Biophysical Moorings

NPRB Project B52 Final Report

Phyllis J. Stabeno¹, Jeffrey M. Napp², Terry Whitledge³

¹NOAA Research, PMEL, 7600 Sand Point Way NE, Seattle, WA, 98115, 206-526-6453, Phyllis.stabeno@noaa.gov
²NOAA Fisheries, AFSC, 7600 Sand Point Way NE, Seattle, WA, 98115
³UAF/SFOS, Institute of Marine Science, PO Box 757220

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Abstract

This project resulted in collection of three years of nearly continuous data at four mooring sites, and hydrographic and plankton sampling around the sites. Major findings from these data include:

- Identified warm and cold years in southeastern Bering Sea - warm (cold) years have little (extensive) ice in March – April.
- Identified transition from strong interannual variability in warm/cold years before 2000 and multi-year variability (stanzas) after 2000 - stanzas of warm years resulted in decreased concentrations of large zooplankton -populations rebounded during cold period.
- Identified sharp division between northern and southern shelves at ~60 °N.
- During cold years, the monthly-mean currents over the southeastern shelf are largely westward, while in warm years the flow is northward during winter.
- Flow on southern middle shelf is complex and not completely dominated by winds - winter bottom currents at M2 are complex, summer bottom currents at M4 are southward.
- Temperature dominates stratification in the south, and temperature and salinity are equally important in the north.
- The strength of stratification is not related to warm or cold years.
- Approximately 1 m of ice melts over the southern (northern) shelf during ice advance (retreat).
- If ice is present after mid-March, spring phytoplankton bloom is related to ice retreat; if ice is absent after mid-March, a spring bloom occurs in May-June, a fall bloom often occurs in late September.

The extensive mooring data provided information for model validation.

Key words: Bering Sea, shelf domains, currents, fluorescence, zooplankton, nutrients, stratification, warm-cold years, north-south structure, sea ice

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## Literature Cited

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This report documents the activities, analytical methods, results and findings of Project B52 of the Bering Sea Integrated Ecosystem Research Program. The project started in 2008 and ended in April 2013. Relationships identified in this analysis were used to inform or parameterize FEAST (B70, Aydin et al.). In addition, there were strong collaborations with several NSF funded components of the Bering Sea Project (NSF Project 1107250, Synthesis, Mordy et al.; NSF Project 0732640 Hydrographic Structure and Nutrients over the Eastern Bering Sea Shelf During Summer, Mordy et al.; NSF Project 0732430 Impacts of Sea-ice on Hydrographic Structure and Nutrients over the Eastern Bering Sea Shelf, Mordy et al.; and NSF project 0732534, Downscaling global climate projections, Bond et al.). There were no no-cost extensions to the program. Progress reports were submitted biannually and can be found on the North Pacific Research Board website.

### Table 1. Study Chronology

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<tr>
<th>What</th>
<th>Who/Ship</th>
<th>Dates</th>
<th>Other information</th>
</tr>
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<tbody>
<tr>
<td>Prep equipment, design and build moorings, develop cruise plans.</td>
<td><em>Stabeno, Napp, Whitledge, Mordy (SNWM)</em></td>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>Recover/deploy moorings M2 and M4 (ice permitting)</td>
<td><em>NOAA ship Miller Freeman</em></td>
<td>May 1 – May 10, 2008</td>
<td>Conducted CTD/bongos along southern hydro. line</td>
</tr>
<tr>
<td>Process and disseminate data Data Delivery to data manager</td>
<td><em>SNWM</em></td>
<td>May 15-Nov 15 Nov. 2008</td>
<td></td>
</tr>
<tr>
<td>Send plankton samples to Poland to be counted</td>
<td><em>Napp</em></td>
<td>Jun 1, 2008 – Jun 1, 2009</td>
<td>The actual time for processing varies.</td>
</tr>
<tr>
<td>Deploy moorings at M5 and M8</td>
<td><em>USCG Healy SNM</em></td>
<td>July, 2008</td>
<td></td>
</tr>
<tr>
<td>Recover/Deploy moorings M2, M4, M5 and M8</td>
<td><em>Miller Freeman and/or Melville SNWM</em></td>
<td>Sep, 2008</td>
<td>CTD/bongos along the 5 primary hydro. lines (70m isobath, &amp; 4 cross shelf transects)</td>
</tr>
<tr>
<td>Process and disseminate data Data Delivery to data manager</td>
<td><em>SNWM</em></td>
<td>Oct – Dec, 2008 March 2009</td>
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</tr>
<tr>
<td>Send plankton samples to Poland to be counted</td>
<td><em>Napp</em></td>
<td>Oct 1, 2008 – Oct 1, 2009</td>
<td>The actual time for processing varies.</td>
</tr>
<tr>
<td>Failed to deploy moorings at M2</td>
<td><em>Oscar Dyson, Stabeno</em></td>
<td>March 2009</td>
<td>Failed because of ice and weather.</td>
</tr>
<tr>
<td>Event</td>
<td>Date:</td>
<td>Notes:</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>----------------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Submitted data to data manager</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover/deploy moorings M2 and M4</td>
<td>Apr 24 – May 7, 2009</td>
<td>Conducted some hydrographic stations</td>
<td></td>
</tr>
<tr>
<td>Processed and disseminated data</td>
<td>May 15 – Sept 30, 2009</td>
<td></td>
<td></td>
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<tr>
<td>Sent plankton samples to Poland to be counted</td>
<td>July 30, 2009</td>
<td>Actual time for processing varies</td>
<td></td>
</tr>
<tr>
<td>Deploy moorings at M5 and M8</td>
<td>Jun/Jul 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prepared equipment and built moorings</td>
<td>Jun - Aug. 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover/Deploy moorings M2, M4, M5 and M8</td>
<td>Sep 23 – Oct 11, 2009</td>
<td>CTD/bongos along the 5 primary hydro lines</td>
<td></td>
</tr>
<tr>
<td>Processed and disseminated data</td>
<td>Oct 2009 – Apr, 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sent plankton samples to Poland</td>
<td>Nov 2009</td>
<td>Actual time for processing varies</td>
<td></td>
</tr>
<tr>
<td>Recover/deploy moorings M2 (over half the mooring was missing)</td>
<td>Apr 23 – May 3, 2010</td>
<td>Due to extensive ice M4, M5 and M8 could not be reached.</td>
<td></td>
</tr>
<tr>
<td>Deployed moorings at M5, did not recover moorings at site.</td>
<td>June 2010</td>
<td>M4 could not be located and M5 was not recovered because of limited space on the boat.</td>
<td></td>
</tr>
<tr>
<td>Processed and disseminated data and data delivered to data manager</td>
<td>Apr – Sep 2010</td>
<td></td>
<td></td>
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<tr>
<td>Conducted hydro and zooplankton survey</td>
<td>Aug 23 – Sep 10, 2010</td>
<td>Conducted last sampling of 70-m isobath and 3 cross lines</td>
<td></td>
</tr>
<tr>
<td>Recover/Deploy moorings M2, M4, M5 and M8</td>
<td>Sep 23 – Oct 3, 2010</td>
<td>M4 could not be found. It was likely dragged by ice or a fishing vessel. Will continue searching for it on future cruises.</td>
<td></td>
</tr>
<tr>
<td>Processed and disseminated data and data delivered to data manager</td>
<td>Oct 2010 – Jul 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sent plankton samples to Poland</td>
<td>November 2010</td>
<td>Actual time for processing varies</td>
<td></td>
</tr>
<tr>
<td>Synthesis of data and ideas, complete manuscripts</td>
<td>2010 - 2012</td>
<td>This is an ongoing task.</td>
<td></td>
</tr>
<tr>
<td>6 manuscripts were submitted and accepted for</td>
<td>Oct – Dec 2011</td>
<td></td>
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</table>
In the out years, the prepping, mooring design and construction, and cruise plan development occur during the 3 months before the beginning of the cruise. Similarly the data processing, qcing etc. take approximately 3 months, with the exception of the counting of zooplankton which can take as long as 1 year. Note, the delivery date of data is contingent upon the successful recovery of the moorings.

**Introduction**

Project B52 is a continuation of a long-term partnership between NOAA and NPRB. List of other NPRB grants which supported the moorings are 203, 315, 410, 517, 602, 701, 1202. Moorings have been maintained on the southeastern Bering Sea shelf at four sites: M2 (56.9°N, 164.1°W) since 1995, M4 (57.9°N, 168.9°W) since 1996, M5 (59.9°N, 171.7°W) and M8 (62.2°N 174.7°W) since 2004 (Fig. 1). This project, together with research by the NOAA program North Pacific Climate Research and Ecosystem Productivity (NPCREP), continued these measurements through 2013. The moorings, together with observations along the 70-m isobath, are core to the long-term observations on the Bering Sea shelf. B52 continued the time series of temperature, salinity, fluorescence, currents, zooplankton abundance (TAPS-8 at M2), nitrate, and oxygen (at M2) at four mooring sites on the Bering Sea shelf. To avoid damage by ice, most of these moorings were subsurface. During the late spring and summer a surface mooring was deployed at M2, which measured meteorological variables (air temperature, humidity, barometric pressure, wind velocity and solar radiation – PAR).

![Fig. 1. Location of the 4 biophysical moorings and the 70-m isobath.](image)
This project supports all five BSIERP hypotheses, by providing critical data to identify long-term physical, chemical, and biological changes in the ecosystem:

1. **Physical forcing affects food availability:** Climate-induced changes in physical forcing will modify the availability and partitioning of food for all trophic levels through bottom-up processes;

2. **Ocean conditions structure trophic relationships:** Climate and ocean conditions influencing water temperature, circulation patterns, and domain boundaries impact fish reproduction, survival and distribution, the intensity of predator-prey relationships, and the location of zoogeographic provinces through bottom-up processes;

3. **Ecosystem controls are dynamic:** Later spring phytoplankton blooms resulting from early ice retreat will increase zooplankton production, thereby leading to increased abundances of piscivorous fish (walleye pollock, Pacific cod, and arrowtooth flounder) and a community controlled by top-down processes with several trophic consequences;

4. **Location matters:** Climate and ocean conditions influencing circulation patterns and domain boundaries will affect the distribution, frequency, and persistence of fronts and other prey-concentrating features and, thus, the foraging success of marine birds and mammals largely through bottom-up processes;

5. **Commercial and subsistence fisheries reflect climate:** Climate-ocean conditions will change and, thus, affect the abundance and distribution of commercial and subsistence fisheries.

**Objectives**

1) **Provide near continuous, water column temperature, salinity, fluorescence, nitrate, and currents at the four primary mooring sites, plus zooplankton and oxygen at selected sites.**

Moorings were deployed at all four sites at least once a year. Below are the mooring designs (Table 2) and the list of moorings deployed for each site (Tables 3 – 6), with the date of deployment and recovery, the number of instruments on the moorings and any comments. Hydrography and net tows were done at the mooring site and at the four corners of the 20 km x 20 km box around each mooring site, whenever possible. In spring, with extensive ice some of these stations were skipped because of ice cover.
Table 2. The design of the moorings. The extensive sea ice precluded the recovery /deployment of M5 and M8 in May of 2009. To resolve this, a simple mooring with temperature at 15, 10 and 5 m was deployed in July at M8 to obtain measurements in the upper column. A summer mooring was also deployed at M5 in July when possible. See Tables 3-6 for details of moorings.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>M2</th>
<th>M4</th>
<th>M5</th>
<th>M8</th>
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<tr>
<td></td>
<td>Summer</td>
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<td>11, 35, 60</td>
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<td>11 m</td>
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<td>Zooplankton biovolume, size composition</td>
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<td>every 4 m</td>
<td>every 4 m</td>
<td>every 4 m</td>
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<td>Meteorological variables</td>
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<td>Bottom depth</td>
<td>73</td>
<td>73</td>
<td>70</td>
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Table 3. Moorings were deployed twice a year at M2. The first set of moorings in 2008, replaced moorings, which had been deployed the previous September. Moorings indicated by “bsm” were all surface moorings. Those indicated by “bst” contained the TAPS-8 and selection of other instruments. Selected data on bst and bsm were reported back in real time and put on the web. Those indicated by “bsp” are bottom-mounted, upward looking ADCP moorings. Moorings indicated by just “bs” were overwintering moorings with top instrument at 11 m.

<table>
<thead>
<tr>
<th>Mooring</th>
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<th>Number of Instr.</th>
<th>Comments</th>
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<td>9/28/2008</td>
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<td></td>
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<tr>
<td>08bsp2a</td>
<td>5/6/2008</td>
<td>Not recovered</td>
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<td></td>
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<tr>
<td>08bs2c</td>
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<td>4/30/2009</td>
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<tr>
<td>08bsp2c</td>
<td>9/29/2008</td>
<td>4/30/2009</td>
<td>11</td>
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<tr>
<td>09bsm2a</td>
<td>4/30/2009</td>
<td>9/25/2009</td>
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<td>09bs2c</td>
<td>9/26/2009</td>
<td>4/30/2010</td>
<td>4</td>
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<td></td>
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<tr>
<td>09bsp2b</td>
<td>9/26/2009</td>
<td>4/27/2010</td>
<td>1</td>
<td></td>
</tr>
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<td></td>
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<tr>
<td>10bsm2a</td>
<td>5/12/2010</td>
<td>10/4/2010</td>
<td>21</td>
<td>Extensive ice required the 2 week delay of deployment of surface mooring</td>
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<tr>
<td>10bsp2a</td>
<td>4/30/2010</td>
<td>10/4/2010</td>
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<td>10bs2c</td>
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<tr>
<td>10bsp2b</td>
<td>10/5/2010</td>
<td>5/19/2011</td>
<td>1</td>
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</table>
Table 4. Moorings were generally deployed twice a year at M4. The first set of moorings in 2008, replaced moorings, which had been deployed the previous September. Moorings indicated by “bsm” were all surface moorings. Those indicated by “bsp” are upward looking ADCP moorings. Moorings indicated by just “bs” were overwintering moorings with top instrument at 11 m. Mooring 09bsp4b was not recovered and all instruments and data were lost.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Deployed</th>
<th>Recovered</th>
<th>Number of Instr.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4 08bs4a</td>
<td>5/9/2008</td>
<td>5/2/2009</td>
<td>14</td>
<td>07bs4b deployed on Sept. 2007 and recovered May 7, 2008 with 15 instruments</td>
</tr>
<tr>
<td>M4 08bsp4a</td>
<td>5/9/2008</td>
<td>9/26/2008</td>
<td>1</td>
<td>07bsp4b deployed on Sept. 2007 and recovered May 7, 2008 with 1 instruments</td>
</tr>
<tr>
<td>M4 08bs4b</td>
<td>9/26/2008</td>
<td>5/2/2009</td>
<td>13</td>
<td></td>
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<tr>
<td>M4 08bsp4b</td>
<td>9/26/2008</td>
<td>5/2/2009</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>M4 09bsm4a</td>
<td>5/2/2009</td>
<td>8/18/2009</td>
<td>19</td>
<td>This surface mooring was dragged by ice and had to be recovered early.</td>
</tr>
<tr>
<td>M4 09bsp4a</td>
<td>5/2/2009</td>
<td>9/27/2009</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>M4 09bs4b</td>
<td>9/27/2009</td>
<td>Not recovered</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>M4 09bsp4b</td>
<td>9/2872009</td>
<td>9/24/2010</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>M4 10bs4a, 10bsp4a</td>
<td>Due to very extensive and persistent ice, these moorings were not deployed. The previous fall deployments were expected to supply necessary data.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M4 10bs4b</td>
<td>9/24/2010</td>
<td>5/20/2011</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>M4 10bsp4b</td>
<td>9/24/2010</td>
<td>5/20/2011</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Moorings were generally deployed once a year at M5. The first set of moorings in 2008 replaced moorings, which had been deployed the previous September. Those indicated by “bsp” are upward looking ADCP moorings. Moorings indicated by just “bs” were overwintering moorings with top instrument at 15 m.

<table>
<thead>
<tr>
<th>Mooring M5</th>
<th>Deployed</th>
<th>Recovered</th>
<th>Number of Instr.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>08bs5b</td>
<td>9/25/2008</td>
<td>5/29/2009</td>
<td>12</td>
<td>07bs5b was deployed in Sept. 2007 and recover on 9/25/08 with 11 instruments</td>
</tr>
<tr>
<td>08bsp5b</td>
<td>9/25/2008</td>
<td>5/29/2009</td>
<td>1</td>
<td>07bsp5b was deployed in Sept. 2007 and recover on 9/25/08 with 1 instrument</td>
</tr>
<tr>
<td>09bs5a</td>
<td>7/1/2009</td>
<td>9/29/2009</td>
<td>15</td>
<td>Weather and time constraints prevented the deployment of full water column mooring in May.</td>
</tr>
<tr>
<td>09bsp5b</td>
<td>9/29/2009</td>
<td>9/26/2010</td>
<td>1</td>
<td>Ice prevented deployment in May</td>
</tr>
<tr>
<td>10bs5a</td>
<td>7/4/2010</td>
<td>9/26/2010</td>
<td>18</td>
<td>Ice prevented deployment in May</td>
</tr>
<tr>
<td>10bsp5a</td>
<td>7/4/2010</td>
<td>9/26/2010</td>
<td>1</td>
<td>Ice prevented deployment in May</td>
</tr>
<tr>
<td>10bs5b</td>
<td>9/27/2010</td>
<td>5/20/2011</td>
<td>15</td>
<td>Ice prevented deployment in May</td>
</tr>
<tr>
<td>10bsp5b</td>
<td>9/27/2010</td>
<td>5/20/2011</td>
<td>1</td>
<td>Ice prevented deployment in May</td>
</tr>
</tbody>
</table>
Moorings were generally deployed once a year at M8, with a second mooring with thermistors in the upper 20 m deployed in July. The first set of moorings in 2008 replaced moorings, which had been deployed the previous September. Those indicated by “bsp” are upward looking ADCP moorings. Moorings indicated by “bsv” only contained temperature measurements in the upper 20 m. Moorings indicated by just “bs” were overwintering moorings with top instrument at 20 m.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Deployed</th>
<th>Recovered</th>
<th>Number of Instr.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>08bsv8a</td>
<td>7/26/2008</td>
<td>8/31/2008</td>
<td>2</td>
<td>This simple mooring was deployed to obtain near-surface temperatures.</td>
</tr>
<tr>
<td>08bs8a</td>
<td>8/31/2008</td>
<td>10/1/2009</td>
<td>11</td>
<td>07bs8a was deployed in Sept. 2007 and recover on 8/31/08 with 11 instruments</td>
</tr>
<tr>
<td>08bsp8a</td>
<td>8/31/2008</td>
<td>10/1/2009</td>
<td>1</td>
<td>07bsp8a was deployed in Sept. 2007 and recover on 8/31/08 with 1 instruments</td>
</tr>
<tr>
<td>09bsv8a</td>
<td>7/7/2009</td>
<td>10/1/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09bs8a</td>
<td>10/1/2009</td>
<td>9/29/2010</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>09bsp8a</td>
<td>10/1/2009</td>
<td>9/29/2010</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>10bs8a</td>
<td>9/29/2010</td>
<td>8/16/2011</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>10bsp8a</td>
<td>9/29/2010</td>
<td>8/16/2011</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

2) Provide derived products: mixed layer depth, timing of the spring phytoplankton bloom and other blooms, heat content, mixed layer depth, and advection at the four sites.

Products from the moorings include mixed layer depth, heat content at M2 and M4, temperature, position of the transition between southern pelagic-dominated shelf and northern benthic-dominated shelf, advection, tidal energy, nitrate concentration, the timing of the spring phytoplankton bloom, estimates of zooplankton from TAPS-8 and backscatter from the ADCPs. In addition, a number of annual cycles were derived using the mooring data, including: total heat content (depth averaged temperature) at M2 and M4, vertical temperature structure at M2, bottom and near-surface temperature at each mooring site, mean currents (near surface and bottom) at each site. A number of derived indices of ice cover were develop to better understand the response of the water column and lower trophic level to sea ice.
3) Use mooring and shipboard measurements as indicators of ecosystem status and to apply the observations to metrics/indices developed during Southeast Bering Sea Carrying Capacity (SEBSCC). Possible indices include wind mixing, ocean stratification, mixing events (strength, date, number of), mixed layer temperature, photosynthetically active radiation, sea ice characteristics, extent of the cold pool, timing of the spring phytoplankton bloom, zooplankton biomass and estimated larval advection.

EcoFOCI contributes to the Ecosystem Status and Management Indicators section of the Ecosystem Considerations Chapter. Our mooring and shipboard measurements contribute to the following indicators:

1. North Pacific Climate Overview, Bering Sea Regional Highlights contributed by N. Bond.

EcoFOCI also contributes indicators to the annual Eastern Bering Sea Report Card (Fig. 2).

Long-term mooring data can be used to create a number of indices. For instance the depth averaged temperature at M2 and the derived anomaly (e.g. Fig. 3) are used to define warm and cold years for the eastern Bering Sea shelf. The chlorophyll-a fluorescence time series at all the moorings provides an index of the timing of the spring and fall phytoplankton blooms, which can be related to both ice-retreat and storminess. The vertical temperature profiles at the moorings provide indicators of mixed layer depth. Sudden increases in mixed-layer depth coupled with winds and fluorescence time series provides an index of how many events during the summer were strong enough to mix nutrients into the euphotic zone.

Mooring M8 is located in Region 1 of the Distributed Biological Observatory (DBO). Data from this site provide a range of statistics to characterize that region and how it varies from year to year. Information includes: minimum and maximum bottom temperature, timing of that site becoming well mixed, strength of vertical density gradient, and direction of currents.
Use data from the moorings and shipboard observations to validate and tune the physical and nutrient-

Fig. 2. The annual Bering Sea Report Card from the Ecosystem Considerations Chapter, including 10 key indicators of the status of the Bering Sea. Ocean temperature is not one of the items because of its high correlations with sea ice extent in the spring. The copepod index comes partially from data collected as part of this program.

Fig. 3. Top panel: Depth averaged temperature measured at M2 during the last 18 years. Bottom Panel: The temperature anomaly, with the annual cycle (1995 – 2009) removed.
phytoplankton-zooplankton (NPZ) models that are being developed.

The data from the biophysical mooring data were frequently used to calibrate biophysical models of the Bering Sea. These included side-by-side model/data comparisons of the vertical profiles of currents, temperature, salinity, and chlorophyll-a at multiple locations, from hourly to interdecadal time scales. The data were especially useful in demonstrating that initial parameter choices for the model produced unrealistically warm conditions in the Bering Sea. A time series of surface shortwave radiation at M2 demonstrated that shortwave forcing was in fact *not* the source of that bias. Subsequent adjustments to other factors – albedo and bulk flux parameters in particular - yielded a much better fit to the extensive mooring dataset. The data were especially powerful in providing multivariate time series at many locations. These allow the examination of the covariance structure among different locations, and among different variables, which are compared with their model equivalent. Note that this is a far more rigorous method of model-data comparison than is possible with any single time series.

Manuscripts

There are ~30 peer reviewed publications (published, submitted and in preparation) as results of this grant. All published manuscripts are listed with the link to the appropriate web pages from which they can be down loaded and the abstract. The complete texts of manuscripts that are submitted, but not published are presented in Chapters 12 –15. Finally, two manuscripts that are presently in preparation for the fourth special issue are presented with detail currently available.
Published Manuscripts

(alphabetized by first author)
Chapter 1


ABSTRACT: Results from a 35 year hindcast of northeast Pacific Ocean conditions are confronted with observational data collected over the Bering Sea shelf within the integration time period. Rotary power spectra of the hindcast currents near NOAA mooring site M2 site fall within the 95% confidence bounds for the observational spectra, except for a high bias in the counter-clockwise rotating component at 10 m depth in the high frequencies (periods <24 h). The model exhibits the most skill in reproducing anomalies of the integrated annual sea ice concentration and monthly subsurface (60 m depth) temperature fields, accounting for 85% and 50% of their observed variability. Analysis of the integrated ice concentration time series reveals evolution in the mean duration of ice-free waters (40 year trend of +6.8 days/decade) and changes in this parameter's variance with time. Correlation and empirical orthogonal function (EOF) analyses reveal the primary temporal-spatial patterns of variability in the temperature and salinity fields over the Bering Sea and northern Gulf of Alaska for near-surface (0–20 m) and subsurface (40–100 m) depth layers. Correlation analysis between the EOF principal components and various climate index and observed time series shows that the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and the Bering Sea annually integrated ice area anomalies are important indices of thermohaline variability; the spatial structures of these modes give insight to their potential impacts upon the ecosystem. We identify a number of ecologically and economically important species whose temporal variability is significantly correlated with the identified spatial patterns.
Chapter 2


ABSTRACT: Coupled physical/biological models can be used to downscale global climate change to the ecology of subarctic regions, and to explore the bottom-up and top-down effects of that change on the spatial structure of subarctic ecosystems—for example, the relative dominance of large vs. small zooplankton in relation to ice cover. Here we utilize a multivariate statistical approach to extract the emergent properties of a coupled physical/biological hindcast of the Bering Sea for years 1970–2009, which includes multiple episodes of warming and cooling (e.g. the recent cooling of 2005–2009), and a multidecadal regional forecast of the coupled models, driven by an IPCC global model forecast of 2010–2040. Specifically, we employ multivariate empirical orthogonal function (EOF) analysis to derive the spatial covariance among physical and biological timeseries from our simulations. These are compared with EOFs derived from spatially gridded measurements of the region, collected during multiyear field programs. The model replicates observed relationships among temperature and salinity, as well as the observed inverse correlation between temperature and large crustacean zooplankton on the southeastern Bering Sea shelf. Predicted future warming of the shelf is accompanied by a northward shift in both pelagic and benthic biomass.


HIGHLIGHTS:

- The Bering Sea experienced four years with low sea ice cover and extraordinarily warm summers (2002-2005), followed by four years with some of the heaviest sea ice cover since the early 1970s and cold summers (2006-2009). During the warm period, integrated water column temperatures were elevated, bottom temperatures were higher, and the cold pool over the southeastern shelf was small and not as cold as in the cold period. During the cold period, integrated water column temperatures were anomalously low, bottom temperatures were below the long term mean, and the cold pool consisted of cold, -1.7°C water that extended across most of the Middle Shelf Domain with cool waters extending to Bristol Bay and the Alaska Peninsula.

- Water column stratification varied spatially, and was sometimes stronger in the warm years and sometimes stronger in the cold years, depending upon location.

- Net primary production and surface chlorophyll a were positively affected by temperature. The size distribution of crustacean zooplankton became smaller in years of warmer temperature.

- In the warm years of 2002-2005, small neritic species of crustacean zooplankton thrived whereas the medium-large copepod, *Calanus marshallae*, and the shelf euphausiid, *Thysanoessa raschii*, were scarce. In the cold years of 1999 and 2006-2008, both *C. marshallae* and *T. raschii* were abundant.

- Catches of both eastern and western Bering Sea groundfish stocks declined in recent years. In the eastern Bering Sea and Aleutian Islands, Pacific cod, yellowfin sole, flathead sole and Greenland turbot, and particularly walleye pollock, have shown declines while Pacific ocean perch, northern rockfish, rock sole, Alaska plaice, and especially arrowtooth...
flounder (whose biomass has quadrupled since the late 1970s) have increasing biomass trends.

- Walleye pollock recruitment may be adversely affected by unusually warm conditions; strong year-classes failed to emerge in the warm years of 2002-2005 despite a declining biomass of pollock. Possibly, there were strong year-classes in the cold years of 2006 and 2008. In the cold years of 2006-2008, age-0 pollock were in good condition and energy-rich, though not as abundant as they were in the warmer years, when they were less energy-rich.

- Age-0 pollock consumed mostly small crustacean zooplankton and smaller pollock in the warmer years, and neither *C. marshallae* nor *T. raschii* were important dietary components. In the cold years, their diets were dominated by *C. marshallae* and euphausiids, and there was less cannibalism.

- Comparison of fisheries statistics between the eastern and western Bering Sea showed that, overall, the aggregated catches of all major fisheries tended to be positive, suggesting that the two sides of the Bering Sea were responding similarly to shared climate forcing.

- Both size-at-age and weight-at-length of groundfish tended to be above the long term mean in the warmer years, and below the mean in the cold years.

- Catches of crabs in the eastern and western Bering Sea declined after the early 1990s (eastern Bering Sea) or the late 1990s (western Bering Sea), but catches began to increase on both sides of the Bering Sea after 2004. The biomass of both red king crab and snow crab have increased in the eastern Bering Sea, although snow crab catches remain low due to conservative catch limits.

- Catches of Pacific herring on both sides of the Bering Sea have been stable since 2001, whereas the Togiak stock in the eastern Bering Sea has declined.

- Catches of salmon in both the eastern and western Bering Sea were above average and dominated by pink and chum salmon in the western Bering Sea and sockeye salmon in the eastern Bering Sea. In both the eastern and western Bering Sea, the catches of chinook salmon are in decline when compared to catches from the mid-1960s to the early 1990s.
Chapter 4


ABSTRACT: The timing and magnitude of stratification can have profound influences on the marine ecosystem. On the Eastern Bering Sea shelf, in the absence of strong wind mixing, stratification can be initiated by the melting of seasonal sea ice or by springtime warming of the surface. Temperature and salinity both influence the stratification of the Eastern Bering Sea shelf with their relative importance varying spatially and temporally. In the northern middle shelf domain (north of ∼60°N), salinity stratification is often as important as temperature stratification. On the southern middle shelf, while the influence of temperature on stratification dominates during summer, the influence of salinity stratification plays a role in the interannual variability. Mooring 2 (M2; 56.9°N, 164.1°W) has been deployed at ∼70 m depth in the southern middle shelf domain since 1995. Data from this mooring show that stratification typically begins to set up in May and to break down in September/October, but these dates can vary by >30 d. While no trend is found in the timing of the spring setup, the fall stratification breakdown exhibited a trend toward later breakdown (∼2 d later per year from 1996 to 2009). Results suggest that it may be difficult to forecast stratification on the Eastern Bering Sea shelf from climate models as simple indices of wind mixing or heat fluxes are not correlated with stratification. Contrary to intuition, the strength of summer stratification is not correlated with depth averaged temperature. Warm years such as 2000 and 2001 can have low stratification and cold years such as 2007 can have very high stratification. This decoupling of stratification and temperature has implications for forecasting the ecosystem in the face of climate change, as we cannot assume that projections of a warmer climate simply imply higher stratification in the future.
ABSTRACT: Adding acoustic systems onto ocean moorings and observatories provides additional data to more fully document ecosystem responses to environmental perturbations. A passive acoustic recorder and three-frequency echosounder system were integrated into a biophysical mooring on the central eastern Bering Sea continental shelf. An unexpected, transient, mid-winter retreat of the seasonal sea ice was observed over the mooring for a 2-week period in March 2009. Interpretation of the passive acoustic data provided information about sea ice conditions and included the detection and identification of vocalizing marine mammals, while the acoustic backscatter provided information on relative zooplankton and fish abundance before, during, and after the retreat. Hydrographic data confirmed the acoustic signal was associated with changing surface ice conditions, and the combined information from the biophysical mooring sensors revealed changes in winter trophic level dynamics during the retreat, which would have otherwise been undetected by traditional ship-based observations. Changes in the acoustic environment, zooplankton dynamics, and acoustic detection of marine mammals were observed amidst a physically stable and uniform water column with no indication of a phytoplankton bloom. These data demonstrate the value of acoustic technologies to monitor changing ecosystems dynamics in remote and hazardous locations.


