Large zooplankton and their predators in a warming Bering Sea: ecosystem and life history modeling approaches

with co-authors
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photo: Corey Arnold
Figure 12. Age-1 pollock (*Theragra chalcogramma*) recruitment on the eastern Bering Sea shelf during the study period (Table 1.22 in Ianelli et al., 2009).
ice cover, Apr 1, from BESTMAS
Bering Ecosystem Study
Ice-ocean Modeling and
Assimilation System:
Zhang et al. 2010, 2012)

Figure 2. Schematic picture of the seasonal plankton development in the Barents Sea. The receding ice edge acts as a biological time-setter, and various stages of the seasonal plankton development can be found along a North-South gradient. (48).

1 - prebloom phytoplankton growth
2 - ice-edge phytoplankton bloom
3 - post bloom deep-chlorophyll maximum
4 - sedimentation of phytoplankton
5 - oligotrophic post-bloom surface layer
6 - upward migration of overwintering zooplankton
7 - spawning of zooplankton
8 - growth and development of a new generation of zooplankton
9 - capelin feeding migration
Climate projection from BESTMAS (Zhang et al. 2010, 2012)

Assimilative ice-ocean hindcast + linear trend of +8°C by 2100 (near mean of CMIP3 ensemble)

Mean over middle–outer shelf (50–200 m depth)
**Figure 11.** Conceptual model of energy flow through the ecosystem on the southeastern Bering Sea shelf during warm and cold conditions.

- **Warm year**
  - Phytoplankton
  - Small zooplankton
  - Large zooplankton
  - Zero age pollock
  - Large fish

- **Cold year**
  - Phytoplankton
  - Small zooplankton
  - Large zooplankton
  - Zero age pollock
  - Large fish

**Warm years =**
- High pollock abundance in first summer
- But poor prey quality;
- Low survival to age 1

*(Hunt et al. 2011)*
Figure 11. Conceptual model of energy flow through the ecosystem on the southeastern Bering Sea shelf during warm and cold conditions.

**Warm year**
- Phytoplankton
  - Small zoop
  - Large zoop
  - Zero age pollock
  - Large fish

**Cold year**
- Phytoplankton
  - Small zoop
  - Large zoop
  - Zero age pollock
  - Large fish

why?
Question 1

Do spring/summer phytoplankton dynamics (temperature, bloom timing, total production) explain why large crustacean zooplankton do better in cold years?
higher mortality

higher mortality

coagulation

small phytoplankton

large phytoplankton

microzooplankton

copepods

adults C V C I-V

nauplii

eggs

krill

small detritus

large detritus

Q₁₀ for phytoplankton growth = 2.0

Q₁₀ for zooplankton growth = 2.8

Q₁₀ for copepod development ~ 3.4

LowLaMB 1.0
(Lower-trophic Lagrangian Model for the Bering Sea)
Surface and bottom temperature from AFSC groundfish surveys

BESTMAS hindcast + forecast (random resampling of hindcast + linear temperature trend, +8°C by 2100)
Validation: ice-edge bloom at 60N, spring 2009 (BEST program)
Primary production
(Apr 1–Jul 15, g C m⁻²)

1978–2012
2040s

Water temperature
(0–35 m, °C)

Calanus production
(Apr 1–Jul 15, g C m⁻²)

Water temperature
(0–35 m, °C)
Question 1

Do spring/summer phytoplankton dynamics (temperature, bloom timing, total production) explain why large crustacean zooplankton do better in cold years?

No! Both phytoplankton and zooplankton production are higher overall in warm years.

Question 2

So what does?
Climate impacts on *Calanus* spp.

<table>
<thead>
<tr>
<th></th>
<th>cold years</th>
<th>warm years</th>
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<tbody>
<tr>
<td><strong>Ice cover</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>late winter</td>
<td>–</td>
<td>+</td>
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<td>prey availability</td>
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<td>(ice algae)</td>
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<td>growth &amp; development</td>
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<td>rates</td>
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<td>overwintering</td>
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<td>success</td>
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Net effect: + –

*large copepods do better in cold years in spite of, not because of, variability in total primary production*

(cf. Hunt et al. 2011)
for each life stage,

\[ \frac{dC}{dt} = \text{assimilation} - \text{metabolism} - \text{mortality} - \text{egg prod.} + \text{molting} \]

\[ \frac{dR}{dt} = f_s \cdot \text{assimilation} - 1.0 \cdot \text{metabolism} - \frac{R}{C} \cdot \text{mortality} \ldots \]

assimilation = \( a \ q \ I_{\text{max}} \ P / (K+P) \ C \)

\( Q_{10} \) temperature dependence

life-history parameters:
- lipid storage fraction
- activity (diapause vs. winter grazing & reproduction)
Sensitivity experiments based on semi-idealized seasonal cycles from EcoFOCI mooring M8 (62°N, 70 m depth) (Sigler et al., submitted)
Population growth rate over 4 y (yr\(^{-1}\))

Minimum (winter) surface temperature

Overwintering less costly

1978–2012 mean conditions

Activity of stage C5 in winter

no diapause

diapause

Fast growth and development

Maximum (summer) surface temperature

Varying both together
Climate impacts on *Calanus* spp.

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<th>Ice Cover</th>
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<th>Warm Years</th>
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<td>Spring-summer Growth &amp; Development Rates</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Overwintering Success</td>
<td>+</td>
<td>-</td>
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Net Effect: + -
Climate impacts on *Calanus* spp.

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**Net effect:** + –

**HYPOTHESES:**

Maybe timing is everything.

In other high-latitude systems, early reproduction in time to match juveniles with the spring bloom is crucial for copepods (Varpe et al. 2007)
<table>
<thead>
<tr>
<th>winter phytoplankton concentration (mg chl m(^{-3}))</th>
<th>start of egg production (yearday)</th>
<th>egg production per unit biomass (yr(^{-1}))</th>
<th>Calanus population growth over 4 y (yr(^{-1}))</th>
</tr>
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<tbody>
<tr>
<td>0.01</td>
<td>104</td>
<td>1.0</td>
<td>0.4</td>
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<tr>
<td>0.2</td>
<td>97</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.5</td>
<td>89</td>
<td>0.5</td>
<td>1.6</td>
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<tr>
<td>1.0</td>
<td>86</td>
<td>0.3</td>
<td>2.9</td>
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Question 2

So if spring/summer phytoplankton dynamics don’t explain why large crustacean zooplankton do better in cold years, what does?

*Prey availability before the spring bloom (and its effect on reproductive timing) is the most plausible hypothesis—moreso than direct temperature effects.*
Question 3

What does all this mean for a warmer future?
Hypothesis: Large crustacean zooplankton need ice algae to be **produced** and also **released** in late winter/early spring.
Hypothesis: Large crustacean zooplankton need ice algae to be **produced** and also **released** in late winter/early spring.

![Graph showing the relationship between surface temperature and early spring ice index from 1978 to 2012, with data points for specific years like 2002, 2007, 2009, and 2040s. The graph is labeled "Early spring ice index (max – min, Feb 15–Apr 1) 1978–2012" and "Southern middle–outer shelf."
Question 3

What does all this mean for the future?

*Broadly speaking, these models suggest that plankton and pollock recruitment in an average year in the 2040s will resemble the warm years of the 2000s (which were very bad for pollock recruitment)…*

*…but the news is not nearly as bad as a direct extrapolation from present-day correlations with temperature would suggest.*