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Influences of sea ice on the Eastern Bering Sea: NCAR CESM simulations and comparison with observations

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ABSTRACT

We examine the influences of sea ice on the Eastern Bering Sea (EBS) regional oceanography on seasonal and inter-annual time scales using the National Center for Atmospheric Research-Community Earth System Model (NCAR CESM) simulations, comparing the modeling results with satellite and *in situ* observations when possible. While the modeled mean seasonal cycle of ice cover in the EBS middle shelf is generally within the uncertainty range of satellite observations, in the northern domain (north of 59°N), the simulation reaches its annual maximum in April instead of in March, as observed by satellite remote sensing; modeled ice reduction in late spring in the region is also slower than observations. Despite this bias, the simulation captures the observed seasonal transit of freshwater from the north to the south via ice advection; en route, the sea ice melts, cooling and freshening the local water column. On inter-annual time scales, modeling results suggest that extensive ice cover persisting into spring in the central EBS leads to cold anomalies in the bottom water, especially on the middle and inner shelves of the southern domain. The corresponding salinity anomalies are positive in the northern coastal domain, and weak but negative in the southern middle shelf. The associated 10-m ocean current anomalies are southward on the shelf and directed offshore in the slope region. Comparing years 1961–2005 versus years 2005–2050, the Probability Distribution Function of ice cover on the EBS middle shelf shifts northward by ~2° latitude.

1. Introduction

The Bering Sea is part of North Pacific Subarctic and is 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 (~500 km) and flat (with depth less than 180 m). As early as November, sea ice begins forming in the northern EBS, and under the prevailing wind conditions, is transported southward 700–1000 km, and in years with extensive sea ice, the ice can cover 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 in the EBS is highly variable on inter-annual scales, but thus far, shows no significant trends since the beginning of the satellite record in 1979 (Brown et al., 2011).

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 (~3 °C) and fresher than during years with little ice (Stabeno et al., 2010, 2012b; Ladd and Stabeno, 2012; Sullivan et al., 2014). The timing of ice retreat also influences the timing of the spring phytoplankton bloom (Sigler et al., 2014), 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). During the summer, the inner or coastal domain (water depth < 50 m) is characterized as well mixed or weakly stratified, while the middle domain (50–100 m) has well defined two-layer structure with a wind mixed surface layer and tidally mixed bottom layer. The outer domain (100–180 m) is more oceanic,

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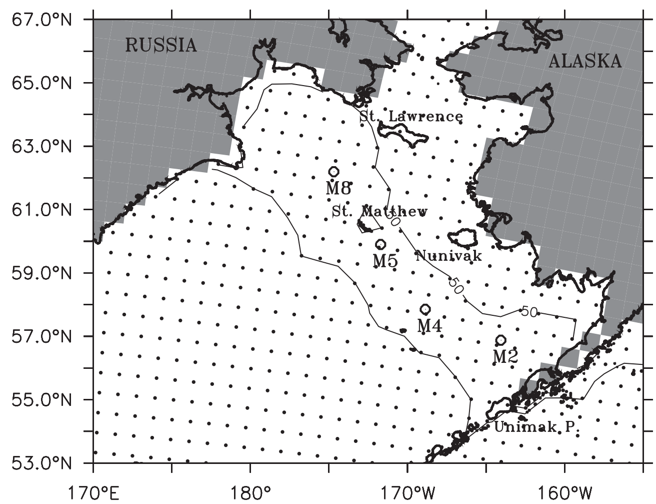

Fig. 1. Study area. The circles mark the ocean moorings in the Eastern Bering Sea shelf used in this study and their names. Gray (white) area is land (ocean) in the CESM model, and the dots indicate ocean grid points. Note that St. Lawrence, St Matthew, and Nunivak Islands are not represented by the CESM grid. Thin black lines indicate the 50-m and 200-m ocean depth in CESM.

with a well-mixed surface layer and bottom layer separated by an intermediate layer. In the middle domain, the influence of winter/spring sea ice persists through the following summer. As part of a biophysical observing network on the EBS shelf, four moorings in the middle domain (M2, M4, M5 and M8) (Fig. 1) provide long time series (10–19 years) of temperature and salinity data (e.g. Stabeno et al., 2010, 2012a, 2012b; Sigler et al., 2014; Sullivan et al., 2014).