ABSTRACT: To estimate temporal changes of nutrients and calculate the seasonal net community production (NCP) on the eastern shelf of the Bering Sea, hydrographic sampling along the 70-m isobath of the middle shelf was conducted in spring (2007–2009), summer (2008–2009), and fall (2007). These were cold years, with sea ice covering much of the eastern Bering Sea in April. Each spring, there was a region with relatively low nitrate in the middle portion (59°–60°N) of the transect prior to the spring phytoplankton bloom. This water appeared to have originated in the coastal domain and was advected offshore into the middle domain. Seasonal NCP (mean±standard deviation) in this region was low (26±12 g C m⁻²), and may be indicative of a portion of the middle shelf ecosystem that is chronically short of fixed carbon in spring. In 2007, the post-bloom cruise occurred during the fall transition when deep mixing, remineralization, and denitrification/anammox compromised seasonal estimates of NCP. In other years (2008–2009), the post-bloom cruise occurred in summer. On those cruises, the euphotic zone, elevated chlorophyll fluorescence, and oxygen supersaturation were occasionally deeper than the pycnocline, and there was a seasonal loss of nitrate and phosphate in the bottom layer. In 2008, preferential uptake of ammonium may have sustained sub-surface production in the north. Therefore, seasonal estimates of NCP were not only evaluated in the upper mixed layer, but throughout the water column. During summer, denitrification/anammox in bottom waters did not appear to compromise seasonal estimates of NCP. Seasonal NCP averaged for 2008 and 2009 was slightly but significantly higher (p<0.0041) in the south (47±9 g C m⁻², n=80) than in the north (41±16 g C m⁻², n=78). In the south, interannual variability of seasonal NCP was related to the wind mixing in spring rather than the presence or absence of ice.
Chapter 7


http://scitation.aip.org/content/asa/journal/jasa/128/1/10.1121/1.3436547

**ABSTRACT:** Ambient sound in the ocean contains quantifiable information about the marine environment. A passive aquatic listener (PAL) was deployed at a long-term mooring site in the southeastern Bering Sea from 27 April through 28 September 2004. This was a chain mooring with lots of clanking. However, the sampling strategy of the PAL filtered through this noise and allowed the background sound field to be quantified for natural signals. Distinctive signals include the sound from wind, drizzle and rain. These sources dominate the sound budget and their intensity can be used to quantify wind speed and rainfall rate. The wind speed measurement has an accuracy of ±0.4 m s⁻¹ when compared to a buoy-mounted anemometer. The rainfall rate measurement is consistent with a land-based measurement in the Aleutian chain at Cold Bay, AK (170 km south of the mooring location). Other identifiable sounds include ships and short transient tones. The PAL was designed to reject transients in the range important for quantification of wind speed and rainfall, but serendipitously recorded peaks in the sound spectrum between 200 Hz and 3 kHz. Some of these tones are consistent with whale calls, but most are apparently associated with mooring self-noise.
ABSTRACT: The Bering Sea is one of the most productive marine ecosystems in the world, sustaining nearly half of U.S. annual commercial fish catches and providing food and cultural value to thousands of coastal and island residents. Fish and crab are abundant in the Bering Sea; whales, seals, and seabirds migrate there every year. In winter, the topography, latitude, atmosphere, and ocean circulation combine to produce a sea ice advance in the Bering Sea unmatched elsewhere in the Northern Hemisphere, and in spring the retreating ice; longer daylight hours; and nutrient-rich, deep-ocean waters forced up onto the broad continental shelf result in intense marine productivity (Figure 1). This seasonal ice cover is a major driver of Bering Sea ecology, making this ecosystem particularly sensitive to changes in climate. Predicted changes in ice cover in the coming decades have intensified concern about the future of this economically and culturally important region. In response, the North Pacific Research Board (NPRB) and the U.S. National Science Foundation (NSF) entered into a partnership in 2007 to support the Bering Sea Project, a comprehensive $52 million investigation to understand how climate change is affecting the Bering Sea ecosystem, ranging from lower trophic levels (e.g., plankton) to fish, seabirds, marine mammals, and, ultimately, humans. The project integrates two research programs, the NSF Bering Ecosystem Study (BEST) and the NPRB Bering Sea Integrated Ecosystem Research Program (BSIERP), with substantial in-kind contributions from the U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. Fish and Wildlife Service.
Chapter 9


ABSTRACT: Sufficient oceanographic measurements have been made in recent years to describe the latitudinal variation in the physics of the eastern Bering Sea shelf and the potential impact of climate change on the species assemblages in the two ecosystems (north and south). Many of the predicted ecosystem changes will result from alterations in the timing and extent of sea ice. It is predicted that the sea ice in the northern Bering Sea will be less common in May, but will continue to be extensive through April. In contrast, the southern shelf will have, on average, much less sea ice than currently observed, but with large interannual and multiyear variability until at least 2050. Thus, even under current climate warming scenarios, bottom temperatures on the northern shelf will remain cold. Based on biophysical measurements, the southern and northern ecosystems were divided by a North–South Transition at $\sim 60^\circ$N. The northern middle shelf was characterized by a freshwater lens at the surface, cold bottom temperatures, and a thicker pycnocline than found on the southern shelf. Subsurface phytoplankton blooms were common. In contrast, the southern shelf stratification was largely determined by temperature alone; the pycnocline was thin (often<3 m) and subsurface blooms were uncommon. Biological responses to climate warming could include greater north–south differences in zooplankton community structure, the transport of large Outer Shelf Domain crustacean zooplankton to the middle shelf, and the disappearance of two principal prey taxa (Calanus spp. and Thysanoessa spp.) of planktivorous fish, seabirds and whales. The response of commercially and ecologically important fish species is predicted to vary. Some species of fish (e.g., juvenile sockeye salmon, Oncorhynchus nerka) may expand their summer range into the northern Bering Sea; some (e.g., pink salmon, O. gorbuscha) may increase in abundance while still other species (e.g., walleye pollock and arrowtooth flounder; Theragra chalcogramma and Atheresthes stomias, respectively) are unlikely to become common in the north. The projected warming of the southern shelf will limit the distribution of arctic species (e.g., snow crab, Chionoecetes opilio) to the northern shelf and will likely permit expansion of subarctic species into the southern Bering Sea. The distribution and abundance of baleen whales will respond to shifts in prey availability; for
instance, if prey are advected northward from the southeastern Bering Sea, an extension of range
and an increase in seasonally migratory baleen whale numbers is anticipated. Thus, alteration of
this ecosystem in response to climate change is expected to result in something other than a
simple northward shift in the distribution of all species.
ABSTRACT: The southeastern, middle shelf of the Bering Sea has exhibited extreme variability in sea ice extent, temperature, and the distribution and abundance of species at multiple trophic levels over the past four decades. From 1972–2000, there was high interannual variability of areal extent of sea ice during spring (March–April). In 2000, this shifted to a 5-year (2001–2005) period of low ice extent during spring, which transitioned to a 4-year (2007–2010) period of extensive sea ice. High (low) areal extent of sea ice in spring was associated with cold (warm) water column temperatures for the following 6–7 months. The ocean currents also differed between warm and cold years. During cold years, the monthly-mean currents over the shelf were largely westward, while in warm years the direction of currents was more variable, with northward flow during December–February and relatively weak flow during the remainder of the year. The types and abundance of zooplankton differed sharply between warm and cold years. This was especially true during the prolonged warm period (2001–2005) and cold period (2007–2010), and was less evident during the years of high interannual variability. During the warm period, there was a lack of large copepods and euphausiids over the shelf; however, their populations rebounded during cold period. Small crustacean zooplankton taxa did not appear to vary between warm and cold years. For both walleye pollock and Pacific cod, year-class strength (recruitment) was low during the prolonged warm period, but improved during the following cold period. Year-class strength did not appear to vary as a function of warm and cold years during the period of high year-to-year variability. Also, recruitment of arrowtooth flounder (a predator of pollock and cod) did not appear influenced by the warm or cold years. Finally, the distribution and relative abundance of fin whales appeared to differ in warm and cold years, with fewer whales on the southeastern, middle shelf during warm years.
ABSTRACT: Integrated ocean observation, from physical and atmospheric forcing mechanisms to the distribution and abundance of top-level predators, is critical to the investigation of marine ecosystems and the impact of climate change on them. We integrated data from a biophysical mooring in the southeast Bering Sea to create a one-year snapshot of ocean dynamics in this remote large marine ecosystem. Distinct patterns in production (chlorophyll), zooplankton biovolume (copepods and euphausiids) and the occurrence of zooplankton predators (fin and right whales) were defined and related to discrete features in the annual physical cycle. Peaks in prey and predator cycles were linked to spikes in fluorescence that occurred at the onset of water column stratification in late spring 2006 and the appearance of sea ice in late winter 2007. These data illustrate the capability and potential of integrated ocean observing systems (IOOS) to describe seasonal variability and linkages in a remote marine ecosystem.
Submitted manuscripts
Chapter 12


Abstract

We examine ice-ocean interactions in the Eastern Bering Sea (EBS) using output from the National Center for Atmospheric Research-Community Earth System Model and satellite observations, and draw comparisons with published results based on ocean in situ data. The model simulation generally captures the observed seasonal advance and retreat of sea ice in the EBS and spatial patterns. In the northern EBS, however, modeled sea ice annual maximum occurs in April instead in March, as observed by satellite observations. Sea ice also retreats slower in spring in the simulations than observed. Simulations indicate that early winter changes in ice coverage in the north are due to a combination of freezing and advection processes, while in the south changes are primarily due to advection from the north and melting. Via this seasonal transit, sea ice cools the entire EBS middle shelf relatively uniformly, but its influence on ocean salinity has greater spatial variability, as suggested by both observations and simulations. On inter-annual time scales, high ice cover in the EBS leads to cold anomalies in the bottom water, especially on the middle shelf, with the strongest anomalies in the southern domain. The corresponding salinity anomalies are positive, with the strongest signal in the northern near-shore locations. The associated current anomalies at 50m are generally southward on the shelf, and northwestward in the slope region. Comparing years 1961-2005 versus years 2005-2050, the Probability Distribution Function of ice time series on the EBS has shifted northward by ~ 2° latitude. The implications of these results on marine ecosystem responses are discussed.

Keywords: Bering Sea, sea ice, numerical model, ocean temperature, salinity
1. **Introduction**

The Bering Sea is a North Pacific subarctic ocean bounded to the north by Bering Strait, which connects the Bering Sea with the Arctic Ocean, and to the south by the Aleutian Island chain (Fig. 1). The Eastern Bering Sea (EBS) shelf is wide (approximately 500 km) and flat (with depth less than 180m). As early as November, sea ice begins forming in the northern EBS, and under the prevailing wind conditions, is transported southward 700 – 1000 km, often covering much of the EBS shelf. Maximum ice extent typically occurs in March, but it can occur as early as February or as late as April (Stabeno et al., 2012a). During melting season, sea ice retreats and by June the Bering Sea is usually ice free. Sea ice extent is highly variable on interannual scales, but thus far, shows no significant trends since the beginning of the satellite record in 1979 (Brown and Arrigo, 2012).

The seasonal changes of sea ice profoundly influence the physical oceanography of the EBS and its ecosystem. During extensive ice years, with sea ice persisting on the southern shelf after mid March, the water column over the southern shelf (south of 60° N) tends to be colder and fresher (Stabeno et al., 2010, 2012b; Ladd and Stabeno, 2012; Sullivan et al., this issue). The timing of ice retreat also influences the timing of the spring phytoplankton bloom (Sigler et al., this issue), zooplankton species composition, and fish recruitment. For instance, a period of limited ice over the southern shelf (2001 – 2005) was characterized by fewer large crustacean zooplankton the following summer (Stabeno et al., 2012a). As a result the young of the year walleye pollock (*Theragra chalcogramma*) had less lipids and failed to survive the following
winter (Heintz, personal communication) resulting in very low recruitment (Stabeno et al., 2012b).

The EBS shelf is divided into three domains (Coachman, 1986). The inner or coastal domain (water depth < 50 m) is characterized as well mixed or weakly stratified during the summer. The middle domain (50 – 100 m) has well defined two layers during the summer with a wind mixed surface layer and tidally mixed bottom layer. The outer domain (100 – 180 m) is more oceanic, with a well-mixed surface layer and bottom layer separated by an intermediate layer. On the middle domain, the influence of the sea ice from the winter and spring often persists through the following summer. As a part of a biophysical observing network on the EBS shelf, four moorings on the middle domain (M2, M4, M5 and M8) (Fig. 1) provide long time series (9 – 18 years) of temperature and salinity data that have been published (e.g. Stabeno et al., 2010, 2012a,b; Sigler et al., this issue; Sullivan et al., this issue).

The purpose of this study is to examine the impacts of seasonal sea ice on the EBS shelf water properties, using output from a global climate model and compare it with in situ ocean (primarily data from moorings) and satellite observations. We will examine sea ice variability in the EBS on seasonal and inter-annual time scales. Pan-Arctic sea ice is projected to decline in the future under Greenhouse Gases (GHGs) forcing but there are large uncertainties (Wang and Overland, 2009). For instance since 2007, winter/spring sea ice extent has been well above average in the EBS even though the summer minimum ice extent in the Arctic has reached record minimums (Stroeve et al. 2007; Stabeno et al., 2012 a,b; Brown and Arrigo 2012).

The paper is organized as the following. In section 2 we describe sea ice satellite observational data and the numerical model output used in this study. In section 3 we present the main results, including comparing model simulations with satellite and in situ observations. In section 4 we draw conclusions and discuss the implications of the results on the EBS marine ecosystem.
2. **Data and methods**

2.1. Satellite and sea ice data

Ice concentration images are derived using data from the Bootstrap algorithm files of daily ice concentration we download from the National Snow and Ice Data Center (NSIDC). The files use data from the Scanning Multichannel Microwave Radiometer (SMMR) aboard the Nimbus-7 satellite or the Special Sensor Microwave/Imager (SSM/I) aboard Defense Meteorological Satellite Program (DMSP) satellites, depending on the year. We used data from years 1987 to 2005.

To examine how the ice cover varies along the EBS middle shelf, a 100 km by 100 km box was defined centered on each of four biophysical moorings (M2, M4, M5, and M8) that have been maintained by NOAA since 1990s. Percent of ice cover from satellite was averaged over these 100 km by 100 km regions and monthly climatologies were calculated.

2.2. Numerical model output

The global climate model we used is the NCAR-CESM (National Center for Atmospheric Research-Community Earth System Model). The NCAR-CESM (and its predecessors) is a global coupled ocean-sea ice-atmosphere-land model (Gent et al. 2012) participating in the IPCC (Intergovernmental Panel on Climate Change) assessment reports. Specific formulations of the sea ice model used in CESM are summarized in Holland et al. (2012). CCSM4 (the version of CESM used in up-to-date publications) simulated Arctic ice extent seasonal cycle in the 20th century follows observations closely (Jahn et al., 2012). Arctic sea ice simulated by CCSM4 in the 21st century has been investigated in a number of studies (e.g., Vavrus et al., 2012).

The particular configuration of the CESM used in this study has 0.9° latitude by 1.25° longitude resolution for the atmosphere and land components, and nominal 1° horizontal resolution for the ocean and sea-ice components. The external climate forcing factors (including
natural and anthropogenic components) vary with time. Because it is a coupled model, the feedbacks between different components of the climate system, such as the ocean and sea ice, are preserved. Monthly averaged ocean and sea ice states from the CESM “historical” (from 1850 to 2005) and “RCP” (Representative Concentration Pathways) (year 2005 onward) simulations were downloaded from NCAR data mass storage. The “historical” simulations of the CESM were initialized from a spun-up state of the climate system under pre-industrial GHGs forcings. The “historical” simulations cover years 1850 to 2005 (we only used output from the late 20th century), while its “RCP” simulations were initialized from the climate state of the model at the end of the “historical” simulations (Gent et al. 2012), and RCP simulations cover years 2006-2100 and later. We use results from the RCP6.0 forcing (radiative forcing stabilizes at 6.0 W/m² by year 2100), a medium emission scenario.

To study the inter-annual variability of sea ice and its impact on the EBS shelf, we extract Empirical Orthogonal Functions (EOFs) of physical variables from multiple years in March. Mean states of the shelf water property and circulation averaged over “high” and “low” ice years are computed and compared against each other. The “high” and “low” ice years are defined based on March ice concentration at M5: if a year’s value is above +1STD of the multi-year time series, that year is a “high” ice year; if it is below -1STD, it’s “low” ice year.

To facilitate the comparison with observations, we carried out an additional CESM RCP6.0 simulation with daily sea ice and ocean output, from December 1, 2016 to June 30, 2017. This time period is used as a “representative” year with substantial ice cover in the EBS (shown later). The comparison between this model output and observations are process oriented. Due to the internal variability of the coupled system, simulated climate state at any given year is not guaranteed to “match” with observations for that year.

When applicable, the model simulations are compared with existing figures in Sullivan et al. (this issue) which summarizes the ocean in situ observations at the four moorings (M2, M4, M5 and M8) (Fig. 1).
3. **Results**

3.1. **Sea ice climatology**

Monthly mean climatology (defined over years 1987-2005) of sea ice concentration was computed from the CESM “historical” simulation and compared with the satellite data (Fig. 2). Satellite data show a gradual increase in ice cover from December through March (growth in December is small), with the percent of ice cover reaching its maximum in March on the middle shelf regardless of latitude. After March, ice cover decreases rapidly. At the southern two sites, ice cover is reduced to zero by May. Farther north, an additional month is required for complete loss of sea ice (June at M5 and M8). The magnitude of the standard deviations at each location suggests that ice cover is more variable at M4 than at the other locations examined.

While the model simulations show same general patterns as the observations, there are marked differences in timing and magnitude. The CESM captures the March maximum at the southern two sites (Fig. 2, M2 and M4); at the northern sites (M5 and M8), CESM reaches annual maximum ice cover in April, a month later than observed. The model simulation underestimates ice cover at all four locations leading up to the March maximum and overestimates ice cover after March. Complete loss of ice occurs one month later than observed in CESM simulations, except at the southernmost site. The magnitude of the variability is well reproduced by CESM except at the M4 location where the model significantly underestimates the interannual variability.

![Figure 3. Monthly mean climatology (averaged over years 1987-2005) of sea ice concentration (percentage) at the mooring sites from CESM simulation (red) and SSM/I data (green). Names of the moorings are marked on each panel. Vertical bars show one standard deviation.](image)
The modeled spatial pattern of ice concentration in March, the month of maximum annual ice extent, is similar to observations (Fig. 3). The biggest discrepancy is that the simulated ice concentration gradient is weaker than observations, especially in the western part of the domain. The model results show significant ice cover over the deep basin in the northern Bering Sea, while sea ice is constrained to the shelf in observations. In addition, in the southeast corner of the EBS shelf, the influence of warm inflow from the Pacific is observed to result in less ice close to the Alaskan Peninsula (Fig. 3 upper panel). Due to the low spatial resolution, the CESM model cannot be expected to reproduce such regional features.

3.2. Ice formation: dynamic versus thermodynamic processes

The mechanisms that result in changes in the areal extent of ice can be divided into two broad categories: dynamic processes and thermodynamic processes. Dynamic processes include advection and mechanical ridging/rafting, while thermodynamic processes are ice melting and freezing. Not surprisingly, ice cover changes seasonally in different locations because of different processes.
At all four mooring locations, dynamical processes (for simplicity, we will call it “advection”) contribute to positive ice growth in January (Fig. 4). At the southern two moorings (M2 and M5), instantaneous ice concentration is a result of advection of ice into the region offset by local melting (Fig. 4b, c). The magnitudes of both the advection and the local melt terms are weaker at M5 than at M2.

Further north at M8, ice growth is dominated by advection into the region, with a small contribution from local formation (Fig. 4a). Thus, ice melt contributes to water column properties throughout the winter over a majority of the shelf. Ice formation is only important in the northernmost region from January through April. After April, local melting contributes to the decline in ice cover even in the north.

Spatially, near Bering Strait and along the inner shelf, ice formation (Fig. 5a) is largely offset by advection out of the region (Fig. 5b). This balance is reversed in the southern and offshore locations, where advection into the region is offset by local ice melt. The pattern thus emerged is that, sea ice is thermodynamically formed in the northern domain and along the coast, and then transported southward and offshore, and subsequently melted in the warmer ambient environment. This is the well-known “freshwater conveyor” effect of seasonal sea ice on the Bering Sea shelf (Pease 1980; Sullivan et al, this issue). During this seasonal transit, the largest ice-ocean exchanges in heat and freshwater occur at the ice edge (Figs. 5 c, d).
The above ice growth and retreat processes have strong interannual variabilities, which are influenced by wind forcing. To illustrate this, empirical orthogonal functions (EOFs) of March ice advective growth (ice area tendency due to dynamics), ice formation/melt (ice area tendency due to thermodynamics), and wind stress are extracted and compared with one another (Fig. 6). The dominant mode of March wind stress inter-annual variability (accounting for over 60% of the variability) is an oscillation between northeasterly and southwesterly winds (Fig. 6c,d). The principal component (PC) of this wind stress mode (black line on Fig. 6d) is highly correlated with PCs of ice area tendencies due to thermodynamics and dynamics (Fig. 6d, red and green lines): the correlation coefficients between the three PCs on Fig. 6d range from 0.80 to 0.97. When the winds are from the northeast, more sea ice is advected into the middle shelf (Fig. 6a), where it melts (Fig. 6b). At the same time, in the northern and coastal regions, freezing (Fig. 6b) and ice removal by advection (Fig. 6a) are
enhanced under northeasterly winds (Fig. 6c). This strong coupling between ice advection and melting is a characteristic of the EBS.

Next we examine relationships between seasonal ice growth/decline (via advection and local formation/melting) and ice-ocean heat and freshwater exchange (Fig. 7).

Advection of ice into the region begins in December in the north (M8) and January farther south (M2 and M5) and cooling of the ocean occurs soon after. At the northern sites (M5 and M8), there is a period in which ice area tendency and ice-ocean fluxes are relatively constant between January, the beginning of the seasonal ice increase, and March or April, the beginning of seasonal decrease (Fig. 7). Advection induced ice area tendency (red lines in Fig. 7) is generally smaller at the northern mooring M8 than at moorings farther south (M5 and M2).

In terms of ice-ocean heat exchange, at all sites and throughout the season, the ocean loses heat. At M2 and M5, during the ice growth season (January or February), the heat loss appears correlated with ice area tendency but lags the latter by a few days (Fig. 7a). The lag-0 correlation coefficients between black and red (green) lines on Fig. 7 are 0.97 (-0.52) and 0.74 (-0.54) for M2 and M5, respectively, which are statistically significant with the 95% confidence level. Heat loss in these locations is controlled by both latent and sensible heat exchange. During ice formation, latent heat would result in a positive heat flux to the ocean. At M8, freezing (Fig. 7a; positive red line) is accompanied by negative heat flux to the ocean (Fig. 7a; black line), implying that sensible heat flux dominates latent heat flux. This is consistent with model output (Fig. 9) showing that the ocean temperature is above the freezing point in January. Because ice
bottom temperature is at the freezing point, there is a sensible heat exchange at the ice-ocean interface.

The relationship between ice tendency and ice-ocean freshwater exchange (Fig. 7b) is straightforward. At all locations, the water column freshens (becomes saltier) whenever ice melts (forms). Thus, the ocean gains freshwater in the south throughout the season while, in the north, the ocean gains salt during ice formation (mainly in January and February) and freshwater during ice melting (in April and May). Ice advective growth (green lines in Fig. 7) plays an implicit role in ice-ocean freshwater exchange through its control on ice thermodynamic growth (Fig. 5).

3.3. Influences on ocean temperature and salinity

The vertical structure and temporal variability of ocean temperature and salinity are related to ice cover. At M5 and M8, the water column in CESM is vertically well mixed or weakly stratified in temperature and salinity at the beginning of the winter (December) as a result of wind mixing (Fig. 8). The weak stratification at M8 (and to a lesser extent at M5) is
maintained through spring under significant ice cover, and at M8, there is a hint of brine rejection into the bottom layer when ice is formed. This is not dissimilar to observations at the moorings. The observed water column at M8 tends to be well mixed under the ice, with a winter season increase in salinity of ~1 psu, which is a result of brine rejection or on-shelf advection during the cold winter months (e.g., Fig. 12 in Sullivan et al., this issue). This observed increased in salinity contrasts with a small (~0.2 psu) depth-averaged decrease in salinity in the model.

At M2, however, the differences between the modeled and observed water column structures are greater. In December, the modeled water column is stratified near the bottom, albeit weakly, especially in salinity (Fig. 8, bottom panels). In observations, during years with little or no ice over the mooring, the water column is well mixed usually by November (Table 2 and Fig. 6 in Sullivan et al., this issue). During years in which ice is extensive over the southern domain, the ice often arrives when the water column is well mixed, but above freezing. The ice cools and freshens the surface waters, but the near bottom waters remain warmer and saltier for several weeks before the water column becomes well mixed. CESM also simulates cooling and freshening at M2 after ice arrival, similar to observations, but stratification persists in the model. In CESM the ocean stratification begins to increase during the melting season at all mooring locations (Fig. 8). Stratification measured at the moorings usually begins after ice concentrations have decreased (Sullivan et al., this issue).

The near-surface ocean gradually cools starting from fall (not shown), but the strongest cooling is concurrent with largest sea ice increase at all moorings (Fig. 9, red lines). This result is
consistent with observations (Sullivan et al., this issue, their Figs. 7-12). In the model, as in observations, cooling at M8 and M5 continues even under significant ice coverage (Fig. 9ab, red line, late January), until the temperature reaches the freezing point and remains constant thereafter. The quasi-steady thermal ocean lasted a couple months at M8, but only briefly at M5. In observations, warming generally begins in March, although if ice retreats, the water column can warm through advection especially at the southern moorings M2 and M4 (Stabeno et al., 2010, 2012a; Sullivan et al., this issue). The model shows a similar pattern, in that after the sea ice diminishes (which occurs sooner in the lower latitudes), the near-surface ocean warms rapidly (Fig. 9).

The modeled seasonal evolution of near-surface salinity is more variable and differs from north to south (Fig. 9, green lines). Starting in December, modeled near-surface salinity at the two northern mooring sites generally decreases. At M8, the linear trend continues throughout the season, although it is also punctuated by episodes of salinity increase. At M5, salinity decreases from December to early February along with ice increase, it then exhibits a period of weak changes from late February to March, followed by a gradual increase. At M2, large synoptic scale variability is observed in the near-surface salinity. In contrast, at each of the mooring sites, observed salinity increases from December to March because of brine rejection and/or on-shelf advection during the cold winter months, after which ice begins to melt, thus freshening the water column (Sullivan et al., this issue).

3.4. Contrast in ocean properties between “high” and “low” ice years

Change in bottom temperature, salinity, and density in high ice years relative to low ice years indicates cooling anomalies over the entire bottom layer, with the strongest
anomaly occurring in the southern
domain (Fig. 10a); concurrently, a
large part of the inner and middle
shelf domain has positive salinity
anomalies (Fig. 10b). While the
gradient in the temperature
anomalies is the strongest in the
north-south direction, the salinity
anomaly has the strongest gradient
in the onshore-offshore direction. As
expected, in this subarctic ocean, the
bottom density anomaly (Fig. 10d) is
dominantly controlled by salinity.

The corresponding upper
ocean circulation is anomalously southward on the shelf except in the Gulf of Anadyr (Fig. 10d,
vectors). The anomalous circulation is close to the shelf-break between 59°N and 60°N with a
slightly offshore direction, but is located further in-shore in the southern domain (south of 59°N),
and shows a strong on-shore movement toward the southeast corner of the EBS when it reaches
the Aleutian Island chain. However, the circulation anomalies next to the shelf-break in the slope
region (200m < depth < 2000m) are opposite to circulation anomalies on the shelf, and move
northwestward.
3.5. Decadal changes: “historical” versus “RCP” simulations

We compare March ice cover at the mooring sites between two periods: years 1961-2005 vs. years 2006-2050, since March is near the annual maximum ice extent (Fig. 2). During the earlier period, ice cover at M2 and M4 is usually low (<50%) while ice cover at M8 is usually high (>50%) (Fig. 11, left panels). Ice cover at M5 fluctuates between low and high conditions on interannual time scales (Fig. 11, left panels). Ice cover at all locations in the later period (Fig. 11, right panels) is smaller relative to the earlier period. M2 and M4 are mostly ice-free in the later period, only occasionally having significant ice cover. In the earlier period, the probability distribution functions (PDFs) of ice cover at M2 and M4 show increased occurrence of low ice cover events while the PDF at M8 has more occurrence of high ice cover events (Fig. 12, left panels); PDF at M5 is approximately flat among all categories (Fig. 12, left panel, M5). In the later period, PDF at M5 has more occurrence of low ice cover events while PDF at
M8 is more or less flat among all categories (Fig. 12, right panels). In this sense, PDF at M8 in the later period is similar to PDF at M5 in the earlier period.

4. Conclusions and Discussion

Seasonal cycle and spatial pattern of the annual maximum ice cover in the EBS modeled by CESM are reasonable compared to satellite observations (Figs. 2, 3). However, biggest discrepancies include delayed onset of the annual maxima (by a month) and slower summer melting in the northern Bering Sea in the simulation (Fig. 2). One possible cause for the slower summer melt could be that the simulation maintains weak stratification of the water column under the ice (Fig. 8), while observations show that the water column is well mixed throughout the winter. The EBS shelf loses heat and gains freshwater during the melting season. If the ocean layer receiving these fluxes is too shallow (due to stratification), this cooling and freshening effect on the surface layer would be too strong. A cooled ocean slows down further melting, causing a negative feedback on ice melting. An anomalously fresh surface layer further increases water column stability. In addition, an initial delay in ice retreat allows ice to remain into the period when spring winds are weakening, further delaying ice break-up and melt. These feedbacks may contribute to the slower melting in the model than in observations.

Modeled seasonal ice advance in the EBS is consistent with the “freshwater conveyor” conceptual model suggested by observations (Pease 1980; Sullivan et al., this issue). Sea ice is both advected in and formed locally in the northern domain. In the southern domain, sea ice is advected from the north and melts locally. The regional differences in the partition between advection and formation/melt influence water column properties, particularly affecting local salinity budgets. The boundary between the northern domain where formation dominates and the southern domain where advection and melt dominate changes seasonally (Fig. 5) and
interannually (Fig. 6). On interannual time scales, the division is strongly influenced by surface
wind.

At all mooring sites and throughout the season, modeled heat flux at the ice-ocean
interface is from the ocean to the ice (Fig. 7a) while freshwater flux can be either into the ocean
(during melting) or out of the ocean (brine rejection during freezing). The salt/freshwater flux in
nature is influenced by island polynyas in the Bering Sea. St. Lawrence Island, to the north of
M8, and to a lesser extent St. Matthews Island to the north of M5, is associated with important
polynyas. CESM does not resolve either polynya. Thus, the model will underestimate ice
formation due to the polynyas and the associated salinity flux into the ocean at these locations.

