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What processes contribute to the spring and fall bloom co-variability on the Eastern Bering Sea shelf?

Wei Cheng [a,b,*], Enrique Curchitser [c,d], Charles Stock [e], Albert Hermann [a,b], Edward Cokelet [b], Calvin Mordy [a,b], Phyllis Stabeno [b], Gaelle Hervieux [c], Frederic Castruccio [c,f]

[a] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 3737 Brooklyn Ave NE, Box 355672, Seattle, WA 98105, USA
[b] Pacific Marine Environmental Laboratory, NOAA, 7600 Sandpoint Way NE, Seattle, WA 98115, USA
[c] Department of Environmental Sciences, Rutgers University, 14 College Farm Rd., New Brunswick, NJ 08901, USA
[d] Institute of Marine and Coastal Sciences, Rutgers University, 71 Dudley Rd., New Brunswick, NJ 08901, USA
[e] Geophysical Fluid Dynamics Laboratory, NOAA, 201 Forrestal Road, Princeton, NJ 08540-6649, USA
[f] National Center for Atmospheric Research, Boulder, CO 80305, USA

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ABSTRACT

Observations indicate that spring and fall phytoplankton blooms on the Eastern Bering Sea (EBS) continental shelf tend to co-vary on inter-annual scales – that is, a year with a strong spring bloom also tends to have a strong fall bloom. Similar co-variability of primary production is also seen in the multi-year (1987–2007) integration of a coupled physical–biological model. Moreover, the modeled seasonal amplitudes of 10-meter chlorophyll-a concentrations at the EBS middle shelf mooring locations, computed using the canonical Redfield ratio and a mean carbon-to-chlorophyll-a ratio, are generally consistent with the in situ mooring measurements. The coupled physical–biological model simulation is used to examine the relative contributions of wind mixing, local nutrient recycling/regeneration, horizontal nutrient advection, and water-column stability to this co-variability. There is no significant correlation between the spring and fall surface wind mixing. Although wind mixing is an important mechanism for bringing nutrients in the lower water column to the surface layers, it is not the mechanism tying the two seasons' productivity together. Local regeneration/recycling of the nutrients initially fueling spring production is an important mechanism for spring-to-fall nutrient accumulation in the bottom layers at the middle shelf. Horizontal advection does not appear to be the dominant factor for supplying nutrients to the middle shelf during the spring-to-fall period. Fall primary production in the model is strongly influenced by the lower water-column stability/stratification. Taken together, these results highlight the importance of local recycling/regeneration of nutrients assimilated by spring phytoplankton bloom in linking together the spring and fall primary productions on EBS middle shelf.

1. Introduction

The Bering Sea is a subarctic marginal sea bounded to the north by the Bering Strait, and to the south by the Aleutian Island chain (Fig. 1). It has a wide (~500 km) and relatively flat (with depth less than 180 m) continental shelf to the east and a deep ocean basin to the west. The Eastern Bering Sea (EBS) shelf is highly productive because of interactions between the ocean, sea ice, and atmospheric forcing. For example, the shelf break of the EBS is known as the "greenbelt" (Springer et al., 1996), where upwelled nutrients from the ocean basin provide fuel for phytoplankton primary production. Seasonal sea ice is another important control on productivity in the EBS. Sea ice can form in the northern EBS as early as November, and under prevailing winds, is transported southward (e.g., Pease, 1980; Danielson et al., 2011; Sullivan et al., 2014). In years with extensive sea ice, the ice can cover much of the EBS shelf in March – the month typically with the maximum ice extent, but maximum ice cover can occur as early as February or as late as April (Stabeno et al., 2012a). During the melting season, sea ice retreats generally from south to north, and by mid-June the Bering Sea is usually ice free.

Sea ice extent in the EBS is highly variable on inter-annual timescales (Brown et al., 2011). During extensive ice years, with sea ice persisting on the southern shelf (south of 60°N) after mid-March, the water column over the southern shelf tends to be colder and fresher than during years with little ice (Coachman and

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* Corresponding author. Tel.: +1 206 526 4581; fax: +1 206 526 6485.
E-mail address: wei.cheng@noaa.gov (W. Cheng).

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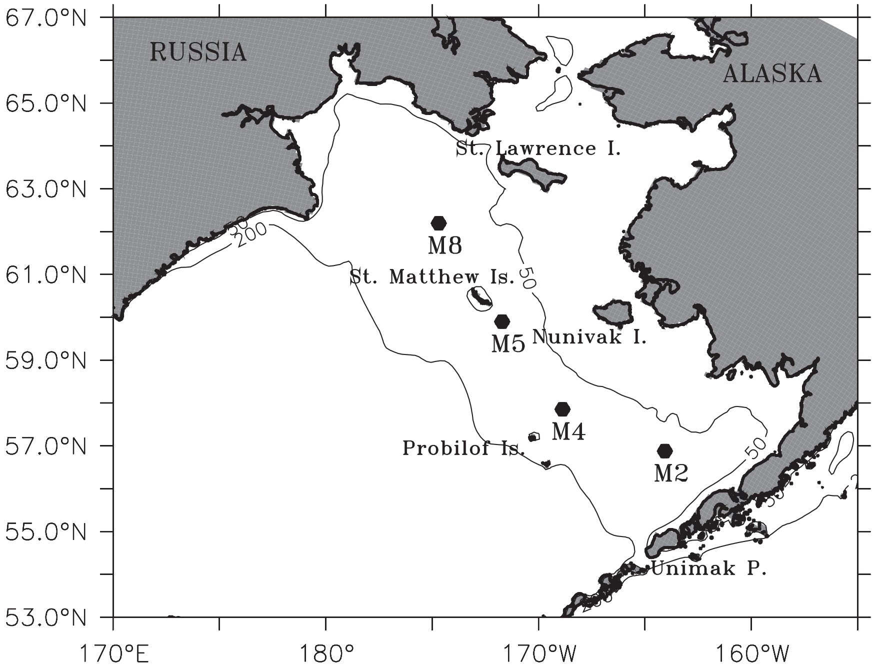

