Climate Change and Trophic Mismatches between Plankton Blooms and Fish Phenology

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Phenology is the study of biological, seasonal cycles and how they are affected by climate and weather.
Why Is Phenology of Interest to Fisheries Oceanographers?

- Haddock (Melanogrammus aeglefinus)
  - Fecundity: 55,000 – 3,358,000
  - Survival: 0.00006-0.004%

- Biggest influence on recruitment variability are oceanic conditions encountered by fish eggs and larvae

Data from NOAA/NMFS/NEFSC
Match-Mismatch Hypothesis

- Developed by Cushing (1974)
- Mismatches lead to poor larval survival, growth & recruitment
Why Can’t Fish Consistently Reproduce during Plankton Blooms?

What Is the Primary Control on Spawning Time?

Degree Day Effect on Gonado-Somatic Index ($I_G$)

Gillet and Quétin (2006)
Phenology Trends Related to Climate Change

Mean trend: -4.4 days decade$^{-1}$

Poloczanska et al. (2013), Nature Climate Change
Phenological shifts (days)
Earlier
Later

Phytoplankton Phenology

Zooplankton

Trends from the California Current Ecosystem

Asch (2015), PNAS

Larval Fish Phenology

Principal Component 1

PC1 = 33% of variance

 Earlier

Later

Phenological shifts (days)

Phyto

Crustacea

Fishes

Trends in UK Ecosystems

Thackeray et al. (2016), Nature
Hypotheses

• Climate change will lead to both *earlier phytoplankton blooms and fish spawning*

• Sensitivity to climate change will differ among trophic levels, leading to a greater frequency of *seasonal mismatches*

• *Range shifts* among fishes may ameliorate the extent of seasonal mismatches
Ocean Ecology in the GFDL ESM2M Model

Tracks C, N, P, Si, Fe, O$_2$, and alkalinity

Tracers of Ocean Phytoplankton with Allometric Zooplankton (TOPAZ)

Recycled nutrients

New nutrients

N$_2$-fixers

Small phyto.

Protists

Filter feeder

Large phyto.

DOM

Detritus

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Slide available courtesy of John Dunne, GFDL
Why Examine Phytoplankton Phenology?

- Growing season changes affect annual primary production and export production.
- Models can be validated globally with ocean color data.

Locations of Zooplankton Phenology Time Series

- Platt et al. (2003), *Nature*
- Mackas et al., (2012), *PiO*
Detection of Phytoplankton Blooms

- **Bloom initiation**: Date when time series first exceeds 75th quantile of annual range

- **Bloom termination**: Time series drops below threshold for > 5 time steps

- **Other metrics**: Bloom midpoint, Bloom duration, Bloom magnitude

- Focus on first bloom of the year

- Emissions scenario: RCP 8.5

- Years: 1862-2099
How Well Does the Model Work?

Bloom Initiation Dates from GFDL ESM2M Model

Midpoint: $r = 0.67$; End: $r = 0.65$; Duration: $r = 0.33$; Magnitude: $r = 0.74$

Bloom Initiation Dates from SeaWiFS Satellite

$M = 0.61$
Are There “Thresholds” in Time Series of Phytoplankton Phenology?

- Bayesian change point detection algorithm (Ruggieri, 2013)
- Can detect changes in slope, mean, and variance

Examples of Changes in Bloom Initiation Dates

- 85.5° N, 174.5° E
- 85.5° N, 167.5° E
- 43.5° N, 139.5° W
Trends in Bloom Initiation Dates

Latitude: 80-90° N

Latitude: 50-60° N

Latitude: 20-30° N

Latitude: 70-80° N

Latitude: 40-50° N

Latitude: 10-20° N

Latitude: 60-70° N

Latitude: 30-40° N

Latitude: 0-10° N
Changes in Other Bloom Characteristics

**Δ Bloom Duration (1901-1950 vs. 2050-2099)**

- Shorter
- Longer

**Δ Bloom Magnitude (1901-1950 vs. 2050-2099)**

- Smaller
- Larger

*Remember:* This is for spring/summer blooms only!
Influences on Bloom Timing

• Critical depth hypothesis (Sverdrup, 1953)
• Dilution-recoupling hypothesis (Behrenfeld, 2010)
• Change in sign of air-sea flux (Taylor & Ferrari, 2011)
• Eddy-driven slumping of density gradients (Mahadevan et al., 2012)