Despite these limitations, in CESM, higher spring ice concentration in the northern EBS
leads to positive salinity anomalies (relative to years with less ice concentration) on a large part of
the bottom water (Fig. 10b), and the anomaly is the strongest in the northern domain near-shore
locations. Weak negative salinity anomalies are seen in the southern end of the middle- and outer-
shelf (Fig. 10b). Correspondingly, bottom water on the entire shelf has cold anomalies in high ice
years relative to low ice years (Fig. 10a), and the anomalies are the strongest in the southern
domain. Both temperature and salinity anomalies persists from spring into summer (not shown).

According to the model, circulation on the middle shelf is anomalously southward during
high ice years; however, next to the shelf-break in the slope region, circulation is anomalously
northwestward during high ice years, opposite to situation on the shelf (Fig. 10 d). Broadly
speaking, the southward circulation anomalies on the shelf are consistent with the southward
wind anomalies during high ice years (Fig. 6). Such wind anomalies are also expected to cause
the Anadyr current to flow stronger in the on-shelf direction toward Bering Strait (Danielson et al.
2012). The reason for the northwestward anomalies in the slope region is unclear. The strength of
the Bering Slope Current is correlated with the multivariate ENSO index and North Pacific Index
on interannual time scales (Ladd, this issue), it is possible that these climate indices have
manifestations in the EBS surface wind and sea ice variability.
Over a 45-year time span (between period 1: 1961-2005 and period 2: 2006-2050), the EBS ice concentration PDF have shifted northward by 2 degrees. PDF of Ice concentration at M8 in the later period is more or less flat, similar to PDF of ice concentration at M5 in the earlier period, while PDF at M5 in the later period becomes similar to PDF at M2 and M4 in the earlier period.

Sea ice has profound effect on the EBS primary production (Hunt et al., 2002; Stabeno et al. 2010; Brown and Arrigo, 2012; Sigler et al., this issue), zooplankton structure (Hunt et al. 2002; Coyle et al., 2011; Eisner et al., this issue), and upper trophic level species (e.g., Wyllie-Echeverria and Wooster, 1998). Timing of ice retreat determines spring bloom. Over the southern shelf, if ice is present after mid-March, an early ice-associated bloom occurs; otherwise the spring bloom usually occurs in May (Stabeno et al. 2001; Hunt et al. 2002). In this regard, CESM captures well the March maximum ice cover in the southern domain in a climatological mean sense.

Lower water temperatures associated with more sea ice reduce energy required for zooplankton overwinter survival, resulting in increased spawning biomass and production (Sigler et al., this issue). In addition, the distribution of low bottom temperatures associated with ice distribution (the cold pool) determine available habitat for some fish species (Hollowed et al. 2012). Conversely, warmer temperatures increase metabolic requirements, leading to food limitation. This could result in reduced net primary production (Lomas et al., 2012), leading to poor overwinter survival of zooplankton (Coyle et al., 2011).

In addition to influences on temperature and salinity, ice melt results in input of ice algae to the water column, and ice algae provides an early sources of food for zooplankton growth and spawning (Sigler et al., this issue). Thus, the “freshwater conveyor” associated with seasonal sea ice in the EBS can also be thought of as conveyor belt for ice alge, and possibly zooplankton. The balances between ice advection and ice formation/melt are important to the ecosystem, and understanding what processes controls the seasonal to interannual variability in these balances
will have important implications. Our results suggest surface winds in the EBS should be closely monitored because of its strong influences on ice advection and local formation.

Global climate models are more often used to study global and basin scale processes, their applications on regional scales are relatively rare. Understanding how climate models work on all scales, however, is critically important to our ability to predict future changes in the physical environment and marine ecosystems, the latter tend to operate on regional scales. Our next step is to investigate the Bering Sea ice-ocean system in a coupled biophysical ocean-ice circulation model. This class of models can afford higher spatial resolutions, although they misrepresent atmosphere-ocean or atmosphere-sea ice interactions. Combining knowledge gained from different models and observations should ultimately improve our understanding of the system.

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Figure Captions

Figure 1. Geographical information of the study area. The black dots mark the ocean moorings in the Eastern Bering Sea middle shelf.

Figure 2. Monthly mean climatology (averaged over years 1987-2005) of sea ice concentration (percentage) at the mooring sites from CESM simulation (red) and SSM/I data (green). Names of the moorings are marked on each panel. Vertical bars show one standard deviation.

Figure 3. Multi-year (1987-2005) mean March sea ice concentration (percentage) from SSM/I data (upper panel) and CESM simulation (lower panel).

Figure 4. Time integrals of ice area tendency $\int_{t_0}^{t} \frac{\partial A}{\partial t} dt, T_0 = Dec1$ (here $A$ is the ice area and $t$ is time) due to dynamics (green) and thermodynamics (red), and their comparisons with the daily instantaneous ice area $A$ (black) at the moorings (names of them are marked on the panels). Ice area is defined as percentage coverage. Results at M4 are not shown because they are similar to results at M2.

Figure 5. Colors show the spatial patterns of ice area tendency (percent/day) due to thermodynamics (a) and dynamics (b), and ice to ocean heat (c, in W/m²) and freshwater (d, in cm/day) fluxes. White areas are ice-free. Positive signs in c) and d) mean into the ocean. Contours in c) and d) mark the 0.8, 0.6, 0.4, and 0.2 ice area (in fraction). All results are averaged over February of the model year shown in Figure 4. Circles mark the mooring locations.

Figure 6. Spatial patterns of EOF1 of the ice area tendency due to dynamics (a) and thermodynamics (b), and spatial pattern of EOF1 of the surface wind stress (c). Thin black lines on a) and b) denote the 50m, 100m, and 200m ocean topography. Contours of a) is redrawn in c).
d) Corresponding principal components (PCs) of the spatial patterns shown in a)–c). CESM March data is used for this analysis. Percentage of variance explained by EOF1 is marked on a)–c).

Figure 7a. Modeled daily ice area tendency due to thermodynamics (red) and dynamics (green) and their comparisons with the simultaneous ice to ocean heat fluxes (black). Positive (negative) heat flux means into (out of) the ocean. Panels a)–c) correspond to M8, M5, and M2 respectively. M4 results are similar to M2 and not shown.

Figure 7b. Same as Fig. 7a except the black lines are ice to ocean freshwater fluxes (cm/day), positive (negative) means into (out of) the ocean.

Figure 8. Colors show modeled ocean temperature (left) and salinity (right) as a function of depth (0-100m) and time at the moorings. The thick black lines on each panel show ice area (percentage) at that mooring. M4 results are not shown because they are similar to M2 results.

Figure 9. Modeled daily ice area (black, units: percentage) and ocean temperature (red, units: °C) and salinity (green, units: psu) at 10m depth at moorings M2, M5 and M8. M4 result is similar to M2 result and therefore not shown.

Figure 10. Shading indicates anomalies in March bottom temperature (a), salinity (b), and density (d) averaged over high ice years minus that over low ice years. Thin black lines in a) and b) mark the 50m, 100m, and 200m isobath. Vectors in d) show the ocean circulation anomalies at 50m depth, dark blue ones are the results on the shelf (depth< 200m), while the light blue ones are results in the slope region (200m<depth<2000m). March bottom density (shade) and 50m currents (vectors) averaged over high ice years are shown in c) as a reference. CESM output from years 1961-2005 is used in this analysis.

Figure 11. Time series of March sea ice area (percentage) at the mooring locations during years 1961-2005 (left panels) and years 2006-2050 (right panels) from CESM. Year 2005 is the end of “historical” period, while year 2006 is the beginning of “RCP” period.
Figure 12. Probability distribution functions (PDFs) of March ice area (percentage) at the mooring locations. Left panels are results from period 1 (years 1961-2005), right panels are from period 2 (years 2006-2050).

References


Magaret Sullivan, M., C. Mordy, S. Salo, and P. Stabeno, this issue: The influence of sea ice on seasonal water column changes on the eastern Bering Sea shelf.


Chapter 13


Climate-mediated changes in zooplankton community structure for the eastern Bering Sea


*Corresponding Author Address

NOAA-Fisheries, Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115, Lisa.Eisner@NOAA.gov, 001-206-526-4060; Jeff.Napp@NOAA.gov;

Kathy.Mier@NOAA.gov

University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 17101 Point Lena Loop Road, Juneau, Alaska 99801, aipinchuk@alaska.edu

NOAA-Fisheries, Alaska Fisheries Science Center, 17109 Point Lena Loop Road, Juneau, Alaska 99801, Alex.Andrews@NOAA.gov

Abstract:

Zooplankton are critical to energy transfer between higher and lower trophic levels in the eastern Bering Sea ecosystem. Previous studies from the southeastern Bering Sea shelf documented substantial differences in zooplankton taxa in the Middle and Inner Shelf Domains between warm and cold years. Our investigation expands this analysis into the northern Bering Sea and the south Outer Domain, looking at zooplankton community structure during a period of climate-mediated, large-scale change. Elevated air temperatures in the early 2000s resulted in regional warming and
low sea ice extent in the southern shelf whereas the late 2000s were characterized by cold
winters, extensive spring sea ice, and a well-developed pool of cold water over the entire Middle
Domain. The abundance of large zooplankton taxa such as Calanus spp. (C. marshallae and C.
glacialis), and Parasagitta elegans, increased from warm to cold periods, while the abundance of
gelatinous zooplankton (Cnidaria) and small taxa decreased. Biomass followed the same trends as
abundance, except that the biomass of small taxa in the southeastern Bering Sea remained
constant due to changes in abundance of small copepod taxa (increases in Acartia spp. and
Pseudocalanus spp. and decreases in Oithona spp.). Statistically significant changes in
zooplankton community structure and individual species were greatest in the Middle Domain, but
were evident in all shelf domains, and in both the northern and southern portions of the eastern
shelf. Changes in community structure did not occur abruptly during the transition from warm to
cold, but seemed to begin gradually and build as the influence of the sea ice and cold water
temperatures persisted. The change occurred one year earlier in the northern than the southern
Middle Shelf. These and previous observations demonstrate that lower trophic levels within the
eastern Bering Sea respond to climate-mediated changes on a variety of time scales, including
those shorter than the commonly accepted quasi-decadal time periods. This lack of resilience or
inertia at the lowest trophic levels affects production at higher trophic levels and must be
considered in management strategy evaluations of living marine resources.

Keywords: Zooplankton, community structure, climate change, eastern Bering Sea

1.0 Introduction:

In recent years, climate change in the western Arctic has led to rapid changes in the eastern
Bering Sea shelf resulting in variations in seasonal sea ice coverage and water column
temperatures, and these variations have affected the entire ecosystem (e.g. Napp and Hunt, 2001;
Stabeno et al., 2012b). Zooplankters are essential prey for many fish, seabirds, and marine
mammals, therefore there is considerable interest in changes in zooplankton abundance and how these changes may propagate through the food web and impact higher trophic levels (Coyle et al., 2011; Hunt et al., 2011). Many planktivorous fishes, seabirds, and marine mammals inhabit both the northeastern and southeastern Bering Sea during summer (e.g. Piatt and Springer, 2003; Friday et al., 2012; Hollowed et al., 2012; Stevenson and Lauth, 2012). Historical research documented variations in single species abundance and cross shelf patterns of zooplankton in the southeastern Bering Sea (Cooney and Coyle, 1982; Coyle and Pinchuk, 2002; Napp et al., 2002; Stabeno et al., 2010; Coyle et al., 2011; Stabeno et al., 2012a & b). However, there are few modern descriptions of the broad-scale distribution of eastern Bering Sea zooplankton, particularly for the northern Bering Sea (Motoda and Minoda, 1974; Coyle et al., 1996 and references therein). To better understand how climate variability and change are affecting the recruitment and broad-scale distributions of planktivores, we need a more thorough understanding of how climate and other forcing affects the production and distribution of zooplankton across the entire region.

The eastern Bering Sea is a large marine ecosystem characterized by a broad continental shelf > 500 km wide and > 1000 km long oriented in a north westerly direction from the Alaskan Peninsula in the south, to below St. Lawrence Island, approximately 63° latitude, in the north. Near the northern boundary, the system shifts from a pelagic to benthic dominated system (e.g. Grebmeier et al., 2006; Stevenson and Lauth, 2012; Sigler et al., this issue). The shelf can be divided into regions or domains, each with their characteristic hydrography, circulation, and fauna (Iverson et al., 1979; Cooney and Coyle, 1982; Coachman, 1986; Kachel et al., 2002). Cross shelf domains are most distinct during summer and fall in the southeastern Bering Sea where there are 3 domains approximated by water depth: Outer (100 – 180 m), Middle (50 – 100 m) and Inner (< 50 m). The Inner Domain is well mixed, the Middle Domain is stratified into 2 layers, and the Outer Domain is stratified, but with 3 layers. In addition to cross shelf variations,
there are latitudinal variations in wind fields, water column properties, and most importantly, sea
ice coverage (Stabeno et al., 2010, 2012a). The northeastern Bering Sea is ice covered every year;
whereas coverage in the south historically varies by more than 100 km (Stabeno et al., 2012a).
The cold pool (a layer of < 2 °C water that resides on the shelf bottom), is formed as a result of
winter cooling and mixing that most often precedes sea ice formation), and typically persists
through the following summer. Its extent and magnitude varies with climatic conditions affecting
the distribution of many upper trophic level organisms in the region (e.g. Wyllie-Echeverria,

The goal of this manuscript is to describe the broad-scale spatial variations in large and small
zooplankton community composition in the north and southeastern Bering Sea during warm and
cold climate states. Additionally, we address several important questions regarding zooplankton
ecology affected by changing climate conditions (see Table 1). The data for these analyses come
from broad-scale surveys of zooplankton conducted by the Bering-Aleutian Salmon International
Survey (BASIS) program at NOAA, and provide the opportunity to describe the spatial cross-
shelf and latitudinal distribution of zooplankton for the entire eastern Bering Sea shelf. These
surveys began in 1999 before the Bering Sea Project (Bering Sea Ecosystem Study [BEST] and
Bering Sea Integrated Ecosystem Research Program [BSIERP]) was launched in 2007 (Wiese et
al., 2012) and have continued into the present after the field components of BEST and BSIERP
ended. During the 2000s the region experienced different multi-year climate regimes (Stabeno et
al., 2012b) above average sea water temperatures and very low sea ice coverage (2000 – 2005), a
single year of average sea water temperatures and sea ice extent (2006), and cold years with
extensive sea ice (2007 – 2009). Thus, in contrast to most regional scientific programs in the last
50 years whose timing or duration allowed limited sampling in a single ecosystem state, our
dataset allows us to evaluate changes in the eastern Bering Sea shelf pelagic ecosystem during
multiple thermal phases.
2.0 Methods:

2.1 Survey station locations and oceanographic sample collection
From mid August to early October, 2003 – 2009, samples were collected in the eastern Bering Sea, at stations located from 54.5 – 63.0 °N and 159.0 – 174.0 °W, and spaced approximately 60 km apart (Cieciel et al., 2009; Farley and Moss, 2009; Fig 1). Stations were divided into shelf regions for analyses using the Bering Sea Integrated Ecosystem Program (BSIERP) designations based on oceanographic/hydrographic, fisheries and ecosystem characterizations (Ortiz et al., 2012). We further grouped these regions into five major domains using approximately 60°N to split the shelf into south and north (Stabeno et al. 2010) and approximating cross-shelf domains defined by Coachman (1986) yielding: S Inner (< 50 m bathymetry, BSIERP regions 2 and 7), S Middle (50 – 100 m, regions 3 and 6), S Outer (100 – 200 m, region 4), N Inner (<40 m, region11), and N Middle (~40 – 100 m, regions 9 and 10).

Vertical profiles of temperature, salinity, and chlorophyll a (Chla) fluorescence were collected at each station with a Sea-Bird Model 25 or Model 9plus CTD. A rosette sampler was used to obtain discrete water samples for surface and bottom nutrients, total Chla (Whatman GF/F) and large size-fractionated Chla (> 10µm, Millipore Isopore polycarbonate membrane filters); all

1 Use of trade names does not signify an endorsement by the U.S. National Oceanic and Atmospheric Administration.
samples were stored frozen (-80 °C) for 6 months maximum and analyzed using standard procedures at shore-based facilities (Parsons et al., 1984; Gordon et al., 1993). Vertical profiles of Chla concentrations were derived from regressions between *in vivo* fluorescence and discrete Chla samples, mean \( r^2 = 0.65 \). Water column stability (energy required to mix the water column to 70 m, J m\(^{-3}\)) was calculated at each station from CTD temperature and salinity data (Simpson et al., 1977). Ice coverage (number of days of ice at each station during the prior winter) and timing of retreat (the last day of ice in spring) for a 60 km\(^2\) square box centered on each station was obtained from the Advanced Microwave Scanning Radiometer (AMSR) on MODIS Aqua from the National Snow and Ice Data Center (NSIDC) (S. Salo, NOAA PMEL, personal comm.). We assumed no ice when concentrations dropped below 15%. Wind mixing data (wind velocity\(^3\), \( u^*3 \)) for August were obtained from National Centers for Environmental Prediction (NCEP) reanalysis data set (N. Bond, NOAA PMEL, personal comm.). Wind mixing data were averaged over a 2° latitude by 5° longitude box centered on a NOAA PMEL mooring at site M4 (57.9°N, 168.9°W; Stabeno et al., 2010). We assumed M4 winds approximated wind fields over our entire survey area, since winds at all four 70 m moorings in the northeast and southeast Bering Sea (M2, M4, M5 and M8) have shown strong coherence during recent years (Stabeno et al., 2010). Winter wind fields for the prior period (October to April) based on shelf-wide model results were used to estimate potential onshore and offshore flow, assuming that southeasterly winds promote stronger onshore flows than northwesterly winds (Danielson et al., 2012).

2.2 Zooplankton sample collection and lab analysis

Zooplankton samples were collected and analyzed using methods described in Coyle et al. (2011). Briefly, small zooplankton assemblages were sampled at every other station with a 0.1 m\(^2\) Juday net with 168 µm mesh (Volkov, 1984; Volkov et al., 2007). The net was towed vertically from within 5 – 10 m of the bottom (or maximum depth of 200 m) to the surface at about 1 m s\(^{-1}\). Juday net samples were sieved into size fractions prior to counting on board ship (Volkov et al.)
2007); however, data from all size fractions combined were used to quantify small zooplankton
taxa. Large zooplankton assemblages were collected at every station with a 60 cm MARMAP-
style bongo frame with a 505 µm mesh net. Oblique tows were conducted from the surface to
within 5–10 m of the bottom, and volume filtered was measured with calibrated General Oceanics
flowmeters. All samples were preserved in 5% formalin: buffered with seawater. Zooplankton
collections from 2003 – 2004 were sorted at the Polish Plankton Sorting and Identification Center
(Szczecin, Poland); collections from 2005 – 2009 were processed at the University of Alaska
(Coyle et al., 2008). The lowest taxonomic level of sorting varied between labs, so we used the
lowest taxonomic stage available across all years. Zooplankton tows were collected primarily
during the daytime. Many euphausiids on the Bering Sea shelf stay within 1 – 2 m of the bottom
during the day (Coyle and Pinchuk, 2002) and those in the water column are difficult to
quantitatively capture with nets (e.g. Sameoto et al., 1993; Wiebe et al., 2004); therefore
euphausiids were not included in analyses. It is also possible that under representation of other
diel migrants (e.g. Metridia spp.) occurred. The small volume filtered by Juday and bongo nets
compared to larger nets (e.g. Multinet or MOCNESS) could have resulted in under sampling of
relatively large and rare taxa. Accordingly, very large medusae such as *Chrysaora melanaster*
were excluded since they were not quantitatively sampled by our bongo nets. Unidentified
copepod nauplii were also excluded, although they were fairly numerous in the Juday net samples
(~ 11% of total abundance). A total of 424 Juday and 717 bongo net samples were collected for
all years combined.

2.3 Statistical analyses
Separate analyses were conducted for large (bongo samples) and small (Juday samples)
zooplankton taxa. Zooplankton data were 4th root transformed (unless otherwise indicated), to
down weight the contribution of dominant taxa to similarity/dissimilarity patterns (Clarke and
Warwick, 2001). Initial analyses were conducted using both abundance (no. m⁻³) and integrated
abundance (no. m$^{-2}$) for comparisons among regions with large changes in bathymetry (Questions 1 and 2, Table 1). We found no substantial differences in the outcome when using number normalized by volume or area; therefore we chose to present abundances normalized by volume filtered (no. m$^{-3}$) to allow for comparisons with most prior studies on the eastern Bering Sea shelf which reported their abundance data normalized by volume filtered. Zooplankton biomass wet weights (g m$^{-3}$, Coyle et al., 2011) were used in Question 2 analyses. The warm regime was designated as 2003 – 2005 and the cold regime as 2006 – 2009 based on late summer/fall mean water column temperature anomalies for 2003 – 2009, estimated from CTD data collected during our surveys (cf. Stabeno et al., 2012b, which categorizes 2006 as a year of average temperatures and sea ice extent). For all analyses, excluding those for Question 1, it was necessary to account for uneven sampling across years. Therefore, a reduced data set was used that included only station locations within equally spaced geographically partitioned regions (Blocks) that were sampled a minimum of two warm and two cold years (Fig. 1). Blocks were created in ArcMap/ArcInfo, 10.1 (ESRI, 2012) using thiessen polygons, polygons constructed around stations by calculating the midline between each pair of adjacent stations (Thiessen and Alter, 1911; Gold, 1991). Blocks were approximately 60 x 60 km for the large taxa (equivalent to the spacing of stations) and approximately 80 x 80 km for the small (equivalent to the diagonal spacing of every other station). The small taxa required larger blocks due to sparser sampling. Separate analysis were conducted for each of the five major domains (S Middle, N Middle, S Inner, N Inner, S Outer) for Questions 3 and 4 analyses (Table 1).

Statistical analyses included cluster analysis, similarity percentage contribution of individual taxa (SIMPER), and permutational, multivariate analysis of variance (PERMANOVA) in the software package, PRIMER-E, version 6.1.15 with PERMANOVA+ version 1.0.5 (Clarke and Warwick, 2001; Clarke and Gorley, 2006; Anderson et al., 2008). All procedures used Bray-Curtis dissimilarities, a statistic commonly used to quantify the dissimilarity in composition between
samples (Bray and Curtis 1957). In our study, these procedures were used to evaluate variations in community composition (the relative abundances of zooplankton taxa). SIMPER calculates the average contribution of each taxon to the overall Bray-Curtis dissimilarity in community composition. PERMANOVA allows the use of distance measures, in our case, Bray-Curtis dissimilarity in community composition, to test for the significance of specific effects, similar to a multivariate ANOVA. The advantage of using a permutation test is that it does not require the data to follow a particular distribution and is therefore more robust than parametric statistics. This procedure also allows for the partitioning of the multivariate variation in abundance according to nested sampling designs and 2-way designs with interactions, as well as the addition of covariates, such as environmental variables (Anderson et al. 2008). Statistical procedures used for each of our research questions are detailed below.

Q1) The taxonomic composition and distribution of zooplankton were evaluated qualitatively using abundance data from all stations and years. For grouping stations, we applied a hierarchical cluster analysis using group average linkage of Bray-Curtis dissimilarities among stations. We then used SIMPER analysis to determine the average percent contribution of each taxa in each station cluster. For grouping taxa, we applied a separate cluster analysis of Bray-Curtis dissimilarities using mean abundance (standardized untransformed data) of each taxon across station clusters. Standardization rather than transformation was necessary for grouping species since we were more interested in relative similarity/dissimilarity patterns rather than down weighting abundant species, which was necessary when grouping stations (Clarke and Warwick, 2001). Clusters were identified by drawing a line across branches on each dendrogram (one for station and one for taxa) determined by at least 50% similarity, length of branches (indicating stability of groups), a permutation procedure that objectively tests for grouping a priori (SIMPROF, Clarke and Warwick, 2001; Clarke and Gorley, 2006), and subjective biological
interpretation of clusters. For the station cluster analysis, we designated station clusters as outliers if they contained less than 1% of the sampled stations.

Q2) The total abundance and total biomass of all large and all small zooplankton in the north and south eastern Bering Sea for each year were estimated by summing the abundance or biomass over all taxa within each block and dividing by number of stations. The average abundance or biomass was computed over all blocks within each region, i.e. the south (< 60 °N, Inner, Middle and Outer Domains) and north (60 – 63 °N, Inner and Middle Domains). Then, we estimated the mean and standard error (SE) of the 4th root transformed data, then back-transformed the data to estimate geometric means and SE of untransformed total abundance and biomass.

Q3a) To test for significant differences in zooplankton community composition between Regimes (warm vs. cold), a PERMANOVA was applied to all domains combined and then to each domain separately. In addition to the Regime effect, a geographic blocking factor (Block) was included as a random effect to account for the uneven sampling across years (defined above). Year was also included in the model as a random nested effect within Regime. Interactions among these effects were also included. A permutational dispersion (PERMDISP) analysis was applied to test for any significant dispersion effects between Regimes (Anderson et al. 2008). This is analogous to a univariate Levene test for homogeneity of variances in ANOVA and tests for differences in distances between the yearly centroids (center of points in multivariate space).

Q3b) A 2-way (Regime and Block) SIMPER analysis was run to determine which zooplankton taxa contributed most to the differences between regimes for domains where significant differences were found between Regimes.
Q3c) A PERMANOVA was applied to each domain to determine if zooplankton communities were significantly different for one or more years. In this case, Year was considered a fixed effect, and Block was considered a random effect accounting for spatial variability and the uneven sampling across years. To determine which consecutive years had significantly different community composition, pairwise multiple comparison tests were applied to consecutive years only. No Bonferroni correction was applied here as PERMANOVA provides exact tests, and a Bonferroni correction would be overly conservative in this case (Anderson et al., 2008).

Q3d) The mean untransformed zooplankton abundances for the most common taxa (ones that jointly contributed to ≥ 97% of the total untransformed abundance for all years combined) were calculated for the north and southeastern Bering Sea to determine which taxa contributed to the interannual variations in community structure and total abundance.

Q4) A set of local environmental variables measured concurrently at the same stations as zooplankton abundance and regional variables measured yearly over the eastern Bering Sea were used to evaluate the conditions most often associated with variations in community composition (dependent variable), for warm vs. cold Regimes within each shelf domain. Variables were removed if they were correlated with other variables (R > 0.8) or were determined to be of lesser biological importance. The variables of interest were included as covariates (independent variables) in PERMANOVA tests for domains where significant differences were found between warm and cold years (based on results of Question 3a). The local covariates included temperature, Chla (a measure of phytoplankton biomass), nitrate, and ammonium measured at the surface (5 m) or above the mixed layer depth; stability over the top 70 m; integrated Chla and mean large size-fractionated Chla/total Chla over the top 50 m; day of ice retreat in spring prior to our late summer/ fall sampling; and temperature, salinity, and ammonium measured at the bottom or below the mixed layer depth. The regional covariate tested was the yearly winter (October-April).
We also tested latitude and longitude to see if there were significant interannual geographic gradients within oceanographic domains. We first removed the within year spatial variability by including a blocking factor (described previously). Then, each covariate was sequentially added using Type I sum of squares which tests for the significance of the addition of that variable with all prior covariates accounted for. The best fit model was chosen by including the most significant covariates in a particular order that gave the lowest mean square error. The Regime effect and interactions were included as the last covariates in the model. Whenever a Regime effect (added last) became insignificant (P > 0.05) compared to the Regime effect before adding environmental covariates (P < 0.05), we concluded that the environmental covariates were explaining at least some of the variability in community composition between warm and cold years. To examine yearly changes in temperature and sea ice variations we plotted surface and bottom temperature, day of sea ice retreat and number of days of ice coverage the prior winter, averaged over stations in the N and S Middle Domains.

Figure 8. Heat map of large zooplankton showing clusters of stations (x axis) by taxa (y axis) using all stations sampled. Shade of each cell indicates the 4th root transformed abundance of each taxon. Approximate domain designations are shown above clusters. Designations at bottom indicate climate regime (W = warm; C = cold; W/C = both) when each cluster was commonly observed. Horizontal lines separate clusters of species (indicating taxa which tended to co-occur over all years and domains combined).
3.0 Results:

3.1 Spatial and temporal patterns of large and small zooplankton (Q1).

The clusters of stations (station clusters) show which stations had similar taxonomic compositions over the eastern Bering Sea shelf for all years combined. For large

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Figure 3. Spatial variation of large zooplankton clusters for each year using 4th root transformed abundance data. Warm years highlighted with red and cold with blue. Refer to Fig. 2 to see taxa abundances for each cluster. Intended for color reproduction on the Web and in print.
zooplankton, the multivariate analyses yielded eight station clusters (Fig. 2, 3). The taxa that made up approximately 80% of the total abundance are listed from high to low for the clusters described below. One pattern that stands out is the replacement of Middle Domain clusters during the transition from warm to cold years (Fig. 3). **Cluster L3** characterized by Cnidaria (gelatinous zooplankton dominated by *Aglantha digitale* in our study), *Parasagitta elegans* (Chaetognatha) and Appendicularia (Larvacea) extended over a broad area in the warm years, particularly 2003 – 2004, and was replaced in cold years by **Cluster L4** characterized by *Calanus* spp.² (Copepoda), Cnidaria and *P. elegans*. In addition, in warm years, there was a cluster confined primarily to the Inner Domain, **Cluster L1**, characterized by *P. elegans*, Cnidaria, *Epilabidocera amphitrites* (Copepoda) and Caridea (shrimp), but in cold years this group was observed less often. Latitudinal variations in the timing of changes were also seen, with increased coverage for **Cluster L4** in the northeastern Bering Sea in 2004 – 2005, and expansion southward and inshore into the Inner Domain in the following cold years. In contrast, in the Outer Domain, **Cluster L8** characterized by *Limacina helicina* (Pteropoda), *Calanus* spp., *Eucalanus bungii* (Copepoda), and *Metridia pacifica* (Copepoda), was observed during all years.

For small zooplankton, the analyses yielded nine station clusters (Fig. 4 and 5). Similar to large taxa, in the Middle Domain there was one cluster with broad spatial coverage in warm years, **Cluster S4**, characterized by *Oithona* spp. (Copepoda), *Pseudocalanus* spp. (Copepoda), Echinodermata larvae, Polychaeta (annelid worms), molluscan Bivalvia larvae and Cirripedia (barnacle larvae), which was replaced in cold years by **Cluster S7**, characterized by

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² *Calanus* spp. referred to in this work is most likely a mixture of *C. marshallae* and *C. glacialis* based on recent genetic analyses by Campbell et al., personal comm. and J. Nelson (2009).
Pseudocalanus spp., Oithona spp., Acartia spp. (Copepoda) and Polychaeta (Fig. 5), with fewer taxa making up the bulk of abundance in cold years. In the Inner Domain, a cluster with broad coverage in the southeastern Bering Sea, Cluster S1, characterized by Oithona spp., Pseudocalanus spp., larval Bivalvia, Centropages abdominalis (Copepoda), Polychaeta, Acartia spp., and Echinodermata larvae was partially replaced in the coldest years, 2008 – 2009, by Cluster S6, characterized by Pseudocalanus spp. and Acartia spp. and C. abdominalis and by Cluster S7. Again, similar to the large taxa, in the Outer Domain there was one cluster common during all years, Cluster S9, characterized by Oithona spp., Pseudocalanus spp., Metridia spp. copepodites, Acartia spp., Microcalanus spp. (Copepoda), and Bivalvia larvae. Small taxa clusters did not show large north – south variations.

