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# Primary production response to seasonal-scale extremes in the Bering Sea simulated by the Community Earth System Model, version 1

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ABSTRACT

The biological response to long-term trends and the co-occurrence of seasonal extremes of the physical environment and primary production in the eastern Bering Sea, as simulated by the Community Earth System Model (CESM1), are presented. This analysis covers the late-twentieth century (1950–2005) and focuses on critical drivers of the eastern Bering Sea ecosystem, including air temperature, sea ice area, wind mixing, and mixed layer depth. Primary production showed strong linear relationships to both air temperature and sea ice area during winter and spring. The only season that had a positive linear correspondence between wind mixing and primary production was summer. Over the fifty-five year period the CESM1 simulates a trend toward warmer air temperatures and a subsequent reduction in sea ice for every season; however, no trends were seen in seasonally averaged wind mixing or mixed layer depth. Corresponding to the air temperature increase was an increase in occurrence of positive seasonal extremes in primary production, as well as a reduction in negative production extremes. There were some instances of seasonal production extremes coinciding with seasonal extremes in the physical environment; however, neither these co-occurrences, nor the direction of the biological response to the physics, were robust throughout the study period.

## 1. Introduction

Marginal seas in the Arctic and Subarctic are expected to be among the most affected by climate change, as slight changes in the water column can have large effects on physical and biophysical processes (Lomas et al., 2012; Moran et al., 2012). Increasing air temperature (Solomon et al., 2007), declining sea ice volume and extent (Markus et al., 2009), and large shifts in marine ecosystems (Grebmeier et al., 2006) are a few examples of environmental changes in the Arctic and Subarctic regions that are occurring at unprecedented rates. Variations in the physical environment that persist over several decades have been found to explain a substantial portion of biological production variability in the North Pacific Ocean (Beamish, 1993). However, shorter duration extremes on the order of weeks to months in the physical environment, often linked to large-scale modes of variability, can also result in substantial changes in the pelagic ecosystem structure of the marginal seas (Bond and Overland, 2005). Event-scale extremes and long-duration anomalies could potentially have a greater impact on ecosystems and humans than would gradual changes in climate means. Meanwhile, as climatic means change, one may expect the frequency of extremes to change as well, with corresponding impacts on the atmosphere, the ocean, and the biological spheres (Solomon et al., 2007; Stafford et al., 2010). Here we use the Community Earth System Model (CESM) to explore seasonal-scale extremes in the physical environment, as well as their impact on primary production in the biologically rich marine ecosystem of the eastern Bering Sea. The specific hypotheses that we address are (1) *Primary production in the Bering Sea increases as air temperature and wind mixing increases, and as sea ice decreases* and (2) *Extremes of seasonal production coincide with extremes of environmental forcing (temperature, wind mixing, and sea ice cover)*.

Since the Arctic and Subarctic domains have been experiencing an increased rate of warming, high-latitude marine and terrestrial ecosystems may experience more stress than lower-latitude marine ecosystems (National Research Council, NRC, 1996). The effects of warming are most noticeable on summer and autumn Arctic sea-ice extent, with September 2012 extent showing a new record low (Jeffries et al., 2012). Diminishing sea-ice cover and corresponding increased temperatures also have the potential to disrupt the current Arctic marine food web, as sea-ice dynamics drive Arctic Ocean primary productivity (NRC, 1996). While Arctic sea ice continues to decline, the Bering Sea of the Subarctic has actually been experiencing a slightly positive trend over the past 30 years, with a record maximum ice extent in March 2012 (Perovich et al., 2012). The Bering Sea is known to be a highly variable physical system, where the timing and extent of sea ice are crucial for determining the timing of spring biological production (Stabeno et al., 2001). The eastern Bering Sea's broad continental shelf and nutrient-rich currents make it one of the most biologically productive marine

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ecosystems (Loughlin et al., 1999; NRC, 1996). The ecosystem of the eastern Bering Sea supports both commercial and subsistence livelihoods, and its productivity accounts for more than half of the marine harvest in United States waters and nearly 25 million lbs of subsistence yield (Bering Sea Interagency Working Group, 2006). The eastern Bering Sea, however, is potentially susceptible to event-scale extremes, as well as long duration climate modes (notably, the Pacific Decadal Oscillation, or PDO; the Pacific North American pattern, or PNA; and the El Niño Southern Oscillation, or ENSO) that may alter primary production within the marine ecosystem and hence affect fishery and subsistence yield. Variations at higher trophic levels are often considered the ultimate target of marine ecosystem studies; here, however, we focus on estimates of primary production because of its important role at the base of the marine food web.

Global circulation models represent a useful tool to explore complex interactions between the physical environment and primary production that supports the higher trophic levels across a range of timescales, from sub-daily to decadal. System models now include sophisticated functions describing ecosystem and biogeochemical processes, which influence carbon-nitrogen cycling, and are becoming more comprehensive and representative of an Earth System (Flato, 2011). These improvements allow a well-rounded diagnosis of climate processes and biophysical feedbacks. The Community Earth System Model version 1 (CESM1) is one such model. The CESM1 builds upon the Community Climate System Model version four (CCSM4) developed by the National Center for Atmospheric of Research (NCAR) through the incorporation of a marine ecosystem model, interactive carbon–nitrogen cycling, terrestrial biogeochemistry, and atmospheric chemistry processes (Hurrell et al., 2013; Moore et al., 2013). A detailed description that expands upon the major improvements for each model component, in comparison to previous versions, is presented in Gent et al. (2011). Analyses of CCSM4 simulations by de Boer et al. (2012) and Walston et al. (2014) conducted in the Arctic and Subarctic domains, respectively, indicate that the model captures the main features of the climatological mean fields of high-latitude climate. Systematic errors in physical forcing variables, such as sea level pressure and geostrophic winds, as well as increased interannual variability centered over the Bering Sea, have been well documented (Walston et al., 2014). Analysis of the ice and ocean fields produced by CESM1 indicate that, despite its limited horizontal resolution, the model can reproduce many aspects of the observed seasonal sea ice advance and retreat in the eastern Bering Sea (Cheng et al., 2014). The most notable shortcoming of the modeled sea ice field is the one month delay in the maximum ice presence in the northern domain. Moore et al. (2013) have analyzed the ability of the CESM to simulate nutrient distributions. They concluded that while surface macronutrient distributions generally agree with observations, the model has a low surface nutrient bias in the Subarctic North Pacific, which they attribute partly to shallow wintertime mixed layer biases.