Fig. 1. Study area. Filled hexagons mark the M2, M4, M5, and M8 mooring locations on the Eastern Bering Sea middle shelf. Gray (white) area is land (ocean) in the ROMS-NEMURO NEP model. Thin black lines denote the 50-m and 200-m ocean depth in the model.

Shigaev, 1992; Stabeno et al., 2010, 2012b; Ladd and Stabeno, 2012; Sullivan et al., 2014). The timing of ice retreat influences the timing of the spring phytoplankton bloom (Brown and Arrigo, 2013; Stabeno et al., 2012b; Sigler et al., 2014), zooplankton species composition (Eisner et al., 2014), and fish recruitment (Hunt et al., 2002, 2011; Hollowed et al., 2012). A fall (September to early October) bloom is also common in the EBS. Using the multi-year (1995–2011) fluorescence data obtained from the long-term monitoring moorings on the EBS middle shelf (M2, M4, M5, and M8; see Fig. 1), Sigler et al. (2014) found correlations between the magnitudes of the spring and fall blooms, that is, a year with a strong spring bloom also tends to have a strong fall bloom, but the observational data are too sparse by themselves to reveal the underlying mechanisms.

In addition to ocean in situ and remote sensing measurements, biophysical modeling is used to examine physical and biological linkages between the ocean environment and ecosystem responses in the EBS (e.g., Jin and co-authors, 2006, 2007, 2009; Gibson and Spitz, 2011). One such modeling system is the Regional Ocean Modeling System (ROMS) coupled to the NEMURO planktonic ecosystem model (Kishi and co-authors, 2007) for the Northeast Pacific (NEP) (hereafter called ROMS-NEMURO NEP). A previous version of the model was used for a biophysical model developed under the Bering Sea Project (Gibson and Spitz, 2011; Gibson et al., 2013; Hermann et al., 2013), also known as the Bering Ecosystem Study-Bering Sea Integrated Ecosystem Research Program (BEST-BSIERP; Sigler et al., 2010). The physical performance of the model is described in Curchitser et al. (2005), Curchitser et al. (2010) and Danielson et al. (2011).

The primary goal of this study is to examine processes influencing seasonal variability of primary production on the EBS middle shelf and, particularly, to explore mechanisms responsible for the co-variability of spring versus fall bloom amplitudes as suggested by mooring observations. Spring phytoplankton bloom dynamics on the EBS shelf have been studied extensively (e.g., Mathis et al., 2010; Brown and Arrigo, 2013; Banas et al., 2016) while fall bloom dynamics have received comparatively less attention (Sigler et al., 2014). To achieve the above goal we focus on mechanisms that influence nutrient supply to the region in the fall – surface wind mixing, local recycling of nutrients from spring production, horizontal advection of nutrients, and water column stability. Undoubtedly, other factors than those listed above can additionally influence primary production on the EBS shelf on various time scales. Focusing on a few key processes is only the first step toward a better understanding of controlling mechanisms.

The remainder of the paper is organized as follows. In Section 2, we first introduce the data used in our analyses – mooring observations, satellite measured sea-ice concentrations, and the ROMS-NEMURO NEP biophysical model and its output, followed by descriptions of model diagnosis metrics. Main results from this study are described in Section 3. This includes model-observation comparison and an examination of possible mechanisms connecting the spring and fall blooms. In Section 4, we discuss caveats of this study and the implications of our results. Main conclusions are summarized in Section 5.

2. Data and analyses

2.1. Mooring data and satellite ice concentration

The four moorings (Fig. 1) used in this study are described in detail in Stabeno et al. (2012a, b). They are located along the 70-m isobath on the EBS shelf. These biophysical moorings (M2, M4, M5, and M8) are maintained by NOAA/PMEL, and the first moorings at M2 were deployed in 1995. In general, they are subsurface moorings (except M2 in the summer, which is a surface mooring). Each mooring measures temperature at ~5 m resolution through most of the water column, salinity at 3–5 depths distributed through water column, and chlorophyll-a fluorescence at ~11 m depth in south and at ~20 m at M8. The raw data were collected hourly. Daily averages of the chlorophyll-a concentration from these moorings are presented in Sigler et al. (2014), and these daily mooring chlorophyll-a data will be used in this study.

Monthly sea ice concentrations in a 100 km by 100 km box surrounding each mooring location are computed from the daily