Figure 4. Heat map of small zooplankton clusters of stations (x axis) by taxa (y axis). Refer to Fig. 2 for details.

Small Zooplankton Clusters of Stations

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Clusters of co-occurring taxa (taxa clusters) show how taxa grouped together over all years and spatial areas combined (Fig. 2, 4, y-axis). Large zooplankton taxa that tended to co-occur included _Neocalanus_ spp., _E. bungii_, _M. pacifica_; these are oceanic copepods resident in the Outer Domain or brought in from beyond the shelf break (Gibson et al. 2013). Other taxa that co-occurred were _P. elegans_, _Calanus_ spp., and _Appendicularia_; all are common taxa with relatively high abundances in the Middle Domain (Coyle et al. 2008, 2011). Small taxa that tended to co-occur included _Evadne_ sp. (Cladocera), _Podon_ sp., _Eurytemora herdmani_ (Copepoda), and _Tortanus discaudatus_ (Copepoda), taxa typically neritic and common nearshore (Gieskes 1971, Johnson 1934, Kos 1977); and _Oithona_ spp., _Acartia_ spp., _Pseudocalanus_ spp., Polychaeta, Bivalvia larvae, and _C. abdominalis_, taxa that often reside in upper layers of the water column (Marlowe and Miller, 1975).

3.2 Total abundance and total biomass of large and small zooplankton during warm and cold regimes (Q2).

Trends in total abundance and biomass varied for large and small zooplankton and between the north and south eastern Bering Sea (Fig. 6). In the south, large zooplankton increased in abundance starting in 2007, peaked in 2008 and declined in 2009; in contrast, small zooplankton
steadily decreased in abundance from 2003 – 2009 (Fig. 6A). In the north, total abundances of large zooplankton increased between 2004 and 2005 and decreased between 2007 and 2009; small zooplankton abundances did not show clear trends with time, and were only noticeably higher in 2004 than in other years (Fig. 6B). The overall magnitude of large zooplankton abundances was similar in the north and south, however, for small zooplankton, abundances were lower in the north compared to the south. Trends in biomass mirrored those in abundance except for small taxa in the south where despite the observed declines in abundance from 2003 to 2009, the biomass remained constant (Fig. 6C, D). It is also worth noting that in spite of high abundance of small taxa during the warm years, their biomass was similar to that of large taxa during the warm period in the south and during all years in the north (Fig. 6).

3.3 Statistical differences among assemblages, shelf domains, and years (Q3)

3.3.1 Zooplankton abundances between regimes by domain (Q3a)

We next evaluated if the observed differences in zooplankton assemblages between regimes were statistically significant for the five major shelf domains. For all domains combined, PERMANOVAs showed significant interactions between Regime and Domain (P = 0.012, P = 0.001, for large and small taxa, respectively), indicating that community structure varied by Regime depending on Domain. Therefore, each domain was evaluated separately for all further analyses. There were significant differences in the community structure between warm and cold

Figure 6. Small and large zooplankton total mean abundance (no. m-3) in the eastern Bering Sea in the A) south (< ~60 °N) and B) north (~60-63 °N), and total mean biomass (g m-3) in the C) south and D) north. Geometric means and standard errors are shown.
regimes for all domains except the N Inner for large taxa and N Inner and S Outer for small taxa, after accounting for significant spatial block effects (Table 2). The strongest differences were observed in the S Middle and S Inner Domains.

3.3.2 Zooplankton taxa differences between warm and cold regimes (Q3b)

Large zooplankton taxa that substantially decreased in abundance (> 2-fold) during the transition from warm to cold regimes include Cnidaria, Gammaridae amphipods, Mysida, the neritic copepod Epilabidocera amphitrites, and the temperate copepod Calanus pacificus (Table 3).

Taxa that substantially increased in abundance from warm and cold regimes include Anomuran and Brachyuran crab larvae, Calanus spp., Parasagitta elegans, the oceanic copepods Neocalanus spp. Eucalanus bungii, Hyperiidea amphipods and Cumacea. Taxa that showed both increases and decreases depending on domain include Appendicularia, Caridea decapods and Limacina helicina. Calanus spp. were the top contributor to changes in community composition between regimes (13% – 23% of total dissimilarity), particularly in the Middle Domain (both north and south). High contributions to dissimilarity (> 10%) were also seen for Caridea decapods in the S Inner, P. elegans and Appendicularia in the S Middle; Limacina helicina in the S Outer, and Appendicularia and Cnidaria in the N Middle Domains.

Most small zooplankton taxa decreased in abundance in the S Inner, S Middle and N Middle Domain from warm to cold years (Table 3). The only small taxa showing increases in cold years were Acartia spp. in all three domains, Metridia spp. copepodites and Pseudocalanus spp. in the S Middle Domain, and Fritillaria spp. (Appendicularia) in the N Middle Domain. Oithona spp. and larval bivalves had high contributions to dissimilarity in community composition between regimes for all three domains, with Acartia spp., Polychaeta, and Echinodermata larvae also important, particularly in the Middle Domain.
Next, we evaluated which consecutive years showed the greatest changes in community composition in each domain to determine if the differences between regimes occurred during our designated break point between warm to cold regimes (i.e. between 2005 and 2006) or if the changes in community composition took place over a period of years.

We also evaluated which taxa showed the largest interannual variations in the south and north eastern Bering Sea.

For large and small zooplankton communities, most regions with the exception of the S Outer showed significant differences (based on pairwise multiple comparisons) between pairs of consecutive years (Table 4) indicating that interannual changes in community composition were observed over our entire study period, not just for the years when the temperature regime changed most rapidly from warm to cold (eg. 2005-2007 in south). For large zooplankton, the greatest interannual variations, in the south were seen by *Calanus* spp., which increased in cold years starting in 2007 (Fig. 7); while in the north, increases were due to Cnidaria in 2005 and 2007, and *Calanus* spp. starting in 2006.

The small taxa that decreased in abundance from warm to cold years in the south were *Oithona* spp. and Bivalvia larvae, while in the north, *Oithona* spp. decreased only in 2005, 2007 and 2009.
Small zooplankton composition in the north was most different in 2009, with higher levels of polychaetes and *Acartia* spp.; no data exist for 2008 to determine if this change was gradual. Overall, *L. helicina*, *M. pacifica*, *Pseudocalanus* spp., and Bivalvia larvae appear to be more abundant in the south, and *Cnidaria* and Polychaeta more abundant in the north. Some of these north–south variations can be explained by the lack of sampling in the Outer Domain in the northeastern Bering Sea.

### 3.4 Environmental factors contributing to observed differences in zooplankton community composition (Q4)

The interannual variations in zooplankton abundance and community composition appear to relate to changes in temperature and sea ice retreat in the eastern Bering Sea. Temperature above and below the mixed layer depth in the N and S Middle Domains showed a declining trend from 2003 – 2009, concurrent with increases in the date of ice retreat and duration of ice coverage (Fig. 8). The greatest difference in timing of ice retreat and ice coverage was found in the S Middle Domain, with increases seen from 2005 – 2008, which...
overlaps the increase in *Calanus* spp. (Fig. 7, 8). Decreases in surface and bottom temperatures 
coincided with decreases in small taxa such as *Oithona* spp. and increases in *Pseudocalanus* spp. 
and *Acartia* spp. in the S Inner and S Middle Domains. Temperatures and small taxa abundance 
were lower in the north than the south (Fig. 7, 8). For large zooplankton taxa, models with 
environmental co-variates were constructed for the S Inner, S Middle, S Outer and N Middle 
Domains (where significant Regime effect was found). Environmental covariates were able to 
account for at least some of the variability in zooplankton community composition between 
regimes for all but the S Middle Domain based on P values for Regime with and without 
environmental covariates (Table 5 vs. 2). Physical and geographic covariates explained the 
greatest amount of variability in large zooplankton community composition (Table 5). 
Temperature below the mixed layer depth was important in the N and S Middle Domains 
although temperature above the mixed layer depth, salinity below the mixed layer depth, ice 
retreat timing, latitude and longitude were also highly significant (P < 0.01), depending on 
domain (Table 5). For small taxa, environmental covariates explained some of the variability in 
community composition between regimes in the S Inner, S Middle and N Middle Domains (Table 
2 vs. 5). Similar to large taxa, physical covariates were highly significant, with temperature above 
and below the mixed layer depth important for the S Inner and S Middle Domains as well as 
stability for the S Middle Domain (Table 5). Overall, temperature explained the greatest amount 
of temporal variability in community structure, and was significant in models for all domains 
except the S Outer for large and the N Middle for small zooplankton. Most of the biologically 
related covariates, nutrients (ammonium and nitrate) at surface and bottom, surface Chla, 
percentage of large phytoplankton, and August wind mixing, were not significant.
4.0 Discussion:

4.1 Overview

This study provides a rare look into how stanzas of warm and cold years affect the zooplankton community structure in both the north and south eastern Bering Sea and the environmental variables associated with these changes. Our analyses demonstrate the considerable cross-shelf variability in zooplankton communities as seen in prior studies (e.g. Cooney and Coyle, 1982), but also shows variability between assemblages in the north and south both in timing of changes in abundance of key taxa and total abundance and biomass. Water temperature showed the strongest relationship with large and small zooplankton community structure. We hypothesize that large taxa abundance has a direct or indirect relationship to bottom temperature (depending on taxa) and a direct relationship to the winter/spring southerly extent of sea ice; while small taxa abundance has a direct relationship to surface and bottom temperature. Ice algae and sea-ice related phytoplankton blooms in cold years may provide an early food source for large zooplankton on the southern shelf (Siger et al. this issue). In contrast, lower temperatures may reduce temperature-dependent growth (e.g. Hirst and Lampitt 1998), negatively impacting reproduction rates of small zooplankton with fewer cohorts produced during the growing season. However, temperature may also affect zooplankton survival, so multiple generations do not guarantee higher abundances. The observed changes in community composition were not abrupt, but showed gradual changes over a period of years, concordant with changes in sea ice and water temperature. Species-specific responses in cold years include both increases in omnivorous Calanus spp., Neocalanus spp., and in predators such as P. elegans, and decreases (with large interannual variability) in predatory Cnidaria (A.digitale).

4.2 Temporal and spatial patterns in community structure between regimes

Assemblages often were clustered together based on domain with separate groups of oceanic (e.g. Neocalanus spp., Metridia pacifica, Eucalanus bungii) and neritic taxa (Podon sp., Evadne sp.,
Polychaeta, Bivalvia larvae). These differences are attributed to, and maintained by, the presence of hydrographic fronts that separate the domains during summer and the consistency of hydrographic and biological processes that are inherent to the different domains (Iverson et al., 1979). The extension of a Middle Domain cluster into the Inner Domain in cold years for large zooplankton, suggests that the Inner Front may not be as strong (or is more leaky) in cold years, possibly resulting in increased transport across the Inner Shelf. Alternatively, the Inner Front may be established later in the season in cold than in warm years allowing more time for Middle Domain taxa to become established in the areas that eventually become the Inner Domain.

Previous studies suggest the Inner Front was established later in the season during years with low sea surface temperatures (SSTs) (1998 and 1999), due to storminess and late ice retreat, than during a year with high SSTs (1997) (Kachel et al., 2002). Additionally, winter wind direction was a significant co-variate for large zooplankton in the S Inner Domain, suggesting the differences in wind fields may be related to onshore transport or timing of set up for the Inner Front (Kachel, et al. 2002, Danielson et al., 2012). Inshore – offshore changes in centers of distribution within domains are also suggested by the importance of latitude or longitude in our best-fit models for small taxa within the N and S Middle Domains and large taxa within the N Middle and S Outer Domains.

The recent regime shifts influenced large and small zooplankton community structure over most shelf domains, but variations were greatest in the S Middle Domain, where the largest physical changes (e.g. sea ice retreat timing, temperature) were observed (Stabeno et al., 2012a). The high significance of surface temperature (and higher abundances) for small taxa in the south but not in the north may be because in the north, the Middle Domain summer surface temperature oscillated around 8 °C, whereas in the south, it declined from almost 12 °C in 2004 to below 8 °C in 2009. The surface layer may be where small taxa predominate, as found in the Gulf of Alaska (Marlowe and Miller, 1975).
North–south variations in Middle Domain zooplankton assemblages were also lower in cold years compared to a single warm year (2005) (Stabeno et al., 2012a). We found a similar result for 2005, but the other warm years (2003, 2004) showed much lower latitudinal variations in zooplankton assemblages. These differences may relate to interannual variability in the N-S strength of the temperature gradients. After the recent period of extended warming, even the north received heat so that in 2003 and 2004 the surface temperature gradients between the north and south were diminished. However, the north in 2005 was colder than in 2003–2004, while the south in 2005 was still warm (Danielson et al., 2011).

4.3 Interannual variations in total abundance and biomass

Total abundance and total biomass of zooplankton also varied by N–S region and regime. In the south, total abundances of large taxa were highest in cold years, and similarly total biomass for large zooplankton taxa increased 5–10 fold between 2005–2007 and 2008–2009. This is relevant to the feeding of small age-0 fishes, such as Walleye Pollock (Gadus chalcogramma, herein referred to as pollock). The improvement in age-0 pollock condition in cold years as evidenced by increased total energy content (kJ gm\(^{-1}\) wet weight) is attributed to the higher availability of large, lipid bearing zooplankton prey such as Calanus spp. and Thysanoessa spp. (Euphausiacea) in cold years (Coyle et al. 2011, Hunt et al., 2011; Heintz et al., 2013). Calanus spp., and Neocalanus spp. are also important prey for other forage fish such as juvenile Pacific salmon (Oncorhynchus spp.), Pacific Herring (Clupea pallasi) and Capelin (Mallotus villosus), planktivorous sea birds and endangered baleen whales such as the North Pacific Right Whale (Eubalaena japonica) (Russell et al., 1999; Springer et al., 2008; Sheffield-Guy et al., 2009; Coyle et al., 2011; Wade et al. 2011; Heintz et al., 2013). Therefore decreases in large lipid-rich crustacean zooplankton in warm years may be detrimental to a variety of predators, not just
pollock. In contrast to large taxa, biomass for small zooplankton in the south eastern Bering Sea was not different between regimes, even though abundances were lower in cold than warm years. This indicates that reductions in abundances of very small taxa such as *Oithona* spp. were compensated for by increases in abundances of larger taxa such as *Pseudocalanus* spp. and *Acartia* spp. Future work is needed to determine its impact on trophic transfer and production at higher trophic levels.

The north eastern Bering Sea did not follow the same pattern as the south. In the north, the abundance of large taxa increased 4-fold between 2004 and 2005, and in 2007 reached the same levels as observed in the south a year later (2008). Increases in the north were due to both *Cnidaria* and *Calanus* spp., while in the south they were due primarily to *Calanus* spp. Unlike in the south, total biomass for large zooplankton remained fairly constant in the north, even though taxonomic composition changed. The abundance and biomass of small taxa in the north declined from 2004 to 2005, coincident with a drop in water temperature, and then remained at that level for the remainder of our time series.

Total zooplankton biomass (sum of the small and large taxa) was highest in the coldest years (2008 – 2009) in the south due to increases in large zooplankton biomass, but remained constant across all years in the north. Large and small taxa contributed equally to total biomass except in the south in 2008-2009, where the contribution to total biomass was 2 – 4 times higher for large compared to small taxa. This result for the southeastern Bering Sea was previously shown by Coyle et al. (2011), however biomass levels for the north and their relation to the south in warm and cold years is new. This suggests that as the climate warms, the total biomass available for higher trophic levels will decrease in the south, but may not change in the northeastern Bering Sea.
4.4 Proposed mechanisms driving variations in abundances of key taxa

Finally, to synthesize the information on changes in abundances and the environmental factors responsible for these changes between regimes and north–south regions, we describe potential mechanisms for some of the key herbivorous and predatory zooplankton taxa: Calanus spp., Neocalanus spp., P. elegans and A. digitale (Cnidaria).

*Calanus* spp. had the greatest impact on large zooplankton community structure between warm and cold regimes. Increases in *Calanus* spp. in cold years have been documented for the southeastern Bering Sea (Hunt et al., 2008; Coyle et al. 2011; Hunt et al. 2011, Stabeno et al., 2008, 2010, 2012b), but data were not available for the north. One proposed mechanism driving increases in cold years in the south is that when ice algae are available there is an early source of food for *Calanus* spp. reproduction (Hunt et al., 2002; Baier and Napp, 2003, Sigler et al., this issue). An early season ice-associated phytoplankton bloom can also provide a source of energy for metamorphosis and growth (Baier and Napp, 2003; Sigler et al., this issue). Lower winter water temperatures will also lower metabolic rates which allow *Calanus* spp. to reduce the energy required for survival. Therefore, a series of cold years may facilitate increases in spawning biomass and reproductive output resulting in a stronger year class (Sigler et al., this issue). A corollary of this is that warmer summer temperatures lead to increased food limitation due to increased metabolic requirements and reductions in net primary production (Lomas et al., 2012), which result in reductions in zooplankton lipid (energy) stores, poor overwinter survival, and fewer copepodites produced the following spring (Coyle et al., 2011).

In the southeastern Bering Sea, late summer abundance of *Calanus* spp. increased in 2007, the first year the majority of the S Middle Domain was ice covered, so the availability of an early spring algal food source, may have been important in this region. In the north, increases in ice coverage and retreat were seen from 2003 – 2006, but had a smaller range of variability than seen
in the south. We do not yet understand what processes promoted increases in *Calanus* spp. in the northeastern Bering Sea starting in 2006; because this region was at least partially ice covered until mid-April in all years and presumably ice algae were available all years. Finally, because the *Calanus* spp. we sampled were a combination of *Calanus marshallae* and *Calanus glacialis*, changes in advection in the north and south of these different taxa may also be at play, and these two taxa may respond to changes in climate and temperature in different ways. *C. marshallae* was previously thought to be dominant in the southeastern Bering Sea, while *C. glacialis* dominated further northward in the Bering, Chukchi and Beaufort Seas (Frost, 1974). The highest abundances of *Calanus* spp. were observed in 2007 in the north and in 2008 in the south, a year after *Calanus* spp. began to increase in each region. This suggests that sequential years of cold conditions are advantageous to build large biomass of the species. Decreases in *Calanus* spp. in 2009 in the current study could be due to increases in predation from *Themisto libellula*, an arctic hyperid amphipod (Pinchuk et al., 2013).

*Parasagitta elegans* also increased in cold years with the largest abundances observed in 2007. *P. elegans* is a voracious predator of the early developmental stages of large and small copepods in the eastern Bering Sea (Baier and Terazaki, 2005), so this increase may be a response to increases in prey availability. On the south eastern shelf for 1995 – 1999, the most frequently consumed prey of *P. elegans* was *Calanus* nauplii in cold icy years when *Calanus* spp. were in higher abundance, with *Pseudocalanus* spp. predominantly consumed in relatively warmer years (Baier and Terazaki, 2005).

*Neocalanus* spp. overwinter off the shelf at depths of 200-2000 m (e.g. Miller et al., 1984). The newly hatched nauplii and copepodites ascend to the upper layer in late winter to early spring, where they complete their development by early summer (Vidal and Smith, 1986), and start to descend to deeper layers. Recent modeling suggests that wind is a primary factor controlling...
inter-annual variability in on-shelf transport of *Neocalanus* spp. (Gibson et al, 2013).

Southeasterly winds, which prevailed during warm years, enhanced the on-shelf transport of oceanic zooplankton over the southern shelf, while northwesterly winds, more common in cold years, reduced onshore transport. This suggests that *Neocalanus* spp. abundance would be lower during cold years since it would be more difficult for this taxa to move onto the southern shelf in spring (Danielson et al 2012, Gibson et al. 2013). However, *Neocalanus* spp. abundance increased in cold years over the S Middle Domain in our data set and there was no significant difference in its abundance between warm and cold years over the Outer shelf. Thus, the explanation for variations in *Neocalanus* spp. abundance over the shelf is likely more complicated with multiple factors important (e.g. transport, food availability, predation).

*Aglantha digitale*, a small (10-40 mm long) hydromedusan jellyfish, was the most numerous Cnidarian collected in our bongo nets from 2005-2009, making up 93% (ranged 87 – 97% by year) of the total Cnidarian abundance. *A digitale* is an ambush predator capable of retaining small, motile prey (Costello and Colin, 2002). This taxon has been shown to ingest adults and larvae of small copepods (*Oithona* spp., *Acartia* spp., *Pseudocalanus* spp., *Temora longicornis*, *Evadne* sp., *Oikopleura* spp., zooplankton eggs, veligers, tintinnids and dinoflagellates (Matsakis and Conover, 1991; Pages et al., 1996; Costello and Colin, 2002) with an estimated maximum prey size of 1.5 mm (Prudkovsky, 2006). Matsakis and Conover (1991) found that medusan carbon weight and total zooplankton carbon biomass varied reciprocally in studies in Bedford Basin, Nova Scotia. For the current study, in the northeastern Bering Sea with the exception of 2009, small copepod abundances tended to be higher when Cnidaria (*A. digitale* primarily) abundances were lower and vice versa (Fig. 7). Thus, predation by *A. digitale* on small copepods may be one factor to help explain these interannual changes in abundances. Higher numbers of Cnidarians in the northeastern Bering Sea may also partially account for lower numbers of small taxa in the north compared to the south. Average abundances of *A. digitale* and total copepods,
respectively, were 42.5 m$^3$ and 3800 m$^3$ in the north and 4.3 m$^3$ and 6600 m$^3$ in the south, for 2005 – 2009 for the Inner and Middle Domains combined. If *A. digitale* consumes an average of 13.9 copepod prey per day (based on feeding experiments at 4°C, Matsakis and Conover, 1991), then for the north and south respectively, they can consume 15% and 1% of the total copepod standing stock per day. In other studies, gelatinous zooplankton often consume < 10% of prey resources, but can consume over 50% during episodic events (Matsakis and Conover, 1991 and references there in; Pages et al., 1996). We also found that *A. digitale* abundances were 63% and 72% higher in a warm year (2005) than in cold years (2006 – 2009) for the north and southeastern Bering Sea, respectively.

5.0 Conclusions

Changes in eastern Bering Sea zooplankton community composition in response to climate change will vary by oceanographic domain and by latitude, with larger effects predicted for the south compared to the northeastern Bering Sea. This impact will be stronger on large, than on small zooplankton community structure. Reductions in sea ice coverage and changes in ice retreat timing and subsequent decreases in food resources in the spring, increases in temperature and basal metabolic requirements, and potential changes in advection may be detrimental for large crustacean taxa such as *Calanus* spp. and *Neocalanus* spp. The negative impact of warming on large, lipid-rich zooplankton taxa is expected to propagate through the food web affecting commercial fisheries, seabirds, and protected species. In the eastern Bering Sea, statistical relationships between water temperature and recruitment of pollock have been used in combination with accepted climate change scenarios to project a future decrease in one of the world’s largest fisheries (Ianelli et al., 2011 and Mueter et al., 2011). Our work helps to elucidate the mechanisms behind that statistical relationship.
Alterations in the composition of small zooplankton assemblages from climate change may also contribute to anticipated effects at higher trophic levels. In the eastern Bering Sea, Oithona spp., dominant during the warm regime, decreased in abundance in the cold regime, while Pseudocalanus and Acartia spp. increased. This species replacement had no net effect on the total biomass, but we speculate that it did affect trophic pathways, as Pseudocalanus and Acartia are considered more favorable as food for other planktivores (e.g. Oithona spp. nauplii are under-represented in larval pollock stomachs). Accordingly under future warming scenarios, global food webs, which include humans, (sensu Rice et al., 2011) may be impacted to a higher degree in regions that become ice-free compared to those which retain seasonal ice coverage.

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References:


Pinchuk, A.I., Coyle, K.O., Farley, E.V., Renner, H.M., 2013. Emergence of the Arctic Themisto libellula (Amphipoda: Hyperiidae) on the southeastern Bering Sea shelf as a result of the recent cooling and their potential impact on pelagic food web. ICES J. Mar. Sci. DOI####


Table 1. Questions addressed in manuscript.

<table>
<thead>
<tr>
<th>Q1</th>
<th>What are the spatial and temporal patterns of large and small zooplankton taxa in the eastern Bering Sea for 2003–2009?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2</td>
<td>How do the total abundances and biomasses of large and small zooplankton vary between warm and cold years for the southeastern and northeastern Bering Sea?</td>
</tr>
<tr>
<td>Q3a</td>
<td>Are the community compositions of large and small taxa different between warm and cold regimes within each domain?</td>
</tr>
<tr>
<td>b</td>
<td>When these communities differed between warm and cold regimes which taxa contributed most to the differences?</td>
</tr>
<tr>
<td>c</td>
<td>Did the observed differences in zooplankton community composition between regimes occur exactly during the break between low and high ice years?</td>
</tr>
<tr>
<td>d</td>
<td>Which taxa showed the largest variations among years?</td>
</tr>
<tr>
<td>Q4</td>
<td>For each domain, which environmental factors explained the greatest amount of variability in zooplankton community composition overall and between warm and cold regimes?</td>
</tr>
</tbody>
</table>
Table 2. PERMANOVA results (P-values from permutation test) for differences in community structure of large and small zooplankton taxa (abundance data) in the warm (2003 – 2005) versus cold (2006 – 2009) years by domain (Fig. 1). Other effects in model are not shown (Block, Year (Regime), and interactions). *Significant at P < 0.05.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Large P(perm)</th>
<th>Small P(perm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Inner</td>
<td>0.002*</td>
<td>0.005*</td>
</tr>
<tr>
<td>S Middle</td>
<td>0.001*</td>
<td>0.001*</td>
</tr>
<tr>
<td>S Outer</td>
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<td>0.731</td>
</tr>
<tr>
<td>N Inner</td>
<td>0.152</td>
<td>0.438</td>
</tr>
<tr>
<td>N Middle</td>
<td>0.024*</td>
<td>0.029*</td>
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</table>
Table 3. Percent contribution by large and small zooplankton taxa to differences (dissimilarity) between warm and cold years. Blue indicates > 2 times back transformed abundance in cold than in warm years. Red indicates > 2 times back transformed abundance in warm than in cold years.

<table>
<thead>
<tr>
<th>Large Zooplankton</th>
<th>S Inner</th>
<th>S Middle</th>
<th>S Outer</th>
<th>N Middle</th>
<th>Small Zooplankton</th>
<th>S Inner</th>
<th>S Middle</th>
<th>N Middle</th>
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<td>6.0</td>
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<td>Oithona spp.</td>
<td>14.9</td>
<td>12.5</td>
<td>14.1</td>
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<td>Cirripedia</td>
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<td>Podon sp.</td>
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<td></td>
<td>Fritillaria spp.</td>
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<td>Acartia spp.</td>
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<td>12.1</td>
<td>13.1</td>
</tr>
<tr>
<td>Parasagitta elegans</td>
<td>9.3</td>
<td>10.7</td>
<td>3.7</td>
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<td>Anomura</td>
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<td>Hyperiidae</td>
<td></td>
<td>5.8</td>
<td>6.3</td>
<td>6.9</td>
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<tr>
<td>Calanus spp.</td>
<td>13.4</td>
<td>22.5</td>
<td>8.8</td>
<td>17.0</td>
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<tr>
<td>Brachyura</td>
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<td>4.3</td>
<td>4.4</td>
<td>6.7</td>
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<tr>
<td>Total %</td>
<td>93.6</td>
<td>90.5</td>
<td>92.6</td>
<td>90.1</td>
<td>Total %</td>
<td>90.6</td>
<td>90.8</td>
<td>90.2</td>
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Table 4. PERMANOVA results (P-values) showing differences in community composition for large and small zooplankton taxa (abundance data) by domain. P-values for at least one difference among years (All years) are followed by pairwise multiple comparisons for consecutive years. * P < 0.05.

<table>
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<tr>
<th>Large zooplankton:</th>
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<th>S Middle</th>
<th>S Outer</th>
<th>N Inner</th>
<th>N Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>All years</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>0.015*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>2003 2004</td>
<td>0.005*</td>
<td>0.007*</td>
<td>0.382</td>
<td>0.290</td>
<td>0.157</td>
</tr>
<tr>
<td>2004 2005</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>0.084</td>
<td>0.001*</td>
<td>0.014*</td>
</tr>
<tr>
<td>2005 2006</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>0.364</td>
<td>0.026*</td>
<td>0.007*</td>
</tr>
<tr>
<td>2006 2007</td>
<td>0.001*</td>
<td>&lt; 0.001*</td>
<td>0.764</td>
<td>0.023*</td>
<td>0.002*</td>
</tr>
<tr>
<td>2007 2008</td>
<td>0.108</td>
<td>&lt; 0.001*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008 2009</td>
<td>0.043*</td>
<td>0.043*</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Small zooplankton:</th>
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<th>S Middle</th>
<th>S Outer</th>
<th>N Inner</th>
<th>N Middle</th>
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</thead>
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<tr>
<td>All years</td>
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<td>&lt; 0.001*</td>
<td>0.011*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>2003 2004</td>
<td>0.003*</td>
<td>0.296</td>
<td>0.743</td>
<td>0.028*</td>
<td>0.154</td>
</tr>
<tr>
<td>2004 2005</td>
<td>0.001*</td>
<td>0.045*</td>
<td>0.044*</td>
<td>0.026*</td>
<td>0.003*</td>
</tr>
<tr>
<td>2005 2006</td>
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<td>0.031*</td>
<td>0.149</td>
<td>0.715</td>
<td>0.020*</td>
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<tr>
<td>2006 2007</td>
<td>0.438</td>
<td>0.084</td>
<td>0.243</td>
<td>0.734</td>
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<tr>
<td>2007 2008</td>
<td>0.038*</td>
<td>0.320</td>
<td>0.770</td>
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<td></td>
</tr>
<tr>
<td>2008 2009</td>
<td>0.087</td>
<td>0.057</td>
<td>0.204</td>
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Table 5. Results of best-fit PERMANOVA models using Type I (sequential) sum of squares showing P-values of environmental covariates for large and small zooplankton community composition. Order of inclusion in the model is shown in parentheses. An insignificant (P > 0.05) Regime (factor) indicates covariates explained some of the variability between regimes.

*Significant at P < 0.05.

