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Processes driving sea ice variability in the Bering Sea in an eddying ocean/sea ice model: Mean seasonal cycle

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ABSTRACT

The seasonal cycle of sea ice variability in the Bering Sea, together with the thermodynamic and dynamic processes that control it, are examined in a fine resolution (1/10°) global coupled ocean/sea-ice model configured in the Community Earth System Model (CESM) framework. The ocean/sea-ice model consists of the Los Alamos National Laboratory Parallel Ocean Program (POP) and the Los Alamos Sea Ice Model (CICE). The model was forced with time-varying reanalysis atmospheric forcing for the time period 1970–1989. This study focuses on the time period 1980–1989. The simulated seasonal-mean fields of sea ice concentration strongly resemble satellite-derived observations, as quantified by root-mean-square errors and pattern correlation coefficients. The sea ice energy budget reveals that the seasonal thermodynamic ice volume changes are dominated by the surface energy flux between the atmosphere and the ice in the northern region and by heat flux from the ocean to the ice along the southern ice edge, especially on the western side. The sea ice force balance analysis shows that sea ice motion is largely associated with wind stress. The force due to divergence of the internal ice stress tensor is large near the land boundaries in the north, and it is small in the central and southern ice-covered region. During winter, which dominates the annual mean, it is found that the simulated sea ice was mainly formed in the northern Bering Sea, with the maximum ice growth rate occurring along the coast due to cold air from northerly winds and ice motion away from the coast. South of St Lawrence Island, winds drive the model sea ice southwestward from the north to the southwestern part of the ice-covered region. Along the ice edge in the western Bering Sea, model sea ice is melted by warm ocean water, which is carried by the simulated Bering Slope Current flowing to the northwest, resulting in the S-shaped asymmetric ice edge. In spring and fall, similar thermodynamic and dynamic patterns occur in the model, but with typically smaller magnitudes and with season-specific geographical and directional differences.

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1. Introduction

The subpolar North Pacific Ocean and the western Arctic basin are connected via the semi-enclosed Bering Sea. The sea ice distribution in this marginal sea is highly seasonal and is impacted by a vigorous mesoscale eddy field (e.g., Johnson et al., 2004). Its waters contain one of the most productive marine ecosystems in the world, and consequently support a large oceanic fishery for both commercial and subsistence use (e.g., Hunt et al., 2011). Hence this region is important both climatically and economically. Understanding the processes that control the temporal evolution of the sea ice distribution is vital to anticipating how the physical-biological system will change in future years and decades (e.g., Wang et al., 2012).

The dominant change in sea ice cover in the Bering Sea is associated with the seasonal cycle. A conveyor belt mechanism, with a northern source, a southern sink, and an intermediate zone where ice is transported southward by northerly winds, has been proposed to explain the basic north–south structure using observations alone (Muench and Ahlnas, 1976; Pease, 1980). These satellite and in situ observations (Muench and Ahlnas, 1976; Pease, 1980; Wang et al., 2009; Stabeno et al., 2001), however, provide a limited perspective on what controls the seasonal extent and thickness of the ice. So numerical simulations are needed to better understand the dynamics and thermodynamics of these variations.

Previous sea-ice modeling studies of the Bering Sea have revealed a strong sensitivity to the types of parameterizations used in the ice model, the structure of the background oceanic circulation, and the details of the atmospheric forcing. Bitz et al. (2005) studied global sea ice in version 2 of the National Center for

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Atmospheric Research Community Climate System Model (NCAR CCSM2), including thermodynamic and dynamic balances on a seasonal mean basis. They noted that in the Bering Sea, the low latitude of the ice edge is associated with small ocean heat flux convergence near the ice edge. Zhang et al. (2010), using the multicategory thickness and enthalpy distribution (TED) sea ice model (Zhang and Rothrock, 2001) embedded in the Los Alamos National Laboratory Parallel Ocean Program (POP), focused on interannual sea ice variations in the Bering Sea, which they found to be dominated by wind-driven changes in ice transport and the ocean thermal front in the southern Bering Sea. Using the Regional Ocean Modeling System (ROMS) that included a sea ice model, Danielson et al. (2011) showed that although the simulated seasonal structure of the sea ice pattern was realistic, the spring retreat of sea ice in the model was too slow compared to observations. Cheng et al. (2014) used the Community Earth System Model (CESM) to examine the effects of sea ice on the upper ocean on the shelf of the Eastern Bering Sea.

Because of the economic and climatic importance of the Bering Sea, a detailed investigation of the processes involved in establishing the climatological seasonal distribution of sea ice is needed. This can then form a baseline for determining the controls on the interannual changes in sea ice (see Li et al., 2014) and those associated with global warming on long time scales.

We study the seasonal cycle of Bering Sea ice distribution in a forced global fine-resolution ocean/sea-ice simulation in the CESM framework. The ocean/sea-ice model consists of POP and the Los Alamos Sea Ice Model (CICE). This simulation was run with Coordinated Ocean-Ice Reference Experiment version 2 (CORE2) interannually-varying atmospheric forcing.

In the following sections, we introduce the sea ice-ocean model (Section 2) and compare the simulated results with available satellite observations (Section 3). Next, we determine the relative importance of the terms in the thermodynamic and dynamic equations controlling sea ice volume variability (Section 4), and we examine the relationship between sea ice variability and atmospheric and oceanic conditions (Section 5). Lastly, we summarize the results and discuss directions for future work (Section 6).