Sea ice and ocean variability in the EBS have been studied in regional ocean–ice circulation models. These models are often driven by “observed” atmospheric states of the recent past, hence the name “hindcast”. For example, a regional hindcast simulation of the northeast Pacific from year 1969 to 2005 is shown to have the most skills in reproducing inter-annual variability of ice concentration in the EBS and subsurface ocean (60 m) temperature anomalies (Danielson et al., 2011a). Zhang et al. (2010) argue that a substantial inter-annual variability of the Bering Sea ice cover is controlled by changes in the wind-driven advection and melting at the ice edge, again using a regional model of the northern hemisphere north of 39°N. Another class of numerical models used to study the ocean and sea ice is climate models. Climate models include all components of the earth's system—atmosphere, land, ocean, sea ice, and simulate the interactions among them.

The purpose of this study is to examine the impacts of sea ice on the EBS shelf water properties, using output from a global climate model, the NCAR-CESM (National Center for Atmospheric Research-Community Earth System Model), and compare model output with *in situ* (primarily data from moorings) and satellite observations. NCAR-CESM is a well-known global climate model but to the best of our knowledge, its simulation in the EBS has not been examined. We will examine sea ice variability on seasonal, inter-annual, and decadal time scales. Pan-Arctic sea ice is projected to decline in the future under Greenhouse Gas (GHG) forcing but there are large uncertainties (Wang and Overland, 2009). Climate signals associated with GHGs and aerosol forcing are not spatially uniform. 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., 2012a, 2012b; Brown and Arrigo, 2012).

The paper is organized as follows. In Section 2 we describe the satellite sea ice concentration and the mooring data used in this study; we also introduce the global climate model and the model output, and describe methodology briefly. Spatiotemporal variability of sea ice simulated by the model and influences of sea ice on the upper ocean are examined, and compared with observations in Section 3. In Section 4 we summarize major findings from this study and discuss the implications of these results on the EBS ecosystem.

2. Data and methods

2.1. Satellite and mooring data

Ice concentration maps are derived using data from the Bootstrap algorithm files of daily ice concentration downloaded from the National Snow and Ice Data Center (NSIDC), available at sidads.colorado.edu/pub/DATASETS/nsidc0079_gsfc_bootstrap_seaice/final-gsfc/north/daily/. 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 (Comiso, 2000), 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, see Fig. 1) that have been maintained by NOAA since the 1990s. Percent of ice cover from satellite was averaged over these 100 km by 100 km regions and a monthly climatology was calculated.

The four moorings used in this study are described in detail in Stabeno et al. (2012a and 2012b). In general, they are subsurface moorings (except M2 in the summer which is a surface mooring) made of chain. Each mooring measures temperature, and salinity throughout the water column and chlorophyll fluorescence at ~11 m.

2.2. Numerical model

The NCAR-CESM is a global coupled ocean–sea ice–atmosphere–land model (Gent et al., 2011) 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-now 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 also 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 (it is ~60 km in the Bering Sea region) for the ocean and sea-ice components. The external climate forcing factors (including natural and anthropogenic components) vary with time. We used two types of model output. First, the monthly averaged ocean and sea ice states from the CESM “historical” and “RCP” (Representative Concentration Pathways) simulations were downloaded from NCAR data mass storage. The “historical” simulations were initialized from a spun-up state of the climate system under preindustrial GHGs forcings, and cover years 1850–2005 (we only used output from 1961 onward), while the “RCP” simulations were initialized from the climate state of the model at the end of the “historical” simulations, and cover years 2006–2100 and beyond (Gent et al., 2011). The GHGs concentration and aerosol load in historical runs are based on observations, while those in the RCP runs are projections from different emission scenarios. RCP runs