<table>
<thead>
<tr>
<th>Large zooplankton</th>
<th>Variable</th>
<th>S Inner</th>
<th>S Middle</th>
<th>S Outer</th>
<th>N Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>longitude</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.006 (1)*</td>
<td>-</td>
</tr>
<tr>
<td>latitude</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.006 (1)*</td>
</tr>
<tr>
<td>Integrated Chla</td>
<td>0.012 (1)*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Winter wind</td>
<td>0.014 (2)*</td>
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<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>direction</td>
<td>S below MLD</td>
<td>-</td>
<td>0.001 (1)*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>T below MLD</td>
<td>-</td>
<td>0.001 (2)*</td>
<td>-</td>
<td>0.001 (2)*</td>
</tr>
<tr>
<td></td>
<td>T above MLD</td>
<td>0.030 (3)*</td>
<td>0.001 (3)*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ice retreat timing</td>
<td>-</td>
<td>-</td>
<td>0.006 (2)*</td>
<td>0.082 (3)*</td>
</tr>
<tr>
<td></td>
<td>Regime (factor)</td>
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<td>0.001*</td>
<td>0.383</td>
<td>0.335</td>
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</table>

<table>
<thead>
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<th>N Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>longitude</td>
<td></td>
<td>-</td>
<td>0.025 (4)*</td>
<td>0.020 (1)*</td>
</tr>
<tr>
<td>latitude</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.042 (2)*</td>
</tr>
<tr>
<td>T below MLD</td>
<td>0.001 (1)*</td>
<td>0.003 (3)*</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T above MLD</td>
<td>0.001 (2)*</td>
<td>0.001 (2)*</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ice retreat timing</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.202 (3)</td>
</tr>
<tr>
<td>stability</td>
<td></td>
<td>-</td>
<td>0.001 (1)*</td>
<td>-</td>
</tr>
<tr>
<td>Regime (factor)</td>
<td>0.393</td>
<td>0.061</td>
<td>0.252</td>
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</table>
**Figure Captions:**

Figure 1. Bering Sea study area showing stations used for analyses in each oceanographic shelf domain for: A) large zooplankton and B) small zooplankton. Black lines indicate spatial “blocks” which are thiessen polygons around points. Blocks containing colored points (reduced data set) were visited at least two years during warm (2003 – 2005) and two years during cold (2006 – 2009) regimes; colors signify domain.

Figure 2. Heat map of large zooplankton showing clusters of stations (x axis) by taxa (y axis) using all stations sampled. Shade of each cell indicates the 4th root transformed abundance of each taxon. Approximate domain designations are shown above clusters. Designations at bottom indicate climate regime (W = warm; C = cold; W/C = both) when each cluster was commonly observed. Horizontal lines separate clusters of species (indicating taxa which tended to co-occur over all years and domains combined).

Figure 3. Spatial variation of large zooplankton clusters for each year using 4th root transformed abundance data. Warm years highlighted with red and cold with blue. Refer to Fig. 2 to see taxa abundances for each cluster. *Intended for color reproduction on the Web and in print*

Figure 4. Heat map of small zooplankton clusters of stations (x axis) by taxa (y axis). Refer to Fig. 2 for details.

Figure 5. Spatial variation of small zooplankton clusters by year using 4th root transformed abundance data. Warm years highlighted with red and cold with blue. Refer to Fig. 4 to see taxa abundances for each cluster. *Intended for color reproduction on the Web and in print.*
Figure 6. Small and large zooplankton total mean abundance (no. m\(^{-3}\)) in the eastern Bering Sea in the A) south (<~60°N) and B) north (~60-63 °N), and total mean biomass (g m\(^{-3}\)) in the C) south and D) north. Geometric means and standard errors are shown.

Figure 7. Untransformed mean zooplankton abundances in the eastern Bering Sea for large taxa in the A) south (<~60 °N) and B) north (~60-63 °N) and for small taxa in the C) south and D) north. *Intended for color reproduction on the Web and in print.*

Figure 8. A) Mean temperature above (surface) and below (deep) the mixed layer depth during our surveys, B) mean day of year for sea ice retreat during the prior spring, and C) mean number of days of sea ice coverage during the prior winter, in the south (S) and north (N) Middle Domains. Standard errors are shown.
Chapter 14


Spring and fall phytoplankton blooms in a productive subarctic ecosystem, the eastern Bering Sea, during 1995-2011

Michael F. Sigler¹, Phyllis J. Stabeno², Lisa B. Eisner¹, Jeffrey M. Napp³, Franz J. Mueter⁴

¹Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 17109 Pt. Lena Loop Rd., Juneau, AK 99801 USA
(907) 789-6037; mike.sigler@noaa.gov and (907) 789-6602; lisa.eisner@noaa.gov

²Pacific Marine Environmental Laboratory, Oceans and Atmospheric Research, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115-0070 USA
(206) 526-6453; phyllis.stabeno@noaa.gov

³Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115-0070 USA
Phone: (206) 526-4148; jeff.napp@noaa.gov

³ University of Alaska Fairbanks, Juneau Center for Fisheries and Oceans, 17309 Pt. Lena Loop Rd., Juneau, AK 99801 USA
Phone: (907) 790-5448; fmueter@alaska.edu

Abstract

The timing and magnitude of phytoplankton blooms in subarctic ecosystems often strongly influence the amount of energy that is transferred through each trophic pathway. In the eastern Bering Sea, spring bloom timing has been linked to ice retreat timing and production of zooplankton and fish. A large part of the eastern Bering Sea shelf (~500 km wide) is ice-covered during winter and spring. Four oceanographic moorings have been deployed along the 70-m depth contour of the eastern Bering Sea shelf with the southern location occupied annually since 1995, the two northern locations since 2004 and the remaining location since 2001. Chlorophyll
a fluorescence data from the four moorings provide 37 realizations of a spring bloom and 33
realizations of a fall bloom. We found that in the eastern Bering Sea: if ice was present after
mid-March, spring bloom timing was related to ice retreat timing (p < 0.001, df = 1,24); if ice
was absent or retreats before mid-March, a spring bloom usually occurred in May or early June
(average day 148, SE = 3.5, n = 11). A fall bloom also commonly occurred, usually in late
September (average day 274, SE = 4.2, n = 33), and its timing was not significantly related to
the timing of storms (p = 0.88, df = 1,27) or fall water column overturn (p = 0.49, df = 1,27).
The magnitudes of the spring and fall blooms were correlated (p = 0.011, df = 28). The interval
between the spring and fall blooms varied between four to six months depending on year and
location. We present a hypothesis to explain how the large crustacean zooplankton taxa *Calanus*
spp. likely responds to variation in the interval between blooms (spring to fall and fall to spring).

1. Introduction

The timing and magnitude of phytoplankton blooms in subarctic ecosystems often
strongly influence the amount of energy transferred through each trophic pathway. In the
southeastern Bering Sea, spring bloom timing has been linked to production of large crustacean
zooplankton and walleye pollock (*Theragra chalcogramma*) (Hunt et al., 2002, 2011; Coyle et
al., 2011); if ice is present after mid-March, an early ice-associated bloom occurs there; otherwise
a spring bloom usually occurs in May (Hunt et al., 2002; Stabeno et al., 2001). Although spring
bloom timing is well-characterized in the southeastern part of the shelf (Brown and Arrigo, 2011,
2013; Hunt et al., 2002, 2011; Rho and Whitledge 2007; Stabeno et al., 2001), less is known
about the spring bloom elsewhere in the eastern Bering Sea (Brown and Arrigo 2013), as well as
the characteristics of the fall bloom (Rho and Whitledge 2007).

The eastern Bering Sea is dominated by a broad continental shelf (~500 km wide), a large
part of which is ice-covered during winter, with the maximum extent varying >100 km among
years. In ice-covered areas, the seasonal cycle of primary production begins with ice algae
(primarily large diatoms), which begin to grow in the spring when light level becomes adequate.
Ice algae are adapted to lower light levels than pelagic phytoplankton (Kirst and Wiencke, 1995)
and grow within the ice and at the ice-water interface depending on the amount of overlying snow
cover. Ice algae begin to grow in mid-February in the Bering Sea (R. Gradinger, University of
Alaska, Fairbanks, pers. comm.) and may provide an early concentrated food source (chlorophyll
*a* maximum ~300 µg l\(^{-1}\); Mock and Gradinger, 2000; Niemi et al., 2011) for zooplankton (e.g.
O’Brien, 1987; Runge and Ingram, 1991). Sea ice algae that are not grazed can seed the spring
phytoplankton bloom or may aggregate and sink out of the upper water column (Tremblay et al.,
 Phytoplankton in the Bering Sea begin to bloom in the spring once the water becomes stratified and the day length becomes long enough (\textit{sensu} Sverdrup 1953). Prior to this, phytoplankton are considered to be light-limited, but have adequate nutrients due to the advection of nutrient rich slope water onto the shelf during the previous winter, which is mixed throughout the water column (Niebauer et al., 1995); nutrient recycling on the shelf also is important (Granger et al., 2011). The phytoplankton spring bloom typically ends when the surface nutrient supply is exhausted and phytoplankton growth becomes nutrient limited (typically below 1 µM nitrate). Grazing pressure from mesozooplankton and microzooplankton also increases as the spring progresses, which lowers phytoplankton standing stocks.

In the summer, phytoplankton concentration in the surface mixed layer is typically low due to nutrient limitation and continued grazing pressure. Episodic wind events can break down stratification and mix nutrients and viable phytoplankton cells to the surface during this period (Sambrotto 1986; Stabeno et al., 2010). During fall, increased storminess and overall cooling of the water column reduces stratification and deepens the mixed layer so that nutrients are mixed to the surface to fuel fall phytoplankton blooms. The fall bloom ends when phytoplankton become light limited, due to decreased day length and deepening of the mixed layer, and when zooplankton grazing reduces standing stocks. Pelagic-benthic coupling (Grebmeier et al., 2006) and luxury consumption by diatoms of nutrients near the sediment may also be important (Droop 1973), since the Bering Sea shelf is a shallow shelf system with 1% light levels located 10-20 m below the pycnocline (Mordy et al., 2012). Phytoplankton present in the water column during late fall, when ice begins to form, can be incorporated into the ice with large diatom cells preferentially selected (Gradinger and Ikavalko, 1998, Niemi et al., 2011). Ice algal cells may grow slowly during winter when light levels are very low (Melnikov 1998) and then begin to grow faster when light increases in spring.

In this paper we focus on the middle domain of the eastern Bering Sea shelf where four oceanographic moorings have been located. The measurements on the moorings include temperature and chlorophyll \(a\) fluorescence. In summer, the middle domain is strongly stratified into two layers, with a wind-mixed upper layer and tidally-mixed lower layer. The middle domain
typically extends from the 50 m isobath to the 100 m isobath, and is bounded by oceanic fronts or
transition zones (Iverson et al., 1979). In winter, the middle domain is usually well mixed and
cold, with a large part (>50%) ice-covered. These four oceanographic moorings provide the
longest, daily record of in situ oceanographic measurements in the eastern Bering Sea. This paper
is the first examination of the chlorophyll \( a \) fluorescence data, excepting previous analyses of the
spring bloom at the southernmost mooring (Hunt et al., 2002, 2011; Stabeno et al., 2001). In this
paper our objectives are to: characterize spring and fall blooms over the eastern Bering Sea
middle shelf; relate their timing and strength to physical characteristics including spring ice
retreat and fall overturn; and discuss some implications of these results for one of the large
crustacean zooplankton taxa characteristic of that domain (\textit{Calanus} spp.).

2. Data and methods

2.1. Moorings

Four oceanographic moorings have been
deployed along the 70-m depth contour of the eastern
Bering Sea shelf with two southern locations sampled
almost continually since 1995 (M2) and 1999 (M4), and
two northern locations since 2004 (M8) and 2005 (M5)
(ure 1). Prior to 2005, moorings were recovered and
redeployed twice a year, once in the spring (April/May)
and again in the late summer or early fall (September /
October). Since 2006, there has been extensive ice on
the northern shelf in spring and M8 (and sometimes M5)
has only been recovered and redeployed once a year in
August or September. Data collected by instruments on
the moorings included temperature (miniature temperature recorders, SeaBird\(^3\) SBE-37 and SBE-
39) and chlorophyll \( a \) fluorescence (WET Labs DLSB ECO Fluorometer). A transition to
fluorometer sensors with wipers that sharply reduced fouling occurred during 2001-2004. Data
were collected at least hourly and instruments were calibrated according to manufacturer’s
specification prior to deployment. During autumn, winter, and early spring, the shallowest
instrument was at 11 m at M2 and M4, at 15 m at M5 and at 20 m at M8. During late spring to
early autumn (the ice-free period), the mooring at M2 included a surface toroid measuring

\(^3\) Use of trade names does not constitute an endorsement by NOAA
temperature at a depth of 1 m, and the upper instrument at M4 was at 11 m, as was the upper
instrument at M5 and M8 if a summer mooring was deployed. For consistency, our analyses
focus on data recorded at 11 m (or the shallowest instrument at M5 and M8 during autumn,
winter and early spring). This standardization is reasonable because for parallel data sets collected
at both 1 and 11 m at M2 and M4, the data recorded at 11 m captured 96% of variability recorded
at 1 m (Stabeno et al., 2007). At these mooring locations, the water column is well-mixed during
winter and develops a 15-35 m wind-mixed layer once stratification develops during spring
(Stabeno et al., 2007). Farther north, at M8 and possibly M5, the spring bloom can occupy a
narrower depth range and slowly sink, so that identified bloom strengths and timings are
approximate.

Additional data were collected when the moorings were deployed and recovered and
were used for quality control of the chlorophyll a fluorescence data collected by mooring
instruments. The additional data included chlorophyll a fluorescence measurements made with a
Seabird SBE 911 plus system with chlorophyll a fluorescence sensors (WET Labs WETStar).
Data were recorded during the downcast, with a descent rate of usually 15 m min\(^{-1}\) to a depth of
35 m, and 30 m min\(^{-1}\) below that. The additional data also included water samples for extracted
chlorophyll a collected during CTD casts. The water samples were filtered through glass fiber
filters (nominal pore size 0.7 µm), then frozen at -80 °C until analysis. Frozen chlorophyll a
samples were analyzed with a calibrated benchtop Turner TD-700 fluorometer using standard
acidification methods (Parsons et al., 1984).

Conversion of \textit{in vivo} chlorophyll a fluorescence (volts) to chlorophyll a concentration
(µg l\(^{-1}\)) was performed for both the moored and CTD chlorophyll a fluorescence sensors using
relationships provided by the manufacturer for each instrument during annual service. We did not
attempt to create a relation between mooring chlorophyll a fluorescence and extracted chlorophyll
a from water samples due to the limited number of water samples at deployment and recovery of
the moorings and the difficulty of matching the timing and location of the water samples and
mooring measurements. The chlorophyll a estimates based on the fluorescence sensors were
compared to the chlorophyll a water samples collected during CTD casts for quality control of the
mooring-based measurements; when high (>40 µg l\(^{-1}\)) values of chlorophyll a occurred or isolated
spikes occurred, these measurements were excluded from the analysis. In addition, the mooring–
based measurements also were reviewed for measurement drift due to fouling and when drift
occurred, these measurements were excluded from the analysis. Typically drift did not occur
during winter and was more common during summer, which was mostly eliminated for
instruments with wipers.
2.2. Sea Ice

Two sources of sea-ice data were used. The first source was the National Ice Center (NIC), with data available from 1972 to 2005; the second source was the Advanced Microwave Scanning Radiometer EOS (AMSR), with data available from 2002 to 2012 (Spreen et al., 2008). These two data sets provide data over the entire period (1972–2012) for which high-quality data on sea-ice extent and areal concentration are available. We downloaded data available from the NIC website (http://www.natice.noaa.gov) for our study period (1995-2005) which were interpolated to a 0.25 degree grid. NIC data are derived from a variety of sources including the Advanced Very High Resolution Radiometer (AVHRR) aboard the Polar Orbiting Environmental Satellites (POES). AMSR data consist of daily ice concentration at 12.5 km resolution, which are available from the National Snow and Ice Data Center (NSIDC; http://nsidc.org). To examine how the ice cover varies along the 70-m isobath, a 100 km by 100 km box was defined around each of our biophysical moorings (M2, M4, M5, and M8) maintained by NOAA. AMSR and NIC data overlap during the four-year period 2002-2005, during which time they have very similar values (M2, Stabeno et al., 2012b). To span the period 1972-2012, we used both NIC and AMSR data, using the average value in the overlap years to derive the annual cycle of percent ice cover for each mooring location.

2.3. Wind

Winds were estimated using daily data from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis (Kalnay et al., 1996). We follow the procedure used in Bond and Adams (2002) to specify particular elements of the atmospheric forcing on a daily basis for selected periods and interpolated wind velocity to the locations of four moorings (Fig. 1). The daily winds from the reanalysis are reliable in this region based on a comparison to independent buoy measurements from 1995 to 2000 (Ladd and Bond, 2002).

2.4. Data analysis

Ice cover for each mooring and year was examined to determine if ice was present at any time that winter or spring and if present, when the ice retreated for the last time. Ice retreat was considered to have occurred when ice cover fell below 15% for the last time during that spring. The temperature records for each mooring and year were examined to determine: 1) when the ocean began warming following ice retreat; and 2) when fall overturn occurred. When ice was

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present the temperature was approximately -1.7 °C. Warming was considered to have started when the near surface temperature rose above -1 °C for the last time that spring. Fall overturn was considered to have occurred once temperature (at 11 m) fell 2 °C below the summer maximum.

We also considered basing timing of the fall overturn on timing of mixed layer depth deepening. Unfortunately, the mooring data at M5 and M8 were inadequate to do this. We tested whether timing of mixed layer depth deepening and fall temperature drop were related, which would support using fall temperature drop as a measure of stratification breakdown and the resultant nutrient replenishment that could support a fall bloom. We found that they are related (Fig. 2) (Pearson’s product-moment correlation = 0.61, df = 20, p = 0.002). The relationship was stronger for M4 (Pearson’s product-moment correlation = 0.95, df = 6, p < 0.001) than M2 (Pearson’s product-moment correlation = 0.50, df = 12, p = 0.07), but the latter relationship was strongly influenced by one data point. In 1997, the mixed layer depth deepened about 40 days after the temperature dropped, which is later than usual and may have occurred because winds were weak that late summer and early fall. If this data point is excluded, the relationship for M2 is much better (Pearson’s product-moment correlation = 0.76, df = 11, p = 0.003).

The average wind speed records by calendar day and location were examined to determine when the first stormy period occurred after day 210 (ca. July 27). The wind data were divided into 10-day periods; if daily average wind was greater than 11 m s⁻¹ for half or more of the ten-day period, then this period was defined as stormy (Sullivan et al., this issue).

Fluorescence for each mooring and year was examined to determine the time and magnitude of the maximum value in spring and fall. These records were plotted and the times and magnitudes of the spring and fall blooms were assigned (Appendix Figure 1). Each year, the spring bloom was assigned to the maximum fluorescence value before day 180 (ca. June 27) and the fall bloom was assigned to the maximum fluorescence value after day 210 (ca. July 27). In some years the fluorescence record was discontinuous and the maximum value could not be determined (e.g., spring bloom at M2 in 1996. The values are tabled in Appendix Table 1.

Figure 10. The relationship of mixed layer depth deepening (day) and temperature drop (day) for moorings M2 and M4. The mooring data at M5 and M8 were inadequate to compute mixed layer deepening.
2. 5. Comparison to shelf-wide patterns for fluorescence

Satellite ocean color data were examined to understand the spatial pattern of chlorophyll $a$ over the middle shelf. In particular, we wanted to find out whether it was reasonable to assume that the mooring fluorescence data were representative of fluorescence values over a much larger area. To do so, we retrieved eight-day composite Level-3 SeaWiFS and MODIS-Aqua chlorophyll $a$ data at 9-km spatial resolution using the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences Data and Information Services Center (Acker and Leptoukh 2007). Data for a rectangular region (54 – 66°N and 157 – 180°W) that encompasses the eastern Bering Sea shelf were extracted from the global coverage datasets (units: mg m$^{-3}$). Open ocean values (offshore of the 500 m isobaths) and nearshore values (inshore of 10 m isobaths) were excluded.

We compared eight full years of overlap between the two data sets (2003-2010) based on correlations and absolute differences (bias) of the logarithmically transformed data on a pixel-by-pixel basis. Estimates from the two satellites were strongly correlated ($r = 0.65$) and bias was found to be negligible (median bias $< 0.01$, 88% of 1.4 million paired observations had absolute bias $< 0.05$). The SeaWiFS data from 1998-2002 were combined with the MODIS-Aqua data from 2003-2011 to produce the longest possible continuous
time series of remotely-sensed chlorophyll $a$ data. Finally, we correlated eight-day composites of
the fluorescence data with 8-day remotely-sensed chlorophyll $a$ data for all non-missing pairs on
a pixel-by-pixel basis to produce correlation maps for each of the four moorings.

2.6. Zooplankton Metabolism

We examined some implications of these results for a large crustacean zooplankton taxa
characteristic of that domain (Calanus spp.). The effect of temperature on the respiration of late
stage Calanus spp. was approximated from literature values. We used a Q$_{10}$ of 2.77 and nitrogen-
specific respiration of Calanus finmarchicus (130 µmol O$_2$ gN$^{-1}$ h$^{-1}$; Saumweber and Durbin,
2006), average bottom temperatures in cold and warm years (-1.8 and 2°C, respectively; Stabeno
et al., 2012a), wet weight measurements on preserved Calanus spp. C5 obtained from the eastern
Bering Sea during August and September (1.82 x 10$^{-3}$ g), and literature values for the relationship
of dry to wet weight (15%) and nitrogen to dry weight (8%) for copepods to estimate respiration
rates.

3. Results

3.1. Spring

Ice was present for about two
out of three-years at M2 (12 of 17),
nearly all years at M4 (15 of 17), and all
years at M5 and M8 (17 of 17). When
ice was present, retreat was significantly
(ANOVA, p < 0.001, df = 3, 57) earlier
in the south (mean M2: Day 88; M4: 99;
M5: 130; M8: 138) (Fig. 3). In some
years when ice was present, retreat
occurred before mid-March (M2 during
2000 and 2002) (Appendix Table 1). Ice
was absent at M2 during 1996, 2001 and
2003-2005 and at M4 during 2001 and
2005. Ice presence reduced ocean
temperature below -1°C in all cases, but
one (ice was present at M2 in 2002, but for only 11 days, and minimum temperature was -0.1°C).
The timing of warming (near-surface temperature > -1°C) was strongly correlated with the time of ice retreat (Pearson’s r = 0.96, df = 40, p < 0.001). The interval between ice retreat and warming was longer in the north (M2 warming averaged Day 100; M4: 110; M5: 153; M8: 181, corresponding to intervals for M2 of 12 days; M4: 11; M5: 23; M8: 43).

The spring bloom usually reached only one peak (34 of 37 cases) (Appendix Figure 1), so that the maximum value and when the maximum value occurred are reasonable measures of the strength and timing of the spring bloom. Double rather than single spring peaks occurred at M2 in 2003 and 2011 and at M4 in 1997.

During years when ice was absent (or was present, but retreated before mid-March), the spring bloom maximum occurred in late May to early June (average day 148, SE = 3.5, n = 11) (Fig. 4, panel row 2, column 5). This pattern occurred for M2 and M4 but not M5 or M8 where ice always was present after mid-March (Fig. 5). There was no statistically significant difference in timing of the spring bloom maximum in years when ice was absent (average day 141) and when ice was present, but retreated before mid-March (average day 153) (two-way t-test, df = 9, p = 0.10). During years when ice was absent or retreated before mid-March, spring bloom maximum averaged 19 µg Chl l⁻¹ (log-transformed, SE = 1.2, n = 11) (Fig. 4, panel row 1, column 5). There was no statistically significant difference in spring bloom maximum in years when ice was absent (average 25 µg Chl l⁻¹) and when ice retreated before mid-March (average 15 µg Chl l⁻¹) (log-transformed, two-way t-test, df = 9, p = 0.14).
In contrast to the late May to early June timing of the spring bloom in years when ice was absent or retreated early, if ice was present after mid-March (day 75), an ice-associated bloom occurred between early April and mid-June and the bloom timing was related to ice retreat timing (Fig. 4, panel row 2, column 5), regardless of mooring (Fig. 5). Later blooms occurred when ice retreat was later (linear regression, y-intercept = 53, slope = 0.66, df = 1, 24, p < 0.001) (Fig. 6). This relationship implies that bloom day is 119 when ice retreat occurs on day 100, 152 when ice retreat occurs on day 150; and 172 when ice retreat occurs on day 180. There was no statistically significant difference in spring bloom strength whether ice was absent or present, but retreated before mid-March (average 19 µg Chl l⁻¹) or ice was present after mid-March (average 17 µg Chl l⁻¹) (log-transformed, two-way t-test, df = 35, p = 0.70); the overall average spring bloom strength was 17 µg Chl l⁻¹ (log-transformed, SE = 1.2, n = 37).

### 3.2. Fall

Fall overturn timing was similar among moorings on average (M2 mean was Day 259; M4: 261; M5: 259; M8: 268 (ANOVA, df = 3, 34, p = 0.49)), but was more variable at M2 and M4 (Fig. 7). Sometimes an early major storm prompted early fall overturn; on five occasions when overturn was earlier than usual (approximately day 240 versus a range of 250-280), the day of the first major storm was earlier than usual (about day 240 versus a range of 240-320) (Figure 8, panel row 4, column 5).
The fall bloom usually reached only one peak (30 of 33 cases) (Appendix Figure 1), so that the maximum value and when the maximum value occurred are reasonable measures of the strength and timing of the fall bloom. Double rather than single fall blooms occurred at M2 once (1998) and M4 twice (2004, 2007). In six cases (1996 M4, 2002 M2, 2005 M4, 2007 M2, 2009 M5, 2010 M8), only the descending limb of the fall fluorescence data is available due to instrument failure, hence the fall bloom peak is uncertain and no values for magnitude or timing were assigned.

There was no significant relationship between fall overturn timing and fall bloom timing (linear regression, df = 1, 27, p = 0.88) (Fig. 8, panel row 2, column 4) or fall bloom strength (linear regression, log-transform, df = 1, 27, p = 0.49) (Fig. 8, panel row 1, column 4).

Fall bloom timing was similar among moorings (M2 mean: Day 276; M4: 277; M5: 258; M8: 281) (ANOVA, p = 0.32, df = 3, 29) (Fig. 9). Fall bloom strength also was similar among moorings (ANOVA, log-transform, p = 0.93, df = 3, 30) (Fig. 9). On average, the fall bloom occurred on day 274 (late September) (SE = 4.2, n = 33) with strength 8 µg Chl l⁻¹ (SE = 1.2, n = 34).

The strengths of the spring and fall blooms were correlated (Pearson’s r = 0.46, df = 28, p = 0.011, log-transformed values) (Fig. 10). The interval of time between the spring and fall blooms ranged from about 4-6 months, with longer intervals occurring for earlier spring blooms (linear regression, intercept = 294, slope = -1.16, df = 1, 27, p < 0.001) (Fig. 11).

3.3. Comparison to shelf-wide patterns
Eight-day composites of chlorophyll $a$ values at both M2 and M4 were moderately to strongly correlated with remotely-sensed chlorophyll $a$ values over broad regions of the eastern shelf (Appendix Figure 2), including the middle shelf in the southeast and most of the northern Bering Sea except Norton Sound. In contrast, chlorophyll $a$ values at M5 were positively correlated with remotely-sensed values over much of the shelf north of about 60°N, but negatively correlated with remotely-sensed values to the south of M5. Chlorophyll $a$ values at M8 were positively correlated with remotely-sensed values over the northwestern part of the shelf and much of the outer shelf and negatively correlated with remotely-sensed values on much of the inner shelf. These negative correlations are likely due to differences in bloom timing.

4. Discussion

4.1. Spring

We found that in the eastern Bering Sea: if ice was present after mid-March, spring bloom timing was related to ice retreat timing; if ice was absent or retreats before mid-March, a spring bloom usually occurred in May or early June. Our findings generally match Brown and Arrigo (2013) based on their satellite-based observations (see exception below), as well as those of Hunt et al. (2002, 2011) and Stabeno et al. (2001). In general, ice-associated phytoplankton blooms are observed near the retreating ice edge on shipboard surveys and in ocean color data, due to melting ice increasing the stability of the water column (Alexander and Niebauer, 1981; Niebauer et al., 1995; Hunt et al., 2010; Brown et al., 2011). While the spring bloom usually moves northward as the eastern Bering...
Sea becomes ice free, sometimes ice melts in the north before disappearing farther south and a
spring bloom occurs in the northern ice-free area before it occurs in the south if light level is
sufficient. For example in 2010, the northern Bering Sea melted earlier than in the south leaving
an area of persistent ice between M2 and M4. Percent ice cover also influences whether or not
ice-associated blooms occur by modulating both light and stratification (Sullivan et al., this
issue).

The relationship between the timing of the spring bloom and ice retreat when ice retreat
occurred after mid-March was statistically significant for the eastern Bering Sea (pooled data
from the north and south; Figure 6), which contradicts Brown and Arrigo (2013), who concluded
that ice retreat timing was a good predictor of spring bloom timing for only the northern Bering
Sea. The different conclusions for the southeastern Bering Sea likely resulted from how the two
data sets were analyzed. Brown and Arrigo (2013) classified their data into four regions
corresponding to M2, M4, M5 and M8 (i.e., similar geographic grouping to our approach). In one
analysis, Brown and Arrigo (2013) regressed spring bloom timing versus ice retreat timing and
found significant relationships for the northern, but not southeastern Bering Sea. In a second
analysis, they classified the southeastern Bering Sea data based on whether or not ice retreat
occurred before (early) or after (late) the mean ice retreat date for the two regions (M2 and M4)
and whether the bloom occurred within (ice-edge bloom) or after (open-water bloom). Open-
water blooms were defined as those occurring 20 days or more after ice retreat. They found no
significant difference in mean timing between open-water blooms of early retreat (or ice free)
years and ice-edge blooms of late retreat years.

Like their first analysis, we regressed spring bloom timing versus ice retreat timing, but
instead classified the data into two groups: ice absent or ice retreat before March 15; and ice
retreat after March 15 following Hunt et al., (2002, 2011). Mid-March was chosen as the time
when sufficient light becomes available for a phytoplankton bloom in the southeastern Bering Sea
(Hunt et al. 2002). We pooled all mooring data for years when ice was present after mid-March
(Figure 6) to test whether ice retreat and the spring bloom move northward as fson progresses.
We suspect that if the Brown and Arrigo (2013) data set were similarly analyzed (regress bloom
timing versus ice retreat timing when ice retreat occurred after mid-March), our results would
match and both data sets would support the conclusion that the spring bloom generally moves
northward as the eastern Bering Sea becomes ice free, and that the bloom occurs later when the
ice retreats later.

The present work corrects and clarifies the relationship of spring bloom timing and ice
retreat timing reported by Hunt et al. (2002) for the southeastern Bering Sea. Their conclusion of
late ice retreats with early ice-related blooms oversimplifies the data; while supported by early
ice-related blooms for 1995, 1997 and 1999, later ice-related blooms occurred for 1975 and 1976
(Hunt et al., 2002, their Figure 7). There is some evidence that there were early blooms under the
ice in these two years, but the data are not very reliable. With more years of data, Hunt et al.
(2011) observed that because ice can remain in the southeastern Bering Sea until May or rarely
June, the calendar date of an ice-associated bloom could be later than that of an open-water
bloom (i.e., if the ice retreat is late, the spring bloom also is late).

In addition to ice retreat timing, wind patterns can affect spring bloom timing. When ice
was absent or retreated before mid-March, spring bloom timing averaged day 148 (May 28) and
varied from day 132 (May 12) to 166 (June 15). Short-lived surface pulses of chlorophyll $a$ can
occur with early ice retreat during a temporary relaxation of winds without significant
stratification (Brown and Arrigo, 2013; Stabeno et al., 2010) and precede the larger primary
bloom in May or early June. When ice retreat occurs after mid-March in the southeastern Bering
Sea, a very early bloom can occur when strong winds advect ice which melts in place during a
temporary relaxation of winds (Brown and Arrigo, 2013; Stockwell et al., 2001). This scenario
matched the two earliest spring blooms we observed in the southeastern Bering Sea (1997 at M2;
2003 at M4, Appendix Table 1). An open-water bloom subsequent to the ice-related spring bloom
also can occur after a strong mixing event. This occurred in 1997, with a strong ice associated
bloom in April and then a very strong storm in late May that resulted in an open water bloom.