2. Coupled ocean/sea-ice model

We use output from a fine resolution (nominally 1/10-degree) global coupled ocean/sea-ice simulation configured in the CESM framework (McClean et al., 2014, in preparation). The ocean and sea ice components are the LANL POP and CICE models that are coupled in CESM via Flux Coupler version 7 (CPL7) (Craig et al., 2012). This simulation was configured on a tripole grid with poles in Canada, Russia and Antarctica. Details of the global ocean bathymetry for this tripole grid are found in McClean et al. (2011). Fig. 1 shows the ocean model bathymetry of the Bering Sea, as well as the regional temperature grid subsampled at ten grid point intervals. Sea-ice variability and its causes were studied in earlier forced coupled POP/CICE simulations configured at lower horizontal resolution, e.g., by Ivanova et al. (2012), Prasad et al. (2005) and Hunke et al. (2008).

POP is a *z*-level ocean general circulation model that solves the three-dimensional primitive equations for ocean temperature, salinity, and momentum (Dukowicz and Smith, 1994). It has an implicit free surface. Partial bottom cells were used for improved representation of flow over the bottom boundary. This POP configuration has 42 vertical levels whose thickness ranges from 10 m in the uppermost level to 250 m in the deep ocean. The horizontal resolution is around 6 km in the Bering Sea. Weak surface salinity restoring with an effective timescale of about 4 years was used in this simulation to limit model drift. This version of POP uses the K-Profile Parameterization (KPP) for vertical mixing. It does not include tidal forcing.

CICE utilizes the energy-conserving thermodynamic sea ice model of Bitz and Lipscomb (1999) to compute ice/snow growth and melt rates. CICE has one thermodynamic snow layer and four thermodynamic ice layers. CICE uses a subgridscale ice thickness distribution with five ice thickness categories: 0.00–0.60 m, 0.60–1.40 m, 1.40–2.40 m, 2.40–3.60 m, >3.60 m. For each ice thickness category, the model calculates the ice and snow thickness changes and vertical temperature profiles based on vertical radiative, turbulent, and conductive energy fluxes. The model includes the effect of brine pockets on effective specific heat capacity and thermal conductivity due to internal melting and freezing. The salinity is prescribed to follow a vertical profile that is constant in time. CICE uses the elastic-viscous-plastic (EVP) sea ice dynamic model of Hunke and Dukowicz (1997) to compute ice velocities. The ice momentum equation involves 5 terms: wind stress, ocean stress, divergence of the internal ice stress tensor, the Coriolis force, and gravitational force due to the sea surface slope. CICE uses an incremental remapping advection scheme to transport sea ice in various thickness categories (Lipscomb and Hunke, 2004).

This ocean/sea ice simulation was forced with CORE2 interannually-varying atmospheric forcing from 1970–1989 (Large and Yeager, 2004, 2009). CORE2 fluxes are based upon 6-hourly (1948–2006) near-surface vector wind, specific humidity, density, and air temperature based on National Center for Environmental Prediction (NCEP) reanalysis, daily downward radiation (1984–2006) from International Satellite Cloud Climatology Project (ISCCP) data (Zhang et al., 2004), and monthly precipitation (1979–2006) from a combination of satellite observations. Climatological mean annual cycles are used for all radiation fluxes (1948–1983) and precipitation (1948–1978) before the satellite observing periods. Some data sets are adjusted using observations. Over the Arctic cap north of 70°N, 12 monthly adjustments are made to the surface air temperature based on the polar exchange at the sea surface (POLES) data (Rigor et al., 2000). Adjustments are also made to the NCEP vector winds using QSCAT satellite scatterometer wind vectors. Turbulent fluxes are obtained using bulk formulae, the near surface NCEP atmospheric state, and upper-level model temperature and velocity (Large and Yeager, 2004, 2009; Griffies et al., 2009, 2012). CORE2 is on a T62 grid with a horizontal resolution of ~100 km (east–west) and ~200 km (north–south) in the Bering Sea. This CORE2 forcing was also used by Danielson et al. (2011) to drive Bering Sea simulations using ROMS (Haidvogel et al., 2008).

This simulation was integrated for years 1970–2009. At the time of our analyses the model had only been run through 1989. Hence, we present results from 1980–1989 as the first 10 years (1970–1979) were treated as a spin-up period. The sea-ice was initialized using uniform 2 m thick ice delineated by an ice edge that was chosen to be consistent with the location of the climatological 15% sea ice concentration contour from the Special Sensor Microwave Imager (SSM/I) data for January. The ocean was initialized from rest using potential temperature and salinity from the World Hydrographic Program Special Analysis Center (WHP SAC) climatology (Gouretski and Koltermann, 2004). See McClean et al. (2014) for further details.

The model saves monthly-mean variables along with accumulated terms in the thermodynamic and dynamic balances (e.g., ice volume tendency terms due to thermodynamics and dynamics). The primary equation of interest is the equation partitioning the ice volume tendency $\frac{\partial V}{\partial t}$ (partial time derivative of ice volume) into two components:

$$\frac{\partial V}{\partial t} = \frac{\partial V_T}{\partial t} + \frac{\partial V_D}{\partial t} \quad (1)$$

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