## 2. Methods

Our study centers around analysis of the historical 20th-century run of the Biogeochemical Elemental Cycling (BEC) model, an ecosystem–biogeochemistry module that runs within the fully coupled ocean component (Parallel Ocean Program version 2, POP2) of the CESM1 (Moore et al., 2004; Smith et al., 2010). A detailed description of the BEC model can be found in Moore et al. (2013). The CESM POP2 is a level coordinate, primitive equation, ocean circulation model (Hurrell et al., 2013) with 60 vertical levels, including 20 in the upper 200 m (Danabasoglu et al., 2012). The ocean model component has a displaced pole centered over Greenland (80°N, 40°W) in the Northern Hemisphere, with a horizontal grid consisting of 384 latitudes and 320 longitudes. The zonal resolution is approximately 1.11° while the meridional resolution varies from 0.27° at the equator to 0.65° north of 60°N (Gent et al., 2011). Parameterizations for the effects of mesoscale and sub-mesoscale eddies have been included to help re-stratify the ocean mixed layer (Danabasoglu et al., 2008; Fox-Kemper et al., 2008; Gent et al., 2011). Danabasoglu et al. (2012) have provided a detailed description and notable developments for the ocean circulation model relative to previous versions of the CCSM/CESM. The CESM–BEC marine ecosystem component is based on a nutrient–phytoplankton–zooplankton–detritus structure, which explicitly represents the distribution of biological components and their response to physical drivers. There are several key species of phytoplankton important for oceanic carbon cycling, the CESM–BEC represents phytoplankton as three functional groups: diatoms, diazotrophs, and small phytoplankton (Moore et al., 2002). While the BEC model has been described extensively in a number of previous papers (Doney et al., 2009; Moore et al., 2004), the CESM1 output on which our analysis is based represents the BEC's first public release (Moore et al., 2013).

A fifty-five-year record (1950 to 2005) of air temperature (an indication of sea surface temperature), wind mixing (as measured by cubed friction velocity $(u^*)^3$) over the shelf break, and sea ice area were examined for the occurrence of extreme seasons. These three features are considered key physical drivers and have been observed to fluctuate over intra-annual, interannual, and interdecadal timescales, impacting the marine ecosystem in the eastern Bering Sea over the same timescales. Each of these forces play an important role in determining the mixed layer depth—the homogenous wind-mixed layer that develops seasonally in the Bering Sea. The depth of the mixed layer provides an indication of how well the water column is stratified and so controls the amount of nutrients and light to primary producers throughout the growing season. Thus, the mixed-layer depth can be regarded as a composite physical variable that can control primary production, so seasonal extremes in mixed layer depth were also considered in our analysis.

The northern and southern portions of the Bering Sea shelf differ in their physical, chemical, and biological oceanographic characteristics (Stabeno et al., 2012a), and as a result, the shelf was subdivided into north and south domains at 60°N (Fig. 1) for our analysis. The relationship between air temperature, sea ice area, and primary production was examined over two polygons that divided the eastern Bering Sea. The northern domain covers an area between 60°N–66°N and 174°E–160°W and consisted of 76 model grid points. The southern domain, covering an area between 52°N–60°N and 178°E–158°W, constituted 84 model grid points. To examine the relationship between wind mixing events and primary production, we analyzed wind mixing over the outer shelf between the 50-m and 3500-m isobaths, with a north–south divide at 60°N.

Simulated daily output was summated and/or averaged into seasonal bins for the entire fifty-five year record (1950 to 2005). Since the eastern Bering Sea is located in the Subarctic Pacific, seasons were defined for consistency with Subarctic Pacific temperatures and corresponding sea-ice growth/melt: January through March was defined as 'winter'; April through June was considered as 'spring'; July through September as 'summer'; and October through December was considered 'fall'.

Simulated production by each phytoplankton group within the model was integrated vertically over the water column and analyzed to determine relative contributions to total primary production in the eastern Bering Sea. The simulated average annual primary production for the Southern domain ($160.34 \pm 6.72\ \mathrm{gCm^{-2}\ yr^{-1}}$) falls within the bounds of observations made on the Southern Bering Sea shelf, i.e., ~160 $\mathrm{gCm^{-2}\ yr^{-1}}$ (Walsh and McRoy, 1986), ~150 $\mathrm{gCm^{-2}\ yr^{-1}}$ (Rho and Whitledge, 2007), and 125–175 $\mathrm{gCm^{-2}\ yr^{-1}}$ (Springer et al., 1996), indicating that the model has some skill for this region. Simulated annual primary production in the northern domain was larger ($187.56 \pm 12.73\ \mathrm{gCm^{-2}\ yr^{-1}}$) than the southern domain, primarily due to the increase in simulated production in the Bering Strait. The seasonal cycle of monthly averaged primary production in the southern domain (Fig. 2) is compared to in-situ primary production measurements covering approximately thirty-years: 1978–1981 and 1997–2000 (Rho