We summarize these findings on spring bloom timing and ice retreat timing (ours; Brown
and Arrigo 2013; Hunt et al., 2002, 2011) as follows. If ice retreats after mid-March, an ice-
associated bloom occurs; this pattern applies throughout the eastern Bering Sea. If the ice retreats
before mid-March, there is no ice-associated bloom because sunlight is insufficient to initiate an
ice-associated bloom. To date, early ice retreat occurs only in the southeastern Bering Sea and not
in the northern Bering Sea; this pattern of persistent ice in the northern Bering Sea is expected to
continue into the foreseeable future (Stabeno et al., 2012a). An open-water bloom occurs if ice
retreats before March 15 or ice is absent; this pattern applies only in the southeastern Bering Sea.

The strengths of spring blooms were similar for years when ice retreated after mid-
March, and for years when ice retreated before mid-March or was absent. We used the maximum
chlorophyll $a$ value to measure spring bloom strength; its timing usually coincides with that of ice
retreat, indicating that these values represent both ice algae and phytoplankton. We anticipated
spring blooms for late retreat years would be weaker due to consumption of nutrients by ice algae
prior to the spring bloom maximum; ice algae growth and the spring phytoplankton bloom
together can create a prolonged period of production or two spring blooms (Niebauer et al., 1995,
We found some evidence that ice algae production reduces the subsequent value of maximum chlorophyll a. The spring bloom maximum averaged 25 (µg chlorophyll a l⁻¹) when ice was absent, 15 when ice retreated before mid-March and 17 when ice retreated after mid-March. Although not significant, these differences imply that phytoplankton bloom strength is diminished if preceded by ice cover and ice algal growth. In contrast to our findings, satellite-based estimates of open-water blooms of early retreat years were >70% more productive than the ice-edge blooms of late retreat years, but under-ice production was not quantified (Brown and Arrigo, 2013). An analysis of measurements of nutrient draw-down would help to resolve this question.

4.2. Fall

A fall bloom commonly occurred in both the northern and southeastern Bering Sea, on average in late September. Winds at M2, M4, M5, and M8 are significantly correlated (Stabeno et al., 2010), which will tend to synchronize fall blooms, as was observed. However bloom timing was not significantly related to either storm or fall overturn timing. A timing effect for the fall bloom may be difficult to detect because the month-long interval when blooms usually occurred is short and because the timing is affected by several interacting factors including wind strength, stratification, fall cooling and light level. For example, fall overturn requires strong winds, but once cooling begins in late September and early October, less wind energy is necessary to overturn the ocean. A fall bloom also depends on sufficient light, introduction of nutrients from below the pycnocline and short periods of stabilization that allow phytoplankton to remain in the sunlit waters and grow.

The timing of the fall overturns at M2 and M4 were much more variable than at M5 and M8 which may be due to north-south differences in stratification. In the south, stratification is almost completely controlled by temperature, while in the north it is equally controlled by temperature and salinity so variations in temperature have more effect on stratification in the south than in the north. This contrast implies that the southeastern Bering Sea is more sensitive to the timing of fall cooling than the northern Bering Sea.

Our mooring data and previous middle-shelf observations (Rho and Whitledge, 2007; Brown et al., 2011) indicated that the strengths of fall blooms were weaker than spring blooms on average. It may be that nutrients are limiting and storm mixing can’t provide sufficient replenishment of nutrients for a strong fall bloom or the bloom is limited by grazing. For instance, if the lower layer has 20 µM l⁻¹ of nitrate and the surface mixed layer is 20 m deep and depleted of nitrate, then deepening the mixed layer by 5 m will result in only 4 µM l⁻¹ of nitrate, compared...
to 18 μM l⁻¹ available for consumption in the top 20 m of water column in spring. In addition, variations in chlorophyll a reflect the result of multiple processes including phytoplankton production, grazing, sinking, and advection. Chlorophyll a will not increase until cell growth exceeds losses by grazing and other factors. While grazing impact has been measured for spring (Cooney and Coyle 1982; Sherr et al., 2013), grazing impact has not been measured for fall, so comparing grazing pressure on spring and fall blooms is not possible. Finally, phytoplankton physiological status will impact the bloom intensity, with healthier cells growing faster, so phytoplankton populations in spring may grow faster than those in fall.

Broad-scale sampling of the eastern Bering Sea shelf found that late summer and early fall chlorophyll a values were higher during warm years compared to cold years (Eisner et al., 2012). Ocean color data for 1998-2007 in the Bering Sea also show that annual mean chlorophyll a and total primary production were higher in warm years than cold years (Brown et al., 2011, Mueter et al., 2009). We used the warm-average-cold year classification of Stabeno et al. (2012) to classify our fall bloom data. Likewise we found that fall bloom strength was stronger in warm (average = 12.3 μg Chl l⁻¹, log-transform) versus cold (6.3) and average (8.6) years, but the differences were not statistically significant (ANOVA, log-transform, df = 2, 31, p = 0.32).

4.3 Spring/fall comparisons

Spring and fall bloom strengths were related, implying that a common factor influences spring and fall primary production (e.g., overwinter replenishment of nutrients). In addition, this relationship likely amplifies secondary production during good years (both spring and fall blooms tend to be strong) and vice versa, bad years (both spring and fall blooms tend to be weak). An analysis of nutrient information, comparing spring-fall differences by year, would help us to understand the mechanism for this relationship, but has not yet been published.

The fall bloom occurred in late September on average, and the timing was less variable than for the spring bloom (varies over ~60 day compared to ~120 day period) regardless of location, so the spring-fall interval largely depends on spring bloom timing. In the northern Bering Sea, where ice is present every year and usually retreats in late May (Fig. 5), the interval typically lasted four months (Fig. 11). The interval also typically lasted four months in the southeastern Bering Sea in years when ice was absent or retreated before March 15. In contrast, the interval lasted up to six months in the southeastern Bering Sea in years when ice was present after March 15, but retreated soon thereafter.

4.4. The representativeness of the fluorescence data
Distinct spring and fall blooms occurred at these moorings located in the middle domain with the spring bloom stronger than the fall bloom. Likewise, a bimodal spring-fall pattern was found for net primary production for the middle domain with spring stronger than fall for both satellite-based (Brown et al., 2011) and temporally and spatially scattered in situ measurements (Rho and Whitledge 2007). During the summer interval between the spring and fall blooms, we found that chlorophyll \(a\) fluorescence was low in the middle domain, similar to Goes et al. (this issue). We also found that the mooring observations of chlorophyll \(a\) fluorescence were consistently correlated with satellite observations of chlorophyll \(a\) fluorescence in the middle domain at the same approximate latitude (Appendix Figure 2). This pattern implies that the mooring information represents conditions of the middle domain over a range of ca. 150-200 km.

The bimodal pattern was replicated for the inner domain except that spring and fall bloom strengths appear similar for satellite-based measurements (Brown et al., 2011). In contrast, the fall bloom was less distinct for the outer domain (Rho and Whitledge 2007; Brown et al., 2012). These patterns imply that bloom patterns differ somewhat among the inner, middle and outer domains, and that the mooring information do not well represent the oceanographic conditions of the inner (influence of the coastal current, river runoff, and tidal and wind mixing) or outer domains (influence of slope, episodic on-shelf flow and upwelling). The broad-scale data collected during the late summer BASIS sampling also indicates that chlorophyll \(a\) concentrations and phytoplankton particle size (large \(\geq 10\) um and small \(< 10\) um) varied among shelf domains (Eisner et al., 2012). The relatively high concentrations found in the outer domain were primarily comprised of small taxa (<25% large); chlorophyll \(a\) concentrations on average were lower in the middle domain during these surveys, but when increases in chlorophyll \(a\) were observed (usually near M4), there was a higher proportion of large taxa (40-70% large). Besides phytoplankton, mixotrophic ciliates (a taxonomic group of microzooplankton that also photosynthesize) also can contribute to total chlorophyll \(a\) measurements in summer (Stoecker et al., this issue).

**4.5 Biological Implications**

**4.5.1 Lower trophic levels**

Spring bloom timing predictably varied between early April and mid-June depending on ice presence/absence and ice retreat timing. In contrast, we found no statistically significant difference in spring bloom maximum among the independent factors examined including ice presence/absence and ice retreat timing. Thus phytoplankton biomass is the same, but the secondary community (zooplankton species) that benefits will depend on how close timing of their spring energy-intensive needs such as reproduction and awakening from winter diapause
matches the timing of the spring bloom. Species that require an early pulse of energy will benefit from years when ice is present, but retreats in late March (conditions that tend to result in early April phytoplankton bloom). In contrast, species with a phenology timed for a late energy pulse will benefit from years with no ice (conditions that tend to result in a late May to early June bloom).

These observations also imply that climate, through its connection to the production, transport, and dissipation of sea ice has the potential to affect the success of zooplankton populations and the strength of coupling between primary production and higher trophic levels.

For example, the large crustacean zooplankton taxa *Calanus* spp. may benefit in years when ice is present after March 15, but retreats relatively early. Baier and Napp (2003) observed that spring *Calanus* concentrations in the southeastern Bering Sea were higher in cold years than in warm years, and that these individuals likely metamorphosed from naupliar to copepodite stages during the early spring bloom. They hypothesized that metamorphosis was a recruitment bottleneck and that an early spring bloom benefitted copepodite recruitment. The spring bloom occurs during April in years when ice is present, but retreats relatively early, which may promote strong recruitment of copepodes. In addition, colder winters with ice present likely reduces metabolism and lipid utilization by *Calanus* spp. and thus may promote winter survival (Coyle et al., 2011).

Recruitment of *Calanus* spp. on the eastern Bering Sea shelf is complicated, involving many different processes. Life history strategies of large crustacean zooplankton (LCZ) in the eastern Bering Sea may be able to take advantage of the oscillations between warm and cold periods, regardless of whether or not there are stanzas of multiple years of the same conditions (Overland et al., 2012). The timing of reproductive events for the *Calanus* congener *Calanus glacialis* varies between different physical and biological environments of the Arctic (Daase et al. 2013). The following scenarios were developed as a working hypothesis to explain some of the present observations and to serve as a guide for future research. In these scenarios, we simplified *Calanus* life history into four major steps: spawning, metamorphosis, accumulation of depot lipids and overwintering. These scenarios make the following assumptions: 1) the timing of spawning by *Calanus* spp. is protracted (from February to May) (Baier and Napp 2003 and references therein) and the longer that conditions are suitable, the more total eggs each individual will produce (E. Durbin, U. Rhode Island, pers. comm.); 2) early-spawned individuals enter diapause before late-spawned individuals; and 3) overwinter respiration is a function of temperature (Saumweber and Durbin 2006). The working hypothesis does not address the role of advection of individuals into or out of the area.
Case A. Cold/Ice-Replete Years

with Early Ice Retreat (Fig. 12). We hypothesize that access to under ice algae (beginning as early as mid February) increases egg production rates of early spawning *Calanus* (Runge and Ingram, 1991). Metamorphosis to the copepodite stage benefits from an early ice retreat and spring bloom production (Baier and Napp, 2003). Summer accumulation of depot lipids is dependent on summer primary and microzooplankton production (Sambrotto et al., 1986; Sherr et al., 2013; Stoecker et al., this volume).

Overwintering for individuals spawned in late winter begins relatively early and these individuals may not be able to take advantage of the fall bloom. The ability of individuals (C5 copepodites) to survive the following winter benefits from low respiration rates (RC5 copepodite = 5.66 µm 02 d-1 at -1.8 °C (see methods)) resulting from cold bottom temperatures. Reproductive output during the following year(s) is maximized when there are subsequent ice-replete years and under ice algae.

Case B. Cold/Ice-Replete Years with Late Ice Retreat. In this scenario, both early and late spawning by *Calanus* spp. females benefits, as reproduction timing coincides with either the ice algae or the spring bloom. The nauplii and copepodites from late spawning would likely develop post-spring bloom (i.e., metamorphosis is not coincident with the spring bloom), and would depend upon summer primary and microzooplankton production to grow and accumulate depot lipids. The onset of overwintering occurs latest for the late-spawned progeny which may take advantage of the fall bloom to accumulate additional lipids before entering diapause. Ability to survive the overwintering period benefits from the cold bottom temperatures present in late fall through early spring.

Figure 12. Timing of *Calanus* reproduction relative to the presence of ice and ice algae, and the spring and fall blooms. The *Calanus* life history is simplified and the timings are approximate. Black is the period of ice cover; gray is the 50th percentiles for the timing of ice retreat. White rectangles are the 50th percentile dates for bloom maximum in the spring and fall. Ice algae blooms during ice cover (solid gray line) and ice retreat (dashed gray line) and begin as early as mid-February (R. Gradinger, personal comm.). A – a cold icy year, with ice retreat shortly after March 15; B – a cold icy year with ice retreat after April 14; C - no ice after March 15.
Case C. Warm/Ice-Deplete Years. Egg production by early spawning of *Calanus* is reduced by the absence or short duration of sea ice and under ice algae. The timing of the spring bloom is late; it benefits late spawning of *Calanus* spp. females. The late spring bloom may coincide with metamorphosis of the early-spawned nauplii to copepodites, but is mismatched with the metamorphosis from the late spawners. Growth and development are dependent upon summer primary and microzooplankton production. Diapause that is delayed until after the fall bloom benefits late spawners. Warm bottom temperatures result in higher respiration rates -- 47% higher daily respiration than during cold years ($R_{C5\;\text{copepodite}} = 8.34 \; \mu m\; O_2\; d^{-1} \text{ at } 2.0 \; ^\circ C$). The impact on lipid reserves is exacerbated if the period without food (beginning of diapause to the following spring bloom) is longer in warm years relative to cold. Thus we hypothesize that survival of *Calanus* spp. over a warm winter is low relative to a cold winter. Predation losses would also likely be higher in warm winters at a given predator abundance due to higher metabolism and food requirements of fishes. Absence of sea ice for a second year results in low reproductive output by the early spawners, and a decrease in the population.

4.4.2. Connections to Higher Trophic Levels

The six to eight month variation in the fall to spring bloom interval also may contribute to the peak of the dome-shaped relationship between juvenile pollock production and sea surface temperature observed by Mueter et al. (2006, 2011) and Coyle et al. (2011). Pollock recruitment was generally high when ice retreated early and adult biomass was low (Mueter et al., 2006); we found that a six-month fall to spring bloom interval occurs in years with an early ice retreat. The likely mechanism is the relationship between early ice retreat, delayed spring bloom, and the production of large crustacean zooplankton as pollock recruitment was generally high when large crustacean zooplankton were abundant (Hunt et al., 2011). The mechanism linking secondary production and pollock recruitment has been attributed to enhanced energy content and overwinter survival of age-0 pollock during cold years when the lipid-rich, large crustacean zooplankton biomass is highest (Heintz et al., accepted).

5. Conclusions

- In the eastern Bering Sea: if ice is present after mid-March, spring bloom timing is related to ice retreat timing; if ice is absent or retreats before mid-March, a spring bloom usually occurs in May or early June.

- Spring and fall bloom strengths are related, implying that a common factor influences spring and fall primary production.
We hypothesize that large crustacean zooplankton such as *Calanus* spp. benefit from
cold, icy winters in the southeastern Bering Sea because ice algae or ice associated
phytoplankton blooms provide an early spring food source and respiration rates are lower
during cold winters.

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Marine Environmental Laboratory. The findings and conclusions in this paper are those of the
authors and do not necessarily represent the views of NOAA’s National Marine Fisheries Service
or Oceans and Atmospheric Research.

**References**

Acker, J.G., Leptoukh, G. 2007. Online analysis enhances use of NASA Earth science data. Eos,
Transactions of the American Geophysical Union 88(2): 14.

Alexander V., Niebauer, H.J.1981. Oceanography of the eastern Bering Sea ice edge zone in
spring. Limnology & Oceanography. 26: 1111-1125.


Baier, C.T., Terazaki, M. 2005. Interannual variability in a predator-prey interaction: climate,


http://www.afsc.noaa.gov/REFM/docs/2012/ecosystem.pdf


Goes, J.I., Gomes, H.R., Haugen, E., McKee, K., D’Sa, E., Chekalyuk, A.M., Stoecker, D., Stabeno, P., Saitoh, S., Sambrotto, R. This issue. Fluorescence, pigment and microscopic characterization of Bering Sea phytoplankton community structure and photosynthetic competency in the presence of a cold pool during summer. Deep-Sea Res. II.


Grebmeier, J.M., Cooper, L.W., Feder, H.M., & Sirenko, B.I. 2006. Ecosystem dynamics of the Pacific-influenced northern Bering and Chukchi Seas in the Amerasian Arctic. Prog. Oceanogr. 71: 331-361.


**Figure Caption**

Figure 1. Study area and mooring locations.

Figure 2. The relationship of mixed layer depth deepening (day) and temperature drop (day) for moorings M2 and M4. The mooring data at M5 and M8 were inadequate to compute mixed layer deepening.

Figure 3. A boxplot of ice retreat (day) by mooring. The box extends from the first quartile to the third quartile, the heavy line dividing the box is the median and the whiskers are the smallest and largest values. The number of years with ice present were 12 (M2), 15 (M4), 17 (M5) and 17 (M8).

Figure 4. Scatterplots of maximum spring bloom strength (ug Chl l⁻¹), spring bloom timing (day), minimum winter-spring temperature (day), day temperature rose above -1 °C and day ice cover fell below 15%. If ice was absent that year, then the ice retreat day is zero.

Figure 5. Scatterplots of spring bloom maximum (day) versus ice retreat (day) by mooring. If ice was absent that year, then the ice retreat date is zero. The diagonal dashed line is the 1:1 line to compare timings of spring bloom and ice retreat. The vertical dashed line is March 15.

Figure 6. Scatterplot of the observed (number) and fitted (line, based on simple linear regression, y-intercept = 53, slope = 0.66, df = 1, 24, p < 0.001) values of spring bloom maximum (day) versus ice retreat (day) for all moorings when ice was present after March 15. The number indicates mooring number.
Figure 7. A boxplot of fall overturn (day) by mooring. The box extends from the first quartile to the third quartile, the heavy line dividing the box is the median and the whiskers are the smallest and largest values. The numbers of years when fall overturn could be determined were 15 (M2), 10 (M4), 16 (M5) and 7 (M8).

Figure 8. Scatterplots of maximum fall bloom strength (ug Chl l⁻¹), fall bloom timing (day), maximum summer-fall temperature (°C), fall overturn (day) and first storm (day).

Figure 9. Scatterplots of fall bloom maximum (day) versus fall overturn (day) by mooring. The diagonal dashed line is the 1:1 line to compare timings of fall bloom maximum and fall overturn. The horizontal dashed line is August 15.

Figure 10. Scatterplot of maximum spring bloom strength (ug Chl l⁻¹) and maximum fall bloom strength. The number indicates mooring number.

Figure 11. Scatterplot of observed (number) and fitted (line, based on linear regression, intercept = 294, slope = -1.16, df = 1, 27, p < 0.001) values for all moorings. The y-axis is the interval between the spring and fall bloom maximum (days). The x-axis is the spring bloom maximum (day). The number indicates mooring number.

Figure 12. Timing of Calanus reproduction relative to the presence of ice and ice algae, and the spring and fall blooms. The Calanus life history is simplified and the timings are approximate. Black is the period of ice cover; gray is the 50th percentiles for the timing of ice retreat. White rectangles are the 50th percentile dates for bloom maximum in the spring and fall. Ice algae blooms during ice cover (solid gray line) and ice retreat (dashed gray line) and begin as early as mid-February (R. Gradinger, personal comm.). A – a cold icy year, with ice retreat shortly after March 15; B – a cold icy year with ice retreat after April 14; C - no ice after March 15.
Appendix Table 1. Annual values compiled for this manuscript; methods for compiling these values are described in the methods section. In all cases “Day” refers to Julian day. Day ice retreat: the day that percent ice cover fell below 15% (a zero value indicates that ice cover never fell below 15%); Day temp >-1 °C: the day that ocean temperature rose above -1 °C (a zero value indicates that ocean temperature never fell below -1 °C); Min WS temp: Minimum temperature during winter and spring; Day max spring bloom: Day that the chlorophyll $a$ ($\mu$g l$^{-1}$) values reached their maximum (NA indicates missing data); Max spring bloom: Maximum chlorophyll $a$ value during winter and spring; Max fall temp: Maximum temperature during summer and fall; Day first storm: first day a storm occurred during summer and fall as defined in the methods; Day overturn: first day that temperature drop indicated overturn was underway; Max SF temp: Maximum temperature during summer and fall; Day max fall bloom: Day that the chlorophyll $a$ values reached their maximum; Max fall bloom: Maximum chlorophyll $a$ value during summer and fall.
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Appendix Figure 1. Plots of chlorophyll $a$ fluorescence by mooring, year and Julian day. The x-axis is Julian day and the y-axis is chlorophyll $a$ ($\mu g \ l^{-1}$). Each plot is labeled with mooring and year. The open symbols indicate the assigned spring (circle) and fall (triangle) blooms.
Appendix Figure 2. Maps of Pearson's product moment correlations between 8-day averages of log-transformed fluorescence at four mooring sites and 8-day averages of log-transformed chlorophyll $a$ as estimated from satellite data (SeaWiFS 1998-2002, Modis Aqua 2003-2011). Black squares denote reference mooring locations for each map. Only correlations individually significant at approximately 95% are shown.
Sea ice and water column structure on the eastern Bering Sea shelf

Margaret E. Sullivan\textsuperscript{ab*}, Nancy B. Kachel\textsuperscript{ab}, Calvin W. Mordy\textsuperscript{ab}. Sigrid A. Salo\textsuperscript{b}, and Phyllis J. Stabeno\textsuperscript{b}

\textsuperscript{a}Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 3737 Brooklyn Ave NE, Box 355672, Seattle, WA 98105-5672 USA
\textsuperscript{b}Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115 USA

*Corresponding Author

7600 Sand Point Way NE,
Seattle, WA 98115 USA
msulliva@u.washington.edu,
Phone: (206) 526-6185, Fax: (206) 526-6485

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Abstract
Seasonal sea ice is a defining characteristic of the eastern Bering Sea shelf, and plays a critical role in determining the vertical structure of temperature and salinity over this shelf. This paper examines ice movement relative to local winds, and the impact of the arrival and retreat of ice on the water column at four mooring sites on the middle shelf. Ice forms primarily in coastal regions and is advected over the southern and outer shelves. Ice drift was ~2% of local wind speed and oriented 44 ° to the right of the winds (R-squared = 0.25). Measurements from 30 ice cores collected in 2006-2009 gave an average salinity of ~6, and an average nitrate concentration of ~1 µM. Time series data collected at the biophysical moorings in the Bering Sea (1995 – 2012) were used to explore the evolution of stratification under the ice. At mooring M8 in the north, the water column mixed and cooled prior to the arrival of ice, hence, little melt occurred when the ice arrived. At the other three moorings, the ocean temperature was 2 – 4 °C above freezing, resulting in extensive ice melt. The melting ice freshened and cooled the upper part of the water column. The water column remained stratified for 10 to 25 days. Mixing was a slower process under the ice than in open water. An estimated 1.3 m of ice melted with the first arrival of ice at three southern moorings and the latent heat of cooling of this ice accounted for approximately half the observed cooling. During ice retreat there appeared to be little ice melt around the southern two moorings, but an estimated 0.8 m at M5 and M8. The extent of ice melt sets up the water column for the following summer.

Keywords: Bering Sea, sea ice, ocean temperature, salinity, currents, stratification, ice melt

1. Introduction
Situated between the North Pacific and the Arctic Ocean, the eastern Bering Sea is a marginal sea ice zone. During summer it is ice free, with ice beginning to form along the coast in the northern Bering Sea as early as November (Pease, 1980). During subsequent months, the sea ice is advected southward with maximum ice extent typically occurring in March or April (Stabeno et al., 2012b). In extensive ice years, sea ice can advance more than 1000 km, which, before the extensive melting now occurring in the Arctic Ocean, was the largest ice advance in any arctic or subarctic region (Niebauer, 1998). Sea ice typically begins retreat in late winter or early spring, and by late June the Bering Sea is ice free. Pease (1980) describes the expansion of ice into the southern Bering Sea as a conveyor belt in which ice forms in polynyas in the northern Bering Sea and is advected southward by winds. Polynyas are most common off southern coastlines due to prevailing northerly winds in winter,
but they also can form when winds are southerly off northern and western coastlines (Niebauer and Schell, 1993, Niebauer et al., 1999). The St. Lawrence polynya occurs along the southern coast of St. Lawrence Island, and is a dominant ice-producing feature (Schumacher et al., 1983; Stringer and Groves, 1991; Danielson et al., 2006; Drucker et al., 2003), with ice being advected mostly south and southwestward (McNutt, 1981). The leading edge of the ice melts as it encounters warmer ocean temperatures in the south or along the shelf break (McNutt, 1981; Zhang et al., 2010).

The eastern Bering Sea continental shelf is broad (>500 km), less than 180 meters deep, and extends more than 1000 km south from Bering Strait to the Aleutian Islands. The shelf is divided into inner (water depth < 50 m), middle (~50-100 m), and outer (~100-180 m) domains (Coachman, 1986), which are separated by transition zones or fronts (Schumacher, et al., 1979; Stabeno, et al., 2001; Kachel, et al., 2002). Ice typically appears first in the coastal domain, and latest in the outer domain. On average, sea ice covers the middle shelf north of 58 °N for five months each year, with ice persisting, on average, for less than one month on the southern shelf (south of 57 °N) (Stabeno et al., 2012a).

These north-south differences in timing of ice retreat and advance, together with a north (weaker) – south (stronger) gradient in tidal energy, result in distinct differences in the water column structure on the northern and southern shelves during the summer (Stabeno et al., 2012a). The northern shelf with its more extensive and persistent ice cover remains cold until solar input warms the ocean, initiates ice melt and sets up summer stratification. This results in a warmer, fresher surface layer overlaying a colder, saltier bottom layer separated by a ~10 m interface. The cold bottom layer (< 2 °C) over the middle shelf is known as the cold pool, and remains largely well mixed due to the tides. Ice retreat in the south typically occurs in March or April with southerly winds, when winds are usually still strong enough to mix the water column (Stabeno et al, 2010). The water column becomes thermally stratified when winds weaken and solar insolation increases (Stabeno et al, 2007). In years with extensive ice in March or April, the bottom temperatures in ice-covered areas in the south are < 2 °C, and part of the cold pool (Wyllie-Echeverria, et al., 1998; Stabeno et al., 2012b). During years when the sea ice does not extend onto the southern shelf, the bottom temperatures remain above 2 °C, and the cold pool exists only over the northern shelf (Stabeno et al., 2012a,b).

The presence or absence of sea ice impacts spatial and temporal variability of biological production across the shelf and slope (Stabeno et al., 2012a,b; Sigler, et al., this volume). Constituents of sea ice, including iron and phytoplankton, are advected southward, and influence the amount and fate of spring production (Aguilar-Islas et al., 2008; Schadelmeier and...
Alexander, 1981). In addition, sea ice impacts the timing of the spring phytoplankton bloom, with a bloom occurring under the ice if ice is present after mid-March, and an open-water bloom occurring in May or June if no ice is present after mid-March (Brown and Arrigo, 2013; Stabeno et al., 2012a; Sigler et al., this volume). Vertical stratification of the water column is important to

![Image](https://via.placeholder.com/150)

**Figure 12.** a) A MODIS True-Color image is combined with MODIS sea surface temperature in the eastern Bering Sea for March 11 - 13, 2007. The large, red letters indicate the following: A polynyas; B heavy ice; and C cloud cover. b) A shelf map showing distribution of ice sampling sites per year (2006-2009), and the bathymetry. The four mooring locations (M2, M4, M5, M8) and geographic names are indicated in both panels.

Support under-ice phytoplankton blooms (Alexander and Niebauer, 1981; Mundy et al., 2009). The southern extent of the cold pool and the timing of spring primary production influence the food chain and higher trophic level predator-prey relationships for the following 6 - 8 months (Sigler et al., this volume), and over longer time scales (Mueter and Litzow, 2008).

The purpose of this paper is to examine the impact of sea ice on the vertical structure of the water column. Measurements from satellites, ice cores and four long-term biophysical moorings distributed along the 70-m isobath from 56.9 °N to 62 °N were used to determine the rate and direction of ice movement, the arrival of ice at moorings, and the extent of ice melt and resulting stratification at each of the mooring sites (Fig. 1). First, the rate and direction of ice movement in
the region were calculated using satellite images. Next, the characteristics of 30 ice cores collected from 2006 – 2009 are presented. Using time series of temperature, salinity and currents from the biophysical moorings (M2, M4, M5 and M8; Fig. 1), the impact of sea ice on the water column structure is examined. Using selected time series from the ~42 yearly records, the thickness of the ice melted at the mooring sites is estimated.

2. Methods

2.1. Satellite Data

Satellite measurements of ocean color and sea surface temperature (SST) were obtained using MODIS (Moderate Resolution Imaging Spectroradiometer) data files from the ocean color website at NASA (http://oceancolor.gsfc.nasa.gov, assessed 2012). SeaDAS, a suite of programs created and maintained by NASA, was used to map true-color and SST images. Individual floes were identified in a series of true-color images and tracked from one image to another, until they were no longer recognizable (Holt, et al, 1992, Leberl, et al, 1983). Ocean color and SST observations cannot be made through clouds, severely limiting the number of useful MODIS images from the Bering Sea. In addition, increased cloud cover is associated with southerly winds, so the set of floes that were tracked were biased against times when southerly winds were prevalent. This limited the analysis to years with a sufficient number of clear days to follow a floe over a period of time, and to larger floes in regions where horizontal shear was weak enough not to deform the floes.

For 2002–2011, ice concentration data from the AMSR_E (Advanced Microwave Scanning Radiometer-Earth Observing System) sensor aboard the MODIS Aqua satellite were downloaded from the National Snow and Ice Data Center website (http://nsidc.org/data/amsre/, assessed 2012; Cavalieri et al., 2003). Ice concentrations from the NASA Special Sensor Microwave Imager (http://nsidc.org/data/docs/daac/ssmi_instrument.gd.html; Maslanik and Stroeve, 1999) were used for fall 1994–2002 to extend the time span prior to the start date of AMSR-E data. Daily-mean ice concentration values were used in this paper. The data were used to calculate mean daily ice concentrations within boxes centered on the four moorings (M2, M4, M5, and M8 in Fig. 1). The grid size of the ice data is approximately 12.5 km × 12.5 km. Following Stabeno et al. (2012a) we used 100 km × 100 km boxes.

2.2 Wind stress and winds
2 uses a state-of-the-art analysis/forecast system to perform data assimilation with data ranging from January 1979 to August 2012 (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/; Kanamitsu et al., 2002), and is an update to the NCEP/NCAR (National Center for Atmospheric Research) reanalysis. Six-hourly wind and wind-stress data were extracted from the NCEP Reanalysis 2 at the grid points nearest to the four mooring locations. NCEP Reanalysis 2 data were obtained from the website maintained by NOAA Earth System Research Laboratory, Physical Sciences Division in Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). NCEP winds are well correlated with the observed winds in the Bering Sea (Ladd and Bond, 2002).