Bloom timing depends on multiple oceanographic factors

Correlations between bloom initiation & stratification between 0 m & 100 m

Contribution of temperature to stratification changes

Contribution of salinity to stratification changes

Bloom timing depends on multiple oceanographic factors
Modeling the Spawning Phenology of Temperate, Epipelagic Fishes

Model Framework:

1. Geographically based and environmentally based spawners (Reglero et al., 2012)

2. During a baseline period (1901-1950), on average fishes spawned coincident with the first phytoplankton bloom of the year.

3. Interannual variability in spawning reflects cumulative degree days (°D).

\[ °D_t = °D_{t-1} + \max[T_t - T_0, 0], \text{ where} \]

\[ T = \text{temperature}, \ T_0 = \text{base temperature, and} \ t = \text{time step (day)} \]

4. No genetic or behavioral adaptation → Degree day threshold for spawning remains constant in 2050-2099.
How Do Rates of Change Compare Amongst Phytoplankton & *Geographic* Spawners?

**Change in Phytoplankton Phenology**
- Time 1: 1901-1950
- Time 2: 2050-2099
- Median = -16.8 days

**Change in Fish Spawning Phenology**
- Median = -42.0 days
Mean Projected Mismatch between Geographic Spawners & Phytoplankton in 2050-2099

- Spawning after bloom ended – 4.0%
- Spawning during bloom – 9.8%
- Spawning before bloom started – 86.2%

**Spawning after the bloom**

**Spawning before the bloom**
Where Will Environmental Spawners Move to?

Temperature During Baseline Period (1901-1950)

Future Temperature (2050-2099)
How do Future Mismatches Differ between Geographic and Environmental Spawners?

Geographic Spawners
- Spawning after bloom ended: Geo: 4.0%  Env: 1.8%
- Spawning during bloom: Geo: 9.8%  Env: 60.3%
- Spawning before bloom started: Geo: 86.2%  Env: 37.9%

Environmental Spawners
- Spawning after bloom ended: Geo: 4.0%  Env: 1.8%
- Spawning during bloom: Geo: 9.8%  Env: 60.3%
- Spawning before bloom started: Geo: 86.2%  Env: 37.9%
“Extreme Events”: Mismatches > 1 Month

Geographic Spawners

Environmental Spawners

% Area with Extreme Mismatches

Atlantic

Pacific

Year

1900 1950 2000 2050 2100

1900 1950 2000 2050 2100
“Extreme Events”: Mismatches > 1 Month

- Ratios between future & baseline probabilities of extreme mismatches

- Ratio = 2 $\rightarrow$ Probability of extreme mismatches doubles

- Ratio = 0.5 $\rightarrow$ 50% reduction in probability of extreme mismatches
Hypotheses

• Climate change will lead to both earlier phytoplankton blooms and fish spawning – Yes

• Sensitivity to climate change will different among trophic levels, leading to a greater frequency of seasonal mismatches – Most likely

• Range shifts among fishes may ameliorate the extent of seasonal mismatches – Yes, but not in all regions
Broader Implications

- Species with fixed spawning grounds may be particularly vulnerable to future changes.

- “Extreme events” deserve greater consideration when addressing the biological impacts of climate change.

- Approach is relevant to other organisms beyond fishes.
Changes in Bloom Initiation Dates

- Compares baseline (1901-1950) and future (2050-2099) periods
- Contour lines separate areas with significant and non-significant changes at $p < 0.05$
Southern Ocean Phenology

Climatology for 1998-2007

Latitude: 40–50° S

Latitude: 50–60° S

Latitude: 60–70° S

Latitude: 70–80° S

- - - SeaWiFS      --- ESM2M

• Differences attributable to overly shallow MLD, Fe limitation, and changes in Chl:C ratio in ESM2M
Modeling Spawning Phenology of Temperate, Epipelagic Fishes

Model Framework:

1. Two categories of spawning behavior:
   - Geographically based spawning
   - Environmentally based spawning

   (Reglero et al., 2012)

Asch and Checkley (2013)
Change in Temperature between 1901-1950 and 2050-2099

0-10 m

100-110 m