The influence of sea ice and snow cover and nutrient availability on the formation of massive under-ice phytoplankton blooms in the Chukchi Sea

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ARTICLE INFO

ABSTRACT

A coupled biophysical model is used to examine the impact of changes in sea ice and snow cover and nutrient availability on the formation of massive under-ice phytoplankton blooms (MUPBs) in the Chukchi Sea of the Arctic Ocean over the period 1988–2013. The model is able to reproduce the basic features of the ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment) observed MUPB during July 2011. The simulated MUPBs occur every year during 1988–2013, mainly in between mid-June and mid-July. While the simulated under-ice blooms of moderate magnitude are widespread in the Chukchi Sea, MUPBs are less so. On average, the area fraction of MUPBs in the ice-covered areas of the Chukchi Sea during June and July is about 8%, which has been increasing at a rate of 2% yr^{-1} over 1988–2013. The simulated increase in the area fraction as well as primary productivity and chlorophyll a biomass is linked to an increase in light availability, in response to a decrease in sea ice and snow cover, and an increase in nutrient availability in the upper 100 m of the ocean, in conjunction with an intensification of ocean circulation. Simulated MUPBs are temporally sporadic and spatially patchy because of strong spatiotemporal variations of light and nutrient availability. However, as observed during ICESCAPE, there is a high likelihood that MUPBs may form at the shelf break, where the model simulates enhanced nutrient concentration that is seldom depleted between mid-June and mid-July because of generally robust shelf-break upwelling and other dynamic ocean processes. The occurrence of MUPBs at the shelf break is more frequent in the past decade than in the earlier period because of elevated light availability there. It may be even more frequent in the future if the sea ice and snow cover continues to decline such that light is more available at the shelf break to further boost the formation of MUPBs there.

1. Introduction

Arctic sea ice extent has decreased dramatically in recent years, particularly in the Pacific sector of the Arctic Ocean including the Chukchi Sea (e.g., Serreze et al., 2007; Stroeve et al., 2012; Comiso, 2012). This ice decrease is in response to increasing air temperatures, changes in ocean heat transport, increased storminess, reduced cloudiness, and increased penetration of solar radiation into the upper ocean (e.g., Perovich et al., 2008; Kay et al, 2008; Steele et al., 2010; Overland et al., 2012; Zhang et al., 2013; Parkinson and Comiso, 2013). With the increased sea ice melt in the Arctic, the proportion of first year ice relative to older, thicker ice in the Pacific sector is much greater than before (e.g., Kwok, 2007; Maslanik et al., 2007, 2011; Stroeve et al., 2012). First year sea ice is not only relatively thin but also more susceptible to the development of melt ponds, both of which transmit more light to the underlying water column (e.g., Light et al., 2008; Frey et al., 2011). Warmer air temperatures also promote more rapid and earlier melting of snow from the surface of the sea ice, which increases penetration of light (Nicolaus et al. 2012). More light penetration not only increases the input of heat, warming the upper water column and strengthening stratification, but also

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promotes greater primary production (e.g., Mundy et al., 2009). Greater primary production, observed by satellite for open water areas and simulated in models for both open water and ice-covered areas, has been found in recent years in response to the decreased sea ice extent and longer phytoplankton growing season, particularly in the Chukchi Sea (e.g., Arrigo et al., 2008; Zhang et al., 2010a).

Despite its extreme polar conditions, the Chukchi Sea is ranked among the most productive seas in the world (e.g., Gosselin et al., 1997; Hill and Cota, 2005). Light, temperature, and nutrients govern the variability of the biological productivity in the Chukchi Sea, as in other Arctic peripheral seas (Andersen, 1989; Smith and Sakshaug, 1990; Gosselin et al., 1997; Hill and Cota, 2005; Lee and Whitledge, 2005). The vast shallow continental shelf of the Chukchi Sea serves as a link between the Pacific and the Arctic oceans. Pacific water, a major source of buoyancy and nutrients to the Arctic Ocean, flows over the Chukchi shelf (Woodgate et al., 2005; Weingartner et al., 2005; Codispoti et al., 2005). Advection of Pacific water, upwelling/downwelling along the shelf break, and cross-shelf exchanges between shelf and basin influence biological and chemical distributions and processes in the Chukchi Sea.

In early July 2011, the ICESCAPE (Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment) project observed a massive phytoplankton bloom in the northern Chukchi Sea > 100 km north of the ice edge (Arrigo et al., 2012, 2014). The occurrence of this massive under-ice phytoplankton bloom (MUPB) is attributed to increased penetration of light to the upper ocean through thin ice and melt ponds (Arrigo et al., 2012, 2014; Palmer et al., 2014) and ocean dynamics such as upwelling in the shelf break areas (e.g., Pickart et al., 2013; Spall et al., 2014). Satellite-based analysis deduced that under-ice phytoplankton blooms, defined by chlorophyll *a* (chl *a*) values above a threshold of 2.5 mg m^{-3} at the time of sea ice retreat from a location, are widespread in the Chukchi Sea and have been prevalent there for more than a decade prior to the 2011 ICESCAPE discovery (Lowry et al., 2014).

