for each species
  - Distribution is not a simple function of temperature
- Most species show at least some variance associated with cold pool
Case study results:

- Temperature reduces spatio-temporal variance
  - 6-8% reduction on average
- Both temperature and cold-pool have larger reduction
  - 9-14% reduction on average
Case study results:

- Temperature reduces spatio-temporal variance
  - 6-8% reduction on average
- Both temperature and cold-pool have larger reduction
  - 9-14% reduction on average
Spatially-varying effects

Does spatially varying effect of cold pool improve forecasting?

Skill-test experiment
1. Run with data through year T
2. Forecast center-of-gravity in year T+1, T+2, ...
3. Compare with later measurements

Published hindcast of distribution shifts for Alaska fishes

Pinsky et al. 2013 Science “Marine taxa track local climate velocity”
Spatially-varying effects

- Temperature and cold-pool improve forecasts of distribution fitting through 2015 and forecasting 2016/2018
  - Temperature helps with *G. chalcogrammus*
  - Cold pool helps with *G. macrocephalus*

Error in 3-year forecast
Spatially-varying effects

Case study results:
• Including both temperature and cold-pool reduce errors in northward center-of-gravity relative to a persistence forecast.

<table>
<thead>
<tr>
<th></th>
<th>Forecasting 2015</th>
<th>Forecasting 2016</th>
<th>Forecasting 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-15.3</td>
<td>32.3</td>
<td>38.1</td>
</tr>
<tr>
<td>Temp</td>
<td>-8.0</td>
<td>-29.0</td>
<td>-33.2</td>
</tr>
<tr>
<td>CP</td>
<td>10.9</td>
<td>23.6</td>
<td>35.7</td>
</tr>
<tr>
<td>Both</td>
<td>12.7</td>
<td>27.2</td>
<td>37.5</td>
</tr>
<tr>
<td>Persist</td>
<td>10.2</td>
<td>19.8</td>
<td>36.0</td>
</tr>
<tr>
<td></td>
<td>11.9</td>
<td>28.6</td>
<td>42.0</td>
</tr>
</tbody>
</table>

Error in 3-year forecast, Averaged across all species.
Spatially-varying effects

Other potential uses

1. Spatially varying effect of calendar date
   - Useful to inter-calibrate samples collected in different months
2. Identify locations with largest changes over time
   - Estimate spatially-varying coefficient associated with year
3. Include regional effects during index standardization
   - Easy method to include non-local environmental conditions in models being used in stock assessment
Combining multiple surveys

Cecilia O’Leary, Jim Ianelli, Jim Thorson, Stan Kotwicki

Photo: Chris Miller, csmphotos.com
Combining multiple surveys

Background

- **Eastern Bering Sea**
  surveyed 1982-2019
- **Northern Bering Sea**
  surveyed sporadically, and 2010, 2017-2019
Combining multiple surveys

Background

- Spatio-temporal model (VAST) used to combine eastern and northern Bering Sea for pollock assessment in 2018
- How to improve estimates in northern Bering Sea in unsampled years?

2019: Not yet public
Combining multiple surveys

Effect of cold-pool extent on density for pollock

Effect of cold-pool extent on density for pollock
Spatially-varying effects

Acknowledgements

• Lorenzo Ciannelli
• Mike Litzow
• Lauren Rogers
• Jim Ianelli
• Cecilia O’Leary
• Stan Kotwicki