QuikSCAT wind data were downloaded from the Jet Propulsion Laboratory, Physical Oceanography Distributed Active Archive Center (http://podaac.jpl.nasa.gov). Scatterometer winds are derived from ripple patterns on the surface of the ocean, and are therefore limited to ice-free areas. Although the instrument sees through clouds, measurements are affected by heavy rain. The records identify pixels where rain was suspected, and these records were excluded from our analysis. Grid spacing for QuikSCAT winds is 12.5 km (0.25 ° longitude), but the data were binned into 2° bins for regional plots.

2.3. Ice core measurements

During four springs (2006-2009), a total of 30 ice cores were collected by NOAA scientists from floes distributed over the eastern Bering Sea shelf (Fig. 1b). In 2006, three floes were sampled on the R/V Thomas G. Thompson (Cruise TN193). The Thompson had limited maneuverability in the ice, so sampling was restricted to floes at the ice edge. Cruises in 2007-2009 were conducted on the icebreaker, U.S. Coast Guard Cutter Healy as part of the Bering Sea Project (http://bsierp.nprb.org/). The Healy is capable of breaking 1.4 meters of ice at 3 knots continuously, and 2.4 meters by backing and ramming. This permitted sampling deep into the pack-ice in water depths between 30 and 100 meters.

Floes were chosen for accessibility and for ease of data collection. Sampling was biased against ice that was too thin to walk on or highly rafted, and to times when air temperature was above -15 °C. All samples were taken in spring when both melting and refreezing were prevalent. In 2006, the three ice stations were located along the ice edge in the outer domain, while the seven stations in 2007, the 11 in 2008, and the nine in 2009 were mostly located deeper within the ice field in the middle domain north of 58 °N (Fig. 1b; Table 1).

At most sites, air temperature, freeboard, ice thickness, and snow cover were recorded; coordinates were recorded at the beginning and end of each site visit using a GPS unit. All cores
were obtained using a Kovacs Mark-II, 9-cm diameter, 1.15-meter-long ice corer driven by an attachable gas engine. Cores were positioned on a black plastic surface, then measured and photographed. Top and bottom conditions and banding were noted. Small holes were drilled and temperatures were recorded every 10 cm along the core using either an Oakton Acorn or an Omega thermometer. All cores were sliced into 10-cm sections and double-bagged for later analysis. On the ship, sections from each core were thawed in the dark. Volume of the melt water was measured and then sub-sampled to measure salinity, and nutrient concentrations. Salinities were measured at sea using a salinometer referenced against IAPSO standard water. Ice density was determined from the dimensions of each ice core, and the volume and density of the ice melt.

Samples for nutrient analysis were filtered using syringe with 0.45 μm cellulose acetate membranes, and collected in 30 ml acid washed, high-density polyethylene bottles after being rinsed three times with sample water. Samples were analyzed shipboard within 1 - 12 hrs of collection. Nitrate and nitrite concentrations were determined using a combination of analytical components from Alpkem, Perstorp and Technicon. WOCE-JGOFS standardization and analysis procedures specified by Gordon et al. (1994) were followed, including reagent preparation, calibration of labware, preparation of primary and secondary standards, and corrections for blanks and refractive index.

For determination of chlorophyll and phaeopigment content a second core was taken at the sites, and sections of ice were melted in ~1.5 times the ice volume in filtered seawater to prevent cell lysis. Sub-samples (~50 ml) were filtered through Whatman GF/C filters, and the filters were frozen at -80 °C, remaining frozen until analysis several months later. Pigments were extracted in cold 90% acetone in the dark for 24 hrs, and determined using a calibrated fluorometer according to Strickland and Parsons (1968).

2.4. Moorings

Four biophysical mooring sites (M2, M4, M5, and M8) are the cardinal locations of the Bering Sea biophysical observing network (Fig. 1). When possible, the moorings are recovered and redeployed twice a year, once in the spring (April/May) and again in the late summer or early fall (September/October). During years with extensive ice, M8 and sometimes M5 were only recovered/deployed in September. Moorings at the M2 site have been maintained almost continually since 1995, while moorings have been deployed at M4 since 1996 (continuously since 2000), at M5 since 2005 and at M8 since 2004. At the writing of this manuscript, these moorings provided 42 fall-through-spring sets of time series describing water column conditions.

4 Use of trade names does not constitute an endorsement by NOAA
Data collected by instruments on the moorings included temperature (miniature temperature recorders, SeaBird SBE-37 and SBE-39) and salinity (SBE-37). Currents were measured using an upward-looking, bottom-mounted, 300 or 600 kHz Teledyne RD Instruments acoustic Doppler current profiler (ADCP) deployed within 500 m of the main mooring. All instruments were calibrated prior to deployment, and the data were processed according to manufacturers’ specifications. The main mooring “line” at each site was chain and the instruments were mounted in-line in metal frames. Such construction is necessary to reduce the chances of losing the mooring due to sea ice and heavy fishing pressure in the region.

Sampling intervals varied among the different instruments and ranged from 10 to 60 minutes. Small data gaps (< 1 day) were filled using linear interpolation or spectral methods. Unless otherwise noted, data presented here have been filtered using a 35-hour, cosine squared, tapered Lanczos filter to remove semidiurnal and diurnal tidal signals, and re-sampled to 6-hour intervals.

The top instrument at each mooring was at a depth between 1 and 20 m. When the mixed layer was deeper than the depth of the top instrument, the data from the top instrument could be reliably extrapolated to the surface (Stabeno et al., 2007). However, when the top instrument was below ~20 m and the ice had retreated from the mooring in the spring, the mixed layer was usually shallower than the top instrument and there was no reliable way of estimating localized near-surface temperatures.

2.5. Calculation of volume of ice melt

Estimates of magnitude of ice melt can be made at the mooring sites from the change in salinity in the water column using the following equation:

\[ h_w S_t + (H-h_w) S_w = H S_f \]  

or

Figure 13. Change in ice concentration (color filled) associated with 2-day mean QuikSCAT winds (vectors) are shown for three time periods: a) February 21 - 23, 2003; b) March 2 - 3, 2003; and c) March 12 - 13, 2003.
where \( h_w \) is the thickness of water resulting from ice melt, \( S_i \) the salinity of the ice, \( H \) the depth of
the upper mixed layer (which may be the whole water column), \( S_w \) the initial salinity of the water
column and \( S_f \) the final salinity of the water column. This is an approximation, since an
introduced piece of ice does not melt completely, but rather the ice is advected over the water,
with only a portion of it melting at that location. When the water reaches the freezing point, there
is no further net melting of the ice.

The thickness of the ice melted, \( h_i \), was calculated using \( h_i = \frac{h_w \rho_w}{\rho_i} \), where \( \rho_w \) is the
density of water and \( \rho_i \) is the density of ice. Using the value of \( h_w \) calculated from salinity, the
change in temperature of the water column per unit area due to latent heat can be calculated using
the following equation

\[
\Delta T \text{ per unit area} = L \frac{h_i}{\rho_i}
\]

where \( L \) is the latent heat of fusion of sea ice and \( T \) is
temperature.

3. Results and Discussion
3.1. Satellite floe-tracking and winds

Ice in the Bering Sea can be broadly
characterized using true-color satellite imagery from
which polynyas (dark shadows leeward of the
coastline), thin ice (gray, often seaward of the open
water of the polynya), and thicker ice (white) can be
identified (Fig. 1a). Ice conditions, including the
location of polynyas and the direction and extent of
ice advance, can change rapidly and are largely forced
by winds (Fig. 2). For example, in late February 2003,
northeasterly winds near Siberia and easterly winds
off the Alaskan coast reduced the ice concentration
near Siberia, St. Lawrence Island, and the Alaskan
coast (Fig. 2a). Nine days later, southerly winds over
the eastern shelf resulted in ice edge retreat in the east

\[
h_w = H (S_w - S_f) / (S_w - S_i)
\]
and compression of the ice along those coastlines (Fig. 2b). In mid-March, northerly winds opened polynyas in the north, advanced the ice edge, and increased the ice concentration at the ice edge (Fig. 2c).

Floe trajectories obtained from true-color satellite images are shown for 2003 and 2007 (Fig. 3), a warm and a cold year, respectively (Stabeno et al., 2012b). These trajectories are primarily from advancing ice. While many floes could only be tracked for a few days, several were tracked for 1–2 weeks while they moved southward more than 100 km. The maps from both years show a corridor in which ice floes moved from the shelf north and east of St. Lawrence Island through Shpanberg Strait, with more westward ice motion in 2003 than 2007 as floes moved beyond Shpanberg Strait. These observations are similar to the conveyor belt corridor observations in Pease (1980). With southerly winds, ice produced from a polynya north of Nunivak Island could also contribute to the conveyor belt corridor (Figs. 2 and 3a). South of the Chukotka Peninsula, floes moved eastward with prevailing currents (Danielson, 2000), and those nearest the coast continued north through Anadyr Strait. A few floes originating southwest of St. Lawrence were tracked to M8 (Fig. 3).

These floe trajectories were used to infer the origin of ice in each of the four mooring areas (Figs. 1 and 3). The origin of the ice at M8 was a combination of ice from the conveyor belt and from the polynya south of St. Lawrence Island (McNutt, 1981; Schumacher et al., 1983), and occasionally Anadyr Strait (Schumacher, et al., 1983). M4 and M5 locations were directly influenced by ice from the conveyor belt corridor (Muench and Ahlnas, 1976; Pease, 1980). The area around M2 was outside the dominant influence of the conveyor belt corridor, and subject to ice formation from polynyas south of Nunivak Island and along the northern Bristol Bay coast during northerly or northeasterly winds.

Tracked floes, which had typical speeds of 0.1 to 0.3 m s\(^{-1}\), were influenced by both winds and currents. These findings are comparable to earlier observations (Shapiro and Burns, 1975; Muench and Ahlnas, 1976; McNutt, 1981; Weeks and Weller, 1984), as well as results from a recent ice model (Zhang et al, 2010), but slower than

Figure 15. Wind vector plots, from 6-hourly NCEP-2 Reanalysis data centered at mooring site M4, for the cold seasons of a) 2005 – 2006 and b) 2006 – 2007. Northward is upward. Ice extent in the 100-km x 100-km around M4 is included as a blue line.
the 0.5 m s⁻¹ average reported by Pease (1980) and the 0.45 m s⁻¹ average reported by Macklin et al. (1984). Ice drift was compared to NCEP2 winds interpolated in space and time, and found to be ~2% of local wind speed (n = 440), and oriented 44° to the right of the wind direction with an R-squared value of 0.25, which is higher than the findings of Macklin et al. (1984).

While wind largely controls the movement of sea ice (Figs. 2, 3), the timing of storms is also important. The influence of wind events on ice formation varied dependent upon the season. Northerly winds during active freeze-up (January into March) created more ice than similar winds would have generated during warming (mid April to May). Nonetheless, northerly winds later in the season could prolong ice cover by continuing to transport ice southward. For example, in the winter of 2005-2006, northerly winds in December and January (Fig. 4a) pushed the ice to its most southern extent in late January. This was in spite of the fact that water column was ~2.8 °C. The next episode of sustained northerly winds did not occur until mid-April (initial water temperature of 0.5 °C), and although the ice advanced at this time, the ice edge did not regain its earlier position, because the increase solar insolation. At the beginning of April the water column warmed from -1 °C to >0 °C. In contrast, during the winter of 2006 – 2007, there were several storms in December and January (Fig. 4b), but the longest period of northerly winds was during March and April, and sea ice reached its maximum extent in late March (Rodionov et al., 2007). The water column cooled in early March (from 1.1 C to -1.7 °C) and did not begin warming until the ice began retreating.

3.2. Sea-ice cores

Thirty ice stations were sampled on the eastern Bering Sea shelf in April and early May on four cruises between 2006 and 2009 (Fig. 1b). Ice thickness ranged from 37 to 127 cm with a single outlier of >329 cm of rafted ice at an inner domain station (Table 1). Mean ice thickness was calculated excluding this outlier. Surface water from nearby hydrographic casts had mean salinity of 31.9, mean water temperature of -1.7 °C, and mean nitrate of 10.2 µM. Salinities in the ice were low (mean ~6, Table 1), reflecting brine rejection during ice formation and brine drainage. There was considerable variability in the shapes of the
salinity profiles (Fig. 5c). Some salinity profiles showed the well-defined C-shape (e.g., green line, Fig. 5c) of marginal ice zones and young ice (Malmgren, 1927, Eicken, 2003). Another common pattern was a double C-shape (e.g., red line, Fig. 5c), often a result of rafting. Mean ice density was $0.89 \pm 0.03 \times 10^3$ kg m$^{-3}$, which is in agreement with the Table 1 summary in Timco and Frederking (1996). Nutrient concentrations were low in the ice cores (mean nitrate ~1 µM), suggesting that ice was not a conveyor of macro nutrients in the Bering Sea. Melting sea ice, however, does provide a significant contribution of iron to the water column (Aguilar-Islas et al., 2008).

Horizontal banding was evident in the ice cores and often, dark coloration occurred at the ice-water interface (Fig. 5). Some banding was correlated with elevated chlorophyll-a and phaeopigments, while in other cores the banding appeared to be sediment. Highest chlorophyll concentrations were most commonly found in the bottom section of each ice core. For example, in 2009, bottom chlorophyll was as high as 209 µg l$^{-1}$, with an average of ~80 µg l$^{-1}$ which was approximately 20 times greater than the average concentration (4 µg l$^{-1}$) found in the rest of the core slices. Mean snow depth on floes was variable, but generally less than 10 cm (Table 1).

3.3. Influence of sea ice on the water column

Typically, the depth-averaged water column temperature reaches a maximum in September (Stabeno et al., 2012a, b), when the mixed layer begins to deepen. In examining the 18 years of data at M2, the depth-averaged temperature is almost as warm in August as in September, and usually the water column has not mixed. Temperature data from August are used to represent maximum summer near-surface temperature. During August, the mixed layer is usually 20-30 m deep. The highest mean August near-surface temperature was 12.5 °C (M2, 2002, a warm year) and the lowest monthly mean bottom temperature was -1.7 °C (M8, 2009, a cold year) (Table 2). The differences between monthly mean surface and bottom temperatures in August range from 5.2 to 10.8 °C.
Figure 6. Time series from M2 showing a) wind stress, b) temperature at 12 depths distributed through the water column, and c) salinity at four depths. The breaks in the time series (b and c) occurred when the winter mooring was replaced by the summer mooring. The gray shading indicates times when the water column was well mixed. There was no ice cover at M2 during this period.
The time at which the water column became well mixed varied from north to south (Table 2), with M8 remaining stratified the longest of the four mooring areas. At M8 during summer, both temperature and salinity contribute equally to stratification, while at the southern moorings stratification is controlled by temperature. Since the vertical differences in temperature are similar north-to-south, the stratification is almost twice as strong at M8 than at the other mooring sites (Stabeno et al., 2010, 2012a; Ladd and Stabeno, 2012), thus delaying mixing.

While there is considerable information on the timing and characteristics of ice retreat and melting (Alexander and Niebauer, 1981; Hunt and Stabeno, 2002; Stabeno et al., 1998; Stabeno et al., 2012b), less is known about the short-term response of the water column to melting sea ice. Instruments at each of the four biophysical moorings in the Bering Sea have measured temperature, salinity and currents in the water column as ice was advected over the moorings. In total, there were 42 sets of data showing the water column response to the ice. Several patterns were evident in the time series at the various moorings. To explore these patterns, seven examples were selected (two from M2, three from M4, one each from M5 and M8).

3.3.1. No ice (Example: M2, autumn 2004 – spring 2005)

From 1995 to the present, there was little (areal coverage of < 20% concentration) or no ice present for five years of observations at M2 and two years at M4. Data from these seven examples show how the water column mixes, cools and becomes more saline without the influence of ice. In October 2004, the water column at M2 was cooling and mixing (Fig. 6).
From a mean August surface temperature of 12.5 °C and mean bottom temperature of 3.2 °C (not shown), the water column became well mixed at 5.7 °C at the end of October. The mean wind stress during the fall of 2004 (mean 0.23 N m⁻²) was not significantly stronger than the long-term (1995 – 2012) mean (0.20 N m⁻²). The water column remained well-mixed through the winter until April 8, with the bottom temperature reaching a minimum of ~2.0 °C in mid April. Minimum water-column temperature in 2004 was anomalously high, and was surpassed by only two other warm-years: January, 2001 (3.0 °C) and January, 2003 (3.4 °C). All three instances are from an unusually warm period, 2001 to 2005 (Stabeno et al., 2012b). Mean minimum winter temperature from 1995 to 2011 at M2 was -0.6 °C, while the mean for the nine years excluding this warm window (2001 – 2005) was -1.7 °C (Table 2). Salinity increased from ~31.7 in early October to ~32.3 in mid February most likely from advection, of more saline water from the outer shelf and slope (Sullivan et al., 2008).

3.3.2. A single ice event (Example: M2, fall 2007 – spring 2008)

During the winter and spring 2007 ice was present near M2 for approximately one month (Fig. 7). During this period, winds were moderate, with isolated storms interspersed with periods of weak winds. The water column became well mixed (defined as when the vertical temperature difference was < 0.04 °C, and the salinity difference was < 0.02) at 3.6 °C in mid November, 2006 (not shown). Ice arrived in the vicinity of the mooring on March 2, and four days later, as the ice coverage reached ~20%, the water column began to stratify with colder, fresher water overlying warmer, saltier water. The top 39 m of the water column cooled to the freezing point (-1.7 °C) by mid March and ice melt freshened the surface salinity by ~0.5. The water column remained stratified for ~20 days. There were four moderate storms during the ice period (Fig. 7, top, 1 – 4). The first storm

Figure 7. Time series from M2, February 27 – April 17, 2007, showing a) wind stress, b) temperature at 12 depths distributed through the water column and the percent areal ice cover in the 100-km x 100-km box around M2, and c) salinity at three depths. The gray shading indicates times when the water column was well mixed.
(March 6-9) coincided with the arrival of the ice; the second (March 18-22) occurred during a period of >90% ice cover; and the third (March 25 – 27) occurred during a period of decreasing ice. The second storm coincided with a slight mixing at 39 – 44 m and the third event resulted in the total mixing of the water column. The primary cause of the greater mixing associated with the third storm, which was only slightly stronger than the second, was likely reduced ice cover. Less areal ice cover permits the more rapid movement of ice floes and also greater direct energy transfer between the atmosphere and the water.

The duration and ice concentration at M2 in 2007 (Fig. 7) typified ice coverage in the south. Ice cover at M2 is more variable, has lower areal concentration and persists for shorter periods of time than at the other three mooring areas (Stabeno et al., 2012a). M2 is outside the direct path of the ice conveyor belt corridor and it is likely that ice near M2 arrived from Nunivak Island and the coastal polynya to the east. Over 17 year period (late winter 1995 to spring, 2011), single winter ice events occurred 6 times at M2 (lasting 20 - 83 days) and 7 times at M4 (lasting 11 - 121 days).

3.3.3. Multiple ice events with incomplete mixing (Example: M4, fall 2010 – spring 2011)

During some years, ice can be intermittent, with ice advancing and retreating several times during the cold season (December – May). The winter and spring of 2011 was such a season at M4. The water column became well mixed at ~1.7 °C in late November 2010 (not shown) and was still well mixed when northerly winds forced the ice over the mooring on January 20 (Fig. 8). Strong winds kept the water column well mixed as the ice cooled and freshened the water. The ice persisted for approximately one week and then retreated with southeasterly winds. Following this initial ice advance and retreat, the winds remained variable, forcing four major ice events over the next three months. As expected, periods of northerly or northeasterly winds resulted in ice advancing, while periods of southerly winds resulted in ice retreat. Maximum areal ice concentration remained below 70%, except for the final ice event.

While variable, salinity (especially at 31 m) generally increased from January into late March in spite of the melting ice evidenced by the cooling of the surface waters. Large freshening events (> 0.3) of the complete water column occurred (e.g., early March, early April), but freshening of just the surface waters (from ice melt) occurred more often. The greatest decrease in salinity (0.6) occurred in late April when ice concentrations approached 100%. The
Figure 8. Time series from M4, January 19 – May 1, 2011, showing a) 6-hourly wind stress, b) 12-hourly wind velocity, c) temperature at 16 depths distributed through the water column and the percent areal ice cover in the 100-km x 100-km box around M4, and d) salinity at three depths. The gray shading indicates times when the water column was well mixed. Asterisks (*) indicate periods of increased temperature and salinity, likely a result of advection. Two storms are indicated in each panel by a red bar.
temperature time series showed recurring, albeit weak, stratification (< 1.5 °C difference between top and bottom), interspersed with well-mixed periods (Fig. 8, gray shading). The cooling and freshening of the upper 20 - 27 m of water with the advent of ice was similar to the event described at M2 in 2007 (Fig. 7). The water column began mixing after each ice retreat and was usually well mixed before the next arrival of ice, only to become stratified again. The two wind events (A and B in Fig. 8 a) were similar in magnitude. During the first storm the water column was uniformly stratified (Fig. 8c; ~1 °C in temperature, 0.3 in salinity). The winds during the first storm mixed the water column, but not completely. During the second storm, the water column mixed completely. Wind mixing became most effective in both cases when ice concentration fell below 30%.

The bottom temperatures often warmed after mixing episodes (Fig. 8b), an indication of advection. Similarly the 0.7 increase in salinity from mid January through late March was also indicative of advection. Mean winter currents at M4 are southward (Stabeno et al., 2010).

Currents, which flow north along the 100-m isobath, can circle around St. Paul Island (Sullivan et al., 2008) and advect warmer, more saline water onto the middle-shelf near M4.

Multiple instances of ice advance and retreat (>2 events per year) were not uncommon at the southern moorings: 4 of 17 years at M2; 1 of 17 at M4; and 3 of 17 at M5. The example discussed here (Fig. 8) had the most ice events. This example, with a persistent series of
advances and retreats, serves as a good example of both wind and advection influencing ice melt and winter stratification events.

3.3.4. A cold year with persistent ice (Example: M4, fall 2007 – spring 2008)

During 2007-2008 (both cold years, Stabeno et al., 2012b), the water column became well mixed on November 15 at 2.8 °C and cooled to -0.4 °C by January 13 (not shown). Ice reached the area in early February coincident with strong winds (Fig. 9). The water column was well mixed for 3 - 4 days in early February, and then became stratified as winds weakened and ice concentration increased to > 20%. The ice-covered water column became well mixed again in late February and remained well mixed or weakly stratified until late March. Once again, there are strong indications that advection played a role in stratifying the water column. In both early February and late March there was a marked increase in temperature and salinity below 40 m, while the temperature and salinity in the upper water column remained relatively constant. Low-pass filtered, near-bottom currents during the February event were > 15 cm s⁻¹ from the south. During the March event, currents were variable and relatively weak (< 10 cm s⁻¹) (Fig. 9 d, e). While the daily mean currents were relatively weak in mid-March (Fig. 9), the tidal currents were significantly stronger, regularly exceeding 40 cm s⁻¹ (Fig. 10).

The first and second increase in bottom temperature and salinity occurred when the currents began to turn eastward. Once the boundary (front) between the warmer, more saline bottom water and the cooler, fresher bottom water passed the mooring, the relationship between the events and the direction of the current became complex. Bottom frontal structures are often not straight lines, but rather are crooked, sometimes following the bottom bathymetry. The low-pass filtered data show a relatively steady increase in stratification in late March (Fig. 9b, c), but the unfiltered data show that the

Figure 10. Hourly time series at M4 of a) temperature at 12 depths, b) hourly salinity at three depths, and hourly current velocity at c) 11 m and d) 55 m. The 2008 time period shown is the same as that indicated by the red bars in Fig. 9. The blue shading indicates periods when the bottom currents have a northward component. Northward is upward.
increase in stratification occurred as a series of events related to the tidal currents. That the surface temperatures remain near freezing is not surprising since there was ~100% ice cover in the 100-km x 100-km box around M4 keeping the upper water column cold and fresh.

3.3.5. Two ice events, one stratified and one well mixed (Example: M5, 2005 – 2006)

During the cold season of 2005 – 2006 extensive ice arrived at M5 in December and finally departed in early June. Four periods of strong ice retreat occurred over this time (Fig. 11). The water column became fully mixed in early November at ~3.1 °C (not shown), and remained so until mid December when ice cover reached ~30%. Two distinct periods of > 90% ice concentration occurred. During the first ice event, late December through late February, the winds were relatively weak for the first 6 weeks and strengthened for the last 2 weeks. In contrast, during the second ice event, the winds were stronger during the first 5 weeks and weaker during the last 2 – 3 weeks. Ice, combined with low wind stress during the first ice event, cooled and freshened only the upper water column (upper 24 – 42 m) without greatly impacting the deeper water. The sharp increase in bottom salinity in early February, and the accompanying increase in temperature was likely due to advection. Areal ice concentration fell to <30% in late February, and under the influence of relatively strong winds, the water mixed. The storms on February 12 with >50% ice cover had little impact mixing the water column, while a week later after the ice began retreating, winds of similar magnitude readily mixed the water column. A second large influx of ice occurred in mid-March. In sharp contrast to the first event, the water column remained largely well mixed through two months of 60-90% ice concentration. During this time the temperature (~ -1.8 °C) and the salinity (~ 31.8) remained relatively constant. That the water column temperature was at the freezing point with constant salinity supports the conclusion that there was little net ice melt during the second ice event.

Figure 11. Time series from M5, December 14, 2005 – May 31, 2006, showing a) wind stress, b) temperature at 11 depths distributed through the water column and the percent areal ice cover in the 100-km x 100-km box around M5, and c) salinity at three depths. The gray shading indicates times when the water column was well mixed.
M5, similar to M4, is solidly within the ice conveyor belt (Fig. 1). Ice cover was often 80-100%, either steadily retaining a high concentration of ice all season, or partially retreating for periods of days to weeks and returning to a high concentration. Areal ice concentration data at M4 show five years of the single ice event, and 10 years of multiple ice events for the period fall 1994 – spring 2011. As such, the cold season of 2005 – 2006 was fairly typical at M5.

3.3.6. Months of ~100% ice cover (Example: M8, 2008 – 2009)

M8 is the farthest north of the four moorings (Fig. 1), and representative of the northern shelf (Stabeno et al., 2012a). The water column at M8 from 2005-2011 mixed notably later (early December to late January) and at colder temperatures (average -1.0 °C) than at M2, M4, or M5 (Table 2). The average minimum winter temperature over those years was -1.8 °C, which was colder than at the southern moorings as a result of higher salinity. In 2008 the water column became well mixed at -0.1 °C in early December (Fig. 12). Sea ice arrived in late December and stratified the water column for a few days until the water column cooled to < -1.7 °C. The high areal ice cover (>90%) and a well-mixed or weakly stratified water column persisted for ~165 days. Surface water began to warm and stratify ahead of May ice melt, and ice concentration was < 20% by the end of May, 2009.

The patterns of strong pre-ice cooling, minimal ice melt, minimal decrease in water temperature, and areal ice concentrations >80% for more than 4 months were typical at M8. The duration of ice cover (Fig. 12) was typical for the period (1995 – 2011) for the northern shelf. Over the 17-year period, ice was present an average of 127 days, with the longest single, near-100% ice concentration event lasting 189 days in 2005 – 2006. Twelve years of the 17 years

Figure 12. Time series from M8, November 15, 2008 – June 30, 2009, showing a) wind stress, b) temperature at 11 depths distributed through the water column and the percent areal ice cover in the 100-km x 100-km box around M8, and c) salinity at three depths. The gray shading indicates times when the water column was well mixed.
examined had only one ice event (80 – 100% coverage) during the cold season, and the remaining five had two.

3.4 Estimating the magnitude of ice melt and its direct influence on temperature

The thickness of the total ice melt can be estimated using the time series from the moorings and Equations (2) and (3). The largest problem with selecting data for this calculation was advection. Care was made in selecting examples where freshening was well defined and advection did not play an important role in modifying the water column. Of the 42 sets of winter and spring data (1995 – 2012), 15 sets were suitable for this calculation (Table 3). For each of these data sets the water column was well mixed at the time of the ice’s arrival; the water column (or at least the upper layer) cooled to the freezing point within a month of ice arrival; and there was measurable cooling and freshening of the water column. Advection did not appear to influence the system in these selected instances.

Among the 14 annual examples (the two sets from M2, 2009 were combined together to provide total cooling for that year) most were from the southern moorings with only three from M5 and none from M8. The lack of examples from M8 was primarily because the water column was already at or near the freezing point when ice first appeared at that mooring site and any stratification resulting from the arrival of ice was minimal and short lived.

From each of the examples, the average initial salinity ($S_w$) and initial ocean temperature ($T_w$) were determined (Table 3). After the arrival of ice, the water column often became stratified and then re-mixed to a depth of $H$. Usually it mixed to the bottom, but in certain instances only the surface was mixed before the retreat of ice. The change in salinity and temperature of this mixed layer was calculated. Using Equation (2) and an ice salinity of 6 (Table 1), $h_w$ was calculated. Using the mean density ($0.89 \times 10^3$ kg m$^{-3}$) from Table 1 the thickness ($h_i$) of ice melted was estimated for each data set, giving a mean thickness of 1.3 m. At -1.7 °C and a salinity of 6, the latent heat of fusion of sea ice (L) is 65 cal g$^{-1}$ (Weeks and Weller, 1984). Using Eq. 3, the change in temperature due to the latent heat of fusion ($\Delta T_i$) was calculated for each example (Table 3). The latent heat of fusion accounted for an estimated 26-100 % of total observed cooling. On average almost half of the cooling of the water column was due solely to ice melt; the remainder was from air-sea interaction either directly or through the ice. A similar estimate can be made when ice melted in place in the spring (Table 4). At the southern moorings most ice retreated through advection. At the northern two moorings, however, often there was a sharp decrease in salinity associated with loss of sea ice. This decrease in salinity resulted in a fresh surface layer with a mean depth of 28 m (Table 4). This fresh water
layer persists at M8 throughout the summer season (Stabeno et al., 2012a). The estimated amount of ice melted ranged from 0.31 m to 1.51 m, with an average of 0.84 m. The balance between atmospheric warming and cooling due to ice melt (latent heat) resulted in the upper-layer temperature remaining cold.

In the winter, the arrival of ice freshened and cooled the southern shelf, while in spring the retreat of ice freshened the northern shelf. These estimates of ice melt are probably underestimates, because ice melt resulting from the advection of warmer water was not included and numerous minimal changes in temperature/salinity were also neglected. The estimation that >1.3 m of ice melted over the middle domain of the southern shelf could not be used to calculate the total ice melt over the southern shelf. Once the water column reached the freezing point, ice continued to be transported southward without modifying the water column and melted at the leading edge often over the slope.

4. Summary and Conclusions

While variability in the winds resulted in sudden changes in the distribution and areal concentration of the ice over the cold season, the winds were primarily from the north resulting in the creation of polynyas along the leeward coasts and a south- or southwestward transport of sea ice over the Bering Sea shelf. The wind-driven conveyor belt of Pease (1980) originated north-northeast of St. Lawrence Island fanning south and westward over the shelf. This main corridor provided ice primarily to the areas around moorings M4 and M5. The St. Lawrence polynya and the region around Anadyr contributed ice to the area around M8. Finally, the Alaskan coastal polynyas in Bristol Bay and south of Nunivak Island were the primary suppliers to sea ice in the vicinity of M2.

The moorings extend along the 70-m isobath of the middle shelf, with M8 on the northern shelf, M5 in the transition zone between north and south, and M2 and M4 on the southern shelf. Thus, examining data from these moorings gives insight on how the middle shelf responded spatially and temporally to ice melt. Over the southern part of the middle shelf (south of ~60°N; Stabeno et al., 2012a), the primary ice melt occurred when the ice was advected southward. Approximately 1.3 m of ice melted, freshening the water column and reducing the concentration of nutrients. Over the northern part of the middle shelf, as represented by M8, there was little ice melt with the first arrival of ice. Most of the melt at this site occurred when ice retreated, and ice melt during retreat left behind a fresh surface layer, which persisted at M8 through the summer. This increased the strength of stratification and delayed the fall mixing of the water column on
the northern shelf by ~1.3 months relative to M2 (Table 2). The transition zone at M5 had
substantial ice melt during both ice advance and retreat (a total ~2.1 m; Tables 3 and 4).

Typically when ice first arrived, the water column (or the surface mixed layer) cooled
and freshened, and remained well mixed. Once the areal ice cover exceeded 20 – 25 %, the
melting ice stratified the water column, with a fresher, colder layer overlaying warmer, more
saline water. This surface layer was usually > 20 m deep. The vertical stratification usually was
relatively weak, $\Delta \rho \Delta t = \sim 0.18$ (using average temperature and salinity values from Table 3 of -1.7
$^\circ$C and 31.7, respectively, for surface layer, and 1.3 $^\circ$C and 32.2 for bottom layer), but persisted
for 10 – 25 days. Storms quickly re-mixed the water column if ice retreated (e.g. Fig. 8); storms
had less influence under extensive ice, but the water column would eventually become well
mixed (e.g. Figs. 7, 9 and 10). Advection plays a role in the stratification of the water column,
particularly in the vicinity of the ice edge front.

Without sea ice, the water column at M2 and M4 usually cools by ~4 $^\circ$C to ~2 $^\circ$C, while
in years with extensive ice the water column cools on average more than 6 $^\circ$C to -1.7 $^\circ$C (Stabeno
et al., 2012b). Multiple consecutive cold (warm) years modify this, making the depth-averaged
summer temperatures colder (warmer). Average cooling in a series of cold years was ~5.5 $^\circ$C,
while average cooling in a series of warm years was ~4.5 $^\circ$C (from Fig. 4A in Stabeno et al.,
2012b). For comparison, more cooling (~ 7.5 $^\circ$C) occurred between warm and cold years. The
greater cooling during cold years rather than warm years comes from two sources. First, the air
temperature during years with extensive ice is colder than years with little or no ice; thus, cooling
due to sensible heat flux is greater. The second and probably more important source of cooling is
the latent heat flux due to ice melt. The cooling from melting 1.3 m of ice (probably an
underestimate) accounts for approximately half the observed cooling of the water column. In
sharp contrast, on the northern shelf near M8, the water column cooled to ~ -1 $^\circ$C before ice
arrived (Table 2). Ice arrival cooled water temperatures to ~ -1.8 $^\circ$C with little melt because water
temperatures were already low.

This discussion of sea-ice melt applies to the middle shelf domain, and not to the coastal
or outer shelf domains. In the coastal domain, ice is formed and shore fast ice and rafting are
common. The water column is typically well mixed by tides which are stronger on the
southeastern shelf than in the north. In the outer shelf domain advection dominates, and intrusions
of warmer, more saline slope water are common (e.g. Stabeno and van Meurs, 1999; Sullivan et
al., 2008; Coachman, 1986). The water column is deeper (> 100 m) and not well mixed even in
the winter (Stabeno et al., 1998). A few hypotheses, however, can be made about how the coastal
and outer domains may respond to ice melt. Probably little ice is melted in the coastal domain
until ice retreat at the end of the cold season. The coastal domain, with its weak alongshore flow, retains the signature of lower salinity through the summer as a result of ice melt (Danielson et al., 2012; Kachel et al., 2002). With the breakdown of the Inner Front in late summer, this freshwater signature spreads out over the shelf (Ladd and Stabeno, 2012). The signature of ice melt on the outer domain is ephemeral; it does not persist through the summer because of the persistent alongshore currents, and onshore intrusions of more saline, nutrient rich water (Stabeno et al., 2010).

It is becoming evident that the presence or absence of sea ice in spring is the single most important component determining the physical and biological structure of the eastern Bering Sea shelf ecosystem, not only in the winter and spring when it is present, but also during the warm season (Stabeno et al., 2010, 2012a, b; Hunt et al., 2002, 2008, 2010). The advance of sea ice early in the season transports fresh water southward, which then melts at the ice edge reducing the salinity of the middle shelf by ~0.4 (Table 3). In contrast late in the cold season, the retreat of ice transports fresh water northward, where it melts providing approximately half of the summer stratification on the northern shelf (Stabeno et al., 2012a; Ladd and Stabeno, 2012). Sea ice had low concentrations of nitrate and, thus, could not contribute to the water column as the ice melted. There are significant amounts of iron, however, in the sea ice (Aguilar-Islas, 2008), which contributes to the production along the slope. Significant concentrations of chlorophyll-a were found in bottom sections of the ice cores. This ice algae, located at the ice-seawater interface, may provide an early concentrated food source (Mock and Gradinger, 2000; Niemi et al., 2011) for zooplankton (e.g. O’Brien 1987, Runge and Ingram 1991). While chlorophyll-a is transported by the ice toward the ice edge, it is not known if the ice also transports large amounts of zooplankton which feed on the ice algae. The absence of ice over the southern shelf during consecutive warm years (2001-2005) likely contributed, directly or indirectly, to a drop in populations of large crustacean zooplankton (e.g. Calanus marshallae, Thysanoessa raschii) and a resultant reduction in the pollock fishery (Hunt et al., 2008, 2010; Coyle et al., 2008, Stabeno et al., 2012b).

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Floering, C. Dewitt and S. McKeever for maintaining, deploying and recovering the instruments on the mooring, D. Kachel and P. Proctor for processing the mooring and ship board measurements, P. Proctor for nutrient analysis on some samples, and A. Hermann for comparison of ice drift data to interpolated NCEP winds. Graphics were provided by K. Birchfield. This research was funded by grants from The North Pacific Research Board (grant B52) and the National Science Foundation (grants 0732430, 1107250, and 0813985), and support from NOAA’s North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) program. This publication was partially funded by the University of Washington Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreements NA17RJ1232 and NA10OAR4320148, and is contribution EcoFOCI-0802 to NOAA’s Ecosystems and Fisheries-Oceanography Coordinated Investigations, contribution 2157 to JISAO, contribution 3975 to NOAA’s Pacific Marine Environmental Laboratory, and BEST-BSIERP publication number XX. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NOAA’s Oceans and Atmospheric Research.

References


Table 1. Ice stations, 2006-2009, with average data from the core. April 19, 2007 Ice Core 2 ice thickness value was excluded from the mean thickness.

<table>
<thead>
<tr>
<th>Date</th>
<th>Ice station</th>
<th>Snow depth (cm)</th>
<th>Ice thickness (cm)</th>
<th>Air temp. (°C)</th>
<th>Mean salinity</th>
<th>Mean temp. (°C)</th>
<th>Mean ice density (10^3 kg m^-3)</th>
<th>Mean nitrate (µM)</th>
</tr>
</thead>
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Table 2. Bering Sea shelf moorings: statistics and information. The location of the moorings and the years during which they were deployed are given on the left. Mixing information includes the range of time, and average date, at which the water column became well mixed with a temperature difference of < 0.02 °C. The years during which areal sea ice concentration was < 20% for the entire cold season were 1996, 2001, 2003 – 2005 at M2, and 2001 and 2005 at M4.

Mooring sites M5 and M8 always had ice present during the cold season.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Mean August Temp 2005 – 2011 (all years)</th>
<th>Fall Water Column Mixing date and temperature</th>
<th>Minimum Temp. 2005 – 2011 (all years) (°C)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Surface (°C)</td>
<td>Bottom (°C)</td>
<td>Date Range (mean)</td>
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<tr>
<td>M2 56.9 °N, 164.1 °W 1995 – 2011</td>
<td>10.1 (10.4)</td>
<td>1.4 (2.0)</td>
<td>10/21 – 12/4 (Nov. 9)</td>
</tr>
<tr>
<td>M4 57.9 °N, 168.9°W 1996, 1999-2011</td>
<td>9.4 (9.7)</td>
<td>1.2 (2.2)</td>
<td>10/18 – 11/24 (Nov. 1)</td>
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<tr>
<td>M5 59.9 °N, 171.7 °W 2005 – 2011</td>
<td>8.9</td>
<td>-0.8</td>
<td>10/16 – 12/21 (Nov. 20)</td>
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<tr>
<td>M8 62.2 °N, 174.7 °W 2005 – 2011</td>
<td>5.0</td>
<td>-1.5</td>
<td>12/4 – 1/25 (Dec. 19)</td>
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</table>
Table 3. Observations and calculations of the impact of melting ice on the water column. $T_w$ ($S_w$) is the depth-averaged temperature (salinity) of the water column when the ice arrives. $\Delta T$ ($\Delta S$) is the average change in temperature (salinity) in the part of the water column that was modified by melting ice. $H$ is depth of the water column cooled (usually the entire water column), $h_i$ is the thickness of ice melted as calculated from changes in salinity, and $h_w$ is the equivalent depth of water melted. $\Delta T_L$ is the change in temperature due to latent heat of fusion and the final column is the fraction of the observed cooling that is caused by the latent heat of fusion. Note that 2009 at M2 had two distinct melting events (a and b) which were combined together (2009t).

<table>
<thead>
<tr>
<th>Mooring – year</th>
<th>$T_w$ (°C)</th>
<th>$\Delta T$ (°C)</th>
<th>$S_w$</th>
<th>$\Delta S$</th>
<th>$H$ (m)</th>
<th>$h_w$ (m)</th>
<th>$h_i$ (m)</th>
<th>$\Delta T_L$ (°C)</th>
<th>$\Delta T_L/\Delta T$</th>
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<tr>
<td>M2 – 1998</td>
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<td>3.4</td>
<td>31.95</td>
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<td>25</td>
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<td>0.51</td>
<td>1.17</td>
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<tr>
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<td>1.75</td>
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<td>1.21</td>
<td>1.42</td>
<td>1.15</td>
<td>0.33</td>
</tr>
<tr>
<td>2010</td>
<td>0.2</td>
<td>1.9</td>
<td>31.96</td>
<td>0.34</td>
<td>70</td>
<td>0.92</td>
<td>1.08</td>
<td>0.88</td>
<td>0.46</td>
</tr>
<tr>
<td>M5 – 2006</td>
<td>0.9</td>
<td>2.6</td>
<td>32.20</td>
<td>0.92</td>
<td>32</td>
<td>1.12</td>
<td>1.32</td>
<td>2.35</td>
<td>0.90</td>
</tr>
<tr>
<td>2007</td>
<td>2.0</td>
<td>3.6</td>
<td>32.20</td>
<td>0.50</td>
<td>70</td>
<td>1.34</td>
<td>1.57</td>
<td>1.28</td>
<td>0.36</td>
</tr>
<tr>
<td>2010</td>
<td>-0.1</td>
<td>1.8</td>
<td>31.55</td>
<td>0.70</td>
<td>70</td>
<td>1.92</td>
<td>2.25</td>
<td>1.83</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean</td>
<td>2.9</td>
<td>0.52</td>
<td>1.15</td>
<td>1.36</td>
<td>1.33</td>
<td>0.48</td>
<td></td>
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</tbody>
</table>
Table 4. Statistics for the amount of ice that melts at moorings sites when the ice retreats.

Column headings are the same as in Table 3.

<table>
<thead>
<tr>
<th>Mooring - year</th>
<th>δS</th>
<th>H</th>
<th>S_w</th>
<th>h_w</th>
<th>h_i</th>
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</thead>
<tbody>
<tr>
<td>M5 - 2007</td>
<td>0.7</td>
<td>25</td>
<td>31.5</td>
<td>0.69</td>
<td>0.81</td>
</tr>
<tr>
<td>2008</td>
<td>0.7</td>
<td>25</td>
<td>31.4</td>
<td>0.69</td>
<td>0.81</td>
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<tr>
<td>2010</td>
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<td>25</td>
<td>31.3</td>
<td>1.28</td>
<td>1.51</td>
</tr>
<tr>
<td>2011</td>
<td>0.3</td>
<td>30</td>
<td>31.4</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>2012</td>
<td>0.9</td>
<td>25</td>
<td>31.4</td>
<td>0.89</td>
<td>1.04</td>
</tr>
<tr>
<td>M8 - 2006</td>
<td>0.2</td>
<td>35</td>
<td>32.4</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>2008</td>
<td>0.7</td>
<td>32</td>
<td>32.8</td>
<td>0.84</td>
<td>0.98</td>
</tr>
<tr>
<td>Mean</td>
<td>0.7</td>
<td>28</td>
<td>31.7</td>
<td>0.71</td>
<td>0.84</td>
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Papers in preparation
Chapter 16

Acoustically-Determined Patterns of Summer Zooplankton Biomass and Vertical Migration Behavior from the Bering Sea Middle Shelf during a Cold Regime

Jeffrey M. Nappa, Adam H. Spear, Phyllis J. Stabenol, Benjamin Bloss, and David Strausz

Abstract

Zooplankton biomass and distribution in the eastern Bering Sea are strongly connected to variations in climate, and influence recruitment success of planktivorous fishes (e.g. walleye pollock, Gadus chalcogramma). The broad continental shelf in this region is remote and not easily sampled by ships, particularly during cold winters and springs when sea ice covers much of the region. Two active acoustic sensors were moored over the eastern Bering Sea shelf during the summers of 2007, 2009, and 2010 and were used to gain insight into the temporal variability of summer zooplankton on this highly productive marine ecosystem. The first sensor, a 300 kHz Acoustic Doppler Current Profiler (ADCP) was intended for current measurements, sampled the entire water column, but was not calibrated for acoustic detection of small scatterers. The second sensor, a Tracor Acoustic Profiling System (TAPS) was calibrated, contained 8 unique frequencies between 100 and 3000 kHz, but only sampled a very small volume. Volume backscatter data from the two samplers each provided indices of zooplankton biomass and distribution through different processing techniques with differing sets of assumptions. The temporal patterns of scattering by small particles varied both seasonally and among years, even...
though all three years had similar environmental forcing. The backscatter volume from the ADCP and the estimated zooplankton biovolume from the TAPS were correlated. Acoustically-derived estimates of large copepod biovolume was highest in 2009 and 2010 and lowest in 2007 in agreement with other data. The diel signal dominated temporal variability and we were unable to detect additional modes of high variability at frequencies below 0.5 day\(^{-1}\). The TAPS-8 estimated sizes of the organisms responsible for diel vertical migration roughly matched our expectation of the identity of those organisms from nets and the literature. Length of time migrators spent in the surface waters was inversely related to the number of daylight hours and increased vulnerability to predation by age-0 fishes. This latter observation, while not new, provides an advantage to planktivores like pollock which must accumulate sufficient depot lipids by the end of summer to survive their first winter.

**Key Words:** Bering Sea, zooplankton, bioacoustics, diel vertical migration, walleye pollock, climate regimes

Figure 4. Eastern Bering Sea and M2 study site where the acoustic instruments collected zooplankton volume backscatter data.
Figure 5. ADCP-derived zooplankton volume backscatter. Top – 2007, Middle – 2009, Bottom – 2010.
Patterns of flow on the eastern Bering Sea shelf: 20 years of observations

P. J. Stabeno and N. B. Kachel

Abstract

Currents are examined on the eastern Bering Sea shelf using data from moorings, satellite-tracked drifters and hydrographic surveys. The major source of water on the Bering Sea shelf is Unimak Pass and the canyons that intersect the shelf break. Absolute geostrophic transport through Unimak Pass varies from an average of 0.25 x 10^6 m^3 s^-1 in the warm months to 0.43 x 10^6 m^3 s^-1 in the cold months. Flow along the 50-m isobath is weak, with a transport of < 0.1 x 10^6 m^3 s^-1 in both summer and fall. The transport along the 100-m isobath is more than twice that along 50-m isobath: 0.2 x 10^6 m^3 s^-1 in the summer at the Pribilof Islands; and a northward geostrophic transport (referenced to the bottom) of 0.31 x 10^6 m^3 s^-1 during spring and summer at 60°N. Northward transport along the 100-m and 50-m isobaths accounts for approximately half of the northward flow through Bering Strait. The transit time north from Unimak Pass to Bering Strait is greater than 13 months. Thus, the source of most of the heat transported into the Arctic through Bering Strait is a result of air-sea interactions in the Bering Sea. Examination of the currents and water properties on the southern shelf indicates that ~50% of the shelf water is exchanged with slope in October – January each year, replenishing >50% of the nutrients consumed the previous growing season.

Key Words: Bering Sea, currents, middle shelf, climate regimes
Fig. 6. Mean currents during summer (May – September) derived from satellite-tracked drifters drogued at 45 m. There are at least 10 independent estimates of velocity in each grid cell.

Fig. 7. Bottom currents at M2 divided into octents determined by wind directions (e.g. for 0 – 45 °T the vector is the average velocity when winds are toward that direction). Note currents are not 45 – 90 ° to the right of the winds (lower left). Number of points in each bin shown in lower right.
Fig. 8. Bottom currents at M5 divided into octents determined by wind directions (e.g. for $0 – 45^\circ$ T the vector is the average velocity when winds are toward that direction). Note currents are not $45 – 90^\circ$ to the right of the winds (middle panel). Number of points in each bin shown in bottom.
Figure 9. Relationship between winds and currents at M8. In the top panels, vectors indicate the mean direction of the flow when the winds are toward the octant indicated (e.g. 270-315). The bottom panels show current direction as a function of wind direction (black line) and the number of points in each direction octant (shaded). The period examined is winter when there is no ice for a) near-surface (~12-17 m), and b) the difference between near-surface and near-bottom flow.
Conclusions

Major results from moorings, accompanying CTD and the analyses that resulted from these findings.

1. Almost 18 years of data from M2 were used to identify warm and cold years over the southeastern Bering Sea. There is close relationship between ice extent in March and April and depth averaged temperature at M2, which permitted the extension of the definition of warm and cold back to 1972.

2. Prior to 2000, the amount of ice in March and April was highly variable, but beginning in spring 2000, the SE Bering Sea enter 5.5 year window of low ice extent and warm conditions. This was followed by 8+ year period (2007 – present) more extensive ice in March and April and very cold conditions on the southern shelf.

3. The types and abundance of zooplankton differed sharply between warm and cold years. This was especially true during the prolonged warm period (2001–2005) and cold period (2007–2010), and was less evident during the years of high interannual variability. During the warm period, there was a lack of large copepods and euphausiids over the shelf, however, their populations rebounded during cold period. Small crustacean zooplankton taxa did not appear to vary between and warm and cold years.

4. Contrary to historical views, there is a sharp division between the northern and southern Bering Sea shelves which occurs at ~60 °N. These differences include tidal strength, sharpness of the interface, cause of vertical stratification, presence of subsurface chlorophyll maxima, and influence of ice melt. These are discussed below.

5. The ocean currents differed between warm and cold years. During cold years, the monthly-mean currents over the southeastern shelf were largely westward, while in warm years the direction of currents was more variable, with northward flow during December–February and relatively weak flow during the remainder of the year.

6. Unlike the more coastal domain on the northern shelf where winds dominate the flow, the flow on the southern middle shelf is more complex. During the winter, the bottom currents at M2 are not always couple to the wind,. This could have important implication for transport of plankton, such as snow crabs larvae.

7. Temperature and salinity both influence the stratification of the Eastern Bering Sea shelf: temperature dominates stratification on the southern shelf, and temperature and salinity are equally important on the northern shelf. The strength of stratification does not vary as a function of warm or cold years.

8. Approximately, 1 m of ice melts over the southern shelf during the ice advance,
modifying the salinity. A similar amount melts over the northern shelf with ice retreat. Ice cover inhibits the vertical mixing of the water column. Approximately 50% of the cooling of the southern shelf is caused by ice melt, with the remainder a result of air-sea interaction.

9. Chlorophyll a fluorescence data from the four biophysical moorings provided 37 realizations of a spring bloom and 33 realizations of a fall bloom. Basic findings: If ice was present after mid-March, spring bloom timing was related to ice retreat timing; if ice was absent or retreated before mid-March, a spring bloom usually occurred in May or early June. A fall bloom also commonly occurred, usually in late September, and its timing was not significantly related to the timing of storms or fall water column overturn. The magnitudes of the spring and fall blooms were correlated.

10. The breadth of the mooring instrumentation from thermistors, conductivity cells, current meters and ADCPs, nitrate sensors, fluorometers, TAPS-8 to measure zooplankton biovolume, and acoustic systems to listen for marine mammals. Passive acoustic data provided information about sea ice conditions and detected and identified of vocalizing marine mammals; the acoustic backscatter provided information on relative zooplankton and fish abundance before, during, and after the retreat; and the hydrographic data confirmed the acoustic signal was associated with changing surface ice conditions. The combined information from the biophysical mooring sensors revealed changes in winter trophic level dynamics during the ice retreat, which would have otherwise been undetected by traditional ship-based observations.

11. The nitrate sensors and nutrient measurements around the moorings provided information of the seasonal draw down of nutrients associated with primary production, and winter replenishment. Nutrients are typically replenished on the shelf from November – January. Summer storms result in mixing of nutrients into the photic zone and a phytoplankton bloom 5 – 7 days later.

12. Subsurface blooms in the region around M8 are common during the summer.

13. The biophysical mooring data were frequently used to calibrate biophysical models of the Bering Sea. These included side-by-side model/data comparisons of the vertical profiles of currents, temperature, salinity, and chlorophyll-a at multiple locations, from hourly to interdecadal time scales.

BSIERP and Bering Sea Project Connections
We found this to be a highly successful program. Collaborations among groups was extensive and the sharing of data and resources strongly contributed to the success of this program. By sharing ship time each research group gained a first-hand understanding of the goals, needs and problems of other groups. The PI meetings were comprehensive and productive. The results of these collaborations are seen in the papers published and the fact that individuals from various groups co-author manuscripts. The success in the program is evident in the series of special issues that have come out of it.

Ship time is always a problem in high latitudes. Participation in this program provided us the opportunity to collect data during the winter/spring when the Bering Sea is covered in ice. In turn, data and samples were collected on our late summer cruises, which extended the sampling period into late summer. This benefited the other scientists of this program.

EcoFOCI had extensive physical, chemical and biological data (moorings and shipboard measurements) collected during the warm period. These data provided the ability to make critical comparisons between warm period (2001–2005) and the cold period sampled by Bering Sea Project. In addition, the long time series at the moorings (M2, M4, M5 and M8) provided context for many of the other measurements made as part of the Bering Sea Project.

This is the best large integrated program that we have participated in.
Management or policy implications

Our long-term biophysical mooring array provides critical and highly cited measurements of the physical drivers of the southeastern Bering Sea ecosystem. These measurements are used by the North Pacific Fishery Management Council (Fig. 10) to inform stock assessments and guide total allowable catch for some of the most economically important fisheries in the U.S. For example, during a recent warm phase in the Bering Sea (2000 – 2005) pollock recruitment was extremely poor and assessments of pollock stocks and environmental conditions warned of possible continued declines. Resource managers responded to the combined stock assessment and ecosystem considerations advice by changing existing management practices – reducing pollock harvest levels. This occurred during a period when the pollock population was facing a variety of environmental stressors, and potentially averted a collapse of the fish stock and the fisheries, communities and economies that depend on it.

Figure 10. Schematic of the pathway for management action for walleye pollock.
Jeffrey M. Napp, J. M., A. H. Spear, P. J. Stabeno; B. Bloss and D. Strausz, Acoustically-
Determined Patterns of Summer Zooplankton Biomass and Vertical Migration Behavior
from the Bering Sea Middle Shelf during a Cold Regime, For submission to the fourth
special issue.

Stabeno, P. J. and N. B. Kachel, Patterns of flow on the eastern Bering Sea shelf: 20 years of
data. For submission to the fourth special issue.

Cheng, W., E. Curchitser, C. Ladd, and P.J. Stabeno (2013): Ice–ocean interactions in the eastern
Bering Sea: NCAR CESM simulations and comparison with observations. *Deep-Sea Res. II*.

Stabeno, R. Sambrotto, R. Gradinger, L. Juranek, M. Prokopenko, M.S. Baumann, and M.
Ostendorf (2013): Integrated assessment of the carbon budget in the Southeastern Bering

Goes, J.I., H. Rosario Gomes, E. D'Sa, D. Stoecker, C.W. Mordy, R. Sambrotto, and P.J. Stabeno
(2013): Distribution of phytoplankton communities in the Bering Sea during the summer of

Acoustic determination of nekton and zooplankton distributions at tidally generated shelf

Prokopenko, M.G., J. Granger, M. Long, C. Mordy, E. Barkan, N. Cassar, E. Cokelet, P. DiFiore,
C. Ladd, R. Sambrotto, and B. Moran (2013): Mixed layer depth controls the instantaneous
Net to Gross Production ratios and potential export efficiency in spring blooms on the


Outreach

Web-page

EcoFOCI maintains a suite of NPRB related web sites that can found at http://www.pmel.noaa.gov/foci/.

Schools, mentoring, radio and press


Ned Cokelet contributed to a public presentation after the spring BEST cruise in May 2009 and discussed with the public goals and findings of the research.

Members of PMEL/Eco-FOCI collaborated with Aleut Community of St. Paul Island in maintaining their temperature and salinity measurements in their harbor and on St. George Island from 2009-2012.

Nancy and Dave Kachel gave Science Day Presentations about BEST/BSIERP at Jane Adams K-8 School, Seattle, WA. December 8, 2010.

Nancy and Dave Kachel gave Science Day Presentations about BEST/BSIERP at Jane Adams K-8 School, Seattle, November 30, 2011.


Scott McKeever. Volunteered as a judge at the Orca Bowl, School of Oceanography, University of Washington, March, 2012.

Nancy and Dave Kachel participated as Science Fair Judges at Jane Adams K-8 School, Seattle, WA. April 2012.
Margaret Sullivan, Speed Networking, Young Leadership Program/NOAA Science Camp, Seattle, WA. July 2012.


Guy, Lisa N. Kachel and Scott McKeever provided outreach to Sea Grant Fellow Kristen Jabanoski via in-person discussion, slide presentation and a tour on 29 January 2013.

Nancy and Dave Kachel gave Science Day Presentations about BEST/BSIERP at Jane Adams K-8 School, Seattle, Kachel, N. Science Day Presentations at Jane Adams K-8 School, Seattle, WA. Feb 6, 2013.

Margaret Sullivan provided EcoFOCI animations to Danielle Dickson (NPRB) for a presentation. The animation shows Bering Sea satellite ice (Modis true-color) with ice-floe tracking (dots) for 2003 (warm year, less ice) and 2007 (cold year, more ice, 20 Feb 2013.

Scott McKeever. Volunteered as a judge at the Orca Bowl, School of Oceanography, University of Washington, February 23, 2013.

Nancy and Dave Kachel participated as Science Fair Judges at Jane Adams K-8 School, Seattle, WA. April 2013.

Nancy Kachel and Jeff Napp made presentations and Scott McKeever gave a facilities tour for undergraduate Seattle University Marine Science class on 22 May 2013.

Carol Ladd, is a mentor for the MPOWIR program, providing mentoring to physical oceanographers from late graduate school through their early careers. The overall goal of MPOWIR is to make mentoring opportunities for junior physical oceanographers universally available and of higher quality by expanding the reach beyond individual home institutions. The aim is to reduce the barriers to career development for all junior scientists in the field, with a particular focus on improving the retention of junior women.

Carol Ladd, Hosted a high school senior (Zach Hall) to discuss a career in science (6/28/2012).

Jeff Napp and Phyllis Stabeno both served on the Science Advisory Board.

**Conference Presentations**


Hermann, A. J.; K. Aydin; N. A. Bond; W. Cheng; E. N. Curchitser; G. A. Gibson; K. Hedstrom; I. Ortiz; M. Wang; P. J. Stabeno The Bering Sea Integrated Ecosystem Research Program: downscaling climate change to a subarctic region with coupled biophysical models. 2010 Ocean Science Meeting Portland OR

Kachel, N. B.; C. W. Mordy; P. J. Stabeno Comparison of four decades of hydrographic structure over the SE Bering Sea Shelf. 2010 Ocean Science Meeting Portland OR


Salo, S. A and P. J. Stabeno, Spatial Scales of Correlation on the Bering Sea Middle Shelf, 2010 Ocean Science Meeting Portland OR

Stabeno, P. J.; N. B. Kachel; C. Mordy; J. M. Napp; M. C. Spillane, The north - south structure of eastern Bering Sea shelf? Implications for a changing ecosystem. 2010 Ocean Science Meeting Portland OR

Stabeno, P. J. N. A. Bond, C. M. Mordy, and J. M. Napp. Comparison between a cold year (2009) and a warm year (2005) and implications for the ecosystem on response to changes in climate, Alaska Marine Science Symposium, Cook Hotel, Anchorage, Alaska.

K. Stafford; S. E. Moore; P. J. Stabeno; V. Holliday; J. M. Napp. Biophysical Ocean Observation in the Southeastern Bering Sea. 2010 Ocean Science Meeting Portland OR

Sullivan, M. E.; C. W. Mordy; P. J. Stabeno; N. B. Kachel; D. G. Kachel; S. A. Salo A Brief History of an Ecosystem Spring Setup as Seen in Annual Ice Cover. 2010 Ocean Science Meeting Portland OR.


Hermann, A.J., Aydin, K., Bond, N.A., Cheng, W., Curchitser, E.N., Gibson, G.A., Hedstrom, K.,


Stabeno, P.J., Napp, J.M., and Sigler, M.F. “North Pacific Climate Regimes and Ecosystem


Stabeno. EcoFOCI. Presentation to head of OAR. Seattle, WA, April 2012. Oral Presentation


Stabeno, Farley, Kachel, Moore, Mordy, Napp, Overland, Pinchuk and Sigler. Climate-mediated processes on the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. Yeosu, Korea, May 2012. Oral Presentation

Reports


Acknowledgements

Special thanks goes to the Program Manager for the Bering Sea Project, Thomas Van Pelt, for his hard work, insight and support to this program. We thank all the scientists from EcoFOCI at both Alaska Fisheries Science Center and the Pacific Marine Environmental Laboratory for their hard work at sea, in processing data and in assisting in analysis. We thank the officers and crews of the NOAA ships Miller Freeman and Oscar Dyson, R/V Thomas G. Thompson, R/V Knorr and USCG Healy for invaluable assistance in deploying and recovery of the moorings, and collecting oceanographic measurements. Special thanks goes to NOAA’s Alaska Fisheries Science Center’s Resource Assessment and Conservation Engineering Division Groundfish and Shellfish Assessment Program who shared shiptime during particularly icy years to deploy moorings at M5 and M8 on several occasions. NOAA’s North Pacific Climate Regimes and Ecosystem Productivity and Fisheries Oceanography Coordinated Investigations provided support including equipment, salaries and shiptime that helps to maintain these long-term moorings.