Here we focus on two overarching questions: (1) What is the spatiotemporal variability of MUPBs in the Chukchi Sea? (2) What is the role of changes in sea ice and snow cover and nutrient availability in the formation of MUPBs? We conducted a numerical investigation of the integrated system of the sea ice and snow cover, the ocean, and marine planktonic ecosystem in the Chukchi Sea over the period 1988–2013 using the coupled pan-arctic **B**iology/**I**ce/**O**cean **M**odeling and **A**ssimilation **S**ystem (**BIOMAS**). Our focus is on MUPBs which are defined hereafter by chl *a* values exceeding a threshold of 10 mg m^{-3}, although the study also describes the existence of under-ice phytoplankton blooms of lower magnitude (such as above a threshold of 2.5 mg m^{-3} as identified in Lowry et al., 2014). This threshold of 10 mg m^{-3} is somewhat arbitrary. However, a change in the threshold, by ± 5 mg m^{-3}, does not change the basic outcome of this study.

2. Model description

2.1. Model elements

BIOMAS is a coupled biophysical model (Zhang et al., 2010a, 2014) that has three model elements: a sea ice model, an ocean circulation model, and a pelagic biological model. The pelagic biological model is an 11-component marine pelagic ecosystem model that includes two phytoplankton components (diatoms and flagellates), three zooplankton components (microzooplankton, copepods, and predator zooplankton), dissolved organic nitrogen, detrital particulate organic nitrogen, particulate organic silica, nitrate, ammonium, and silicate (see Fig. 3 in Zhang et al., 2014;

also see Kishi et al., 2007). Values of key biological parameters used in the model are listed in Zhang et al. (2010a). The model does not simulate sea ice algae.

The ocean circulation model is based on the Parallel Ocean Program (POP) developed at Los Alamos National Laboratory (Smith et al., 1992). The POP ocean model is modified by Zhang and Steele (2007) so that open boundary conditions can be specified. The POP ocean model is further modified by Zhang et al. (2010b) to incorporate tidal forcing arising from the eight primary constituents (M2, S2, N2, K2, K1, O1, P1, and Q1) (Gill, 1982). The tidal forcing consists of a tide generating potential with corrections due to both the earth tide and self-attraction and loading following Marchuk and Kagan (1989).

The sea ice model is a thickness and enthalpy distribution (TED) sea ice model (Zhang and Rothrock, 2003; Hibler, 1980). The TED sea ice model has eight categories each for ice thickness, ice enthalpy, and snow depth. The centers of the eight ice thickness categories are 0, 0.38, 1.30, 3.07, 5.97, 10.24, 16.02, and 23.41 m (also see Zhang et al., 2010b). Thus the first category is actually the open water category, while the other seven categories represent ice of various thicknesses. It is adopted from the **P**an-arctic **I**ce/**O**cean **M**odeling and **A**ssimilation **S**ystem (PIOMAS; Zhang and Rothrock, 2003) and able to assimilate satellite observations of sea ice concentration, following Lindsay and Zhang (2006), and sea surface temperature (SST), following Manda et al. (2005) (also see Schweiger et al., 2011).

The model estimates the attenuation of photosynthetically active radiation (PAR) in the water column following $PAR(z) = PARfrac \times E_0 \exp[(-\alpha_1 - \alpha_S PF - \alpha_L PD)z]$, where *PARfrac* is the fraction of net shortwave radiation that is photosynthetically active, E_0 is the area mean net shortwave radiation on the ocean surface, α_1, α_S, and α_L are light attenuation coefficients due to seawater and flagellates and diatoms, and *z* is depth (see Zhang et al., 2010a). E_0 is the area weighted average of net shortwave radiation over each of the open water and ice categories calculated by the sea ice model following Maykut and Untersteiner (1971) and Hibler (1980). For open water, net shortwave radiation is directly applied to the ocean surface; for ice categories of various thicknesses, net shortwave radiation is allowed to penetrate through snow and sea ice, with an attenuation coefficient of 20 m^{-1} for snow (Grenfell and Maykut, 1977) and 1.5 m^{-1} for ice (Maykut and Untersteiner, 1971). Note that the sea ice model does not yet include a melt pond parameterization, although we plan to implement this in the future. The value of *PARfrac* ranges from 0.39 to 0.53 globally (Pinker and Laszlo, 1992), reflecting the fact that only part of the solar radiation spectrum is available for photosynthesis. For simplicity, we use a constant value of *PARfrac*=0.43 for this study (Zhang et al., 2010a).

2.2. Model configuration

The BIOMAS model domain covers the Northern Hemisphere north of 39°N (Fig. 1a). The BIOMAS finite-difference grid is based on a generalized orthogonal curvilinear coordinate system with a horizontal dimension of 600×300 grid points. The "north pole" of the model grid is placed in Alaska. Thus, BIOMAS has its highest horizontal resolution along the Alaskan coast and in the Chukchi, Beaufort, and Bering seas. For the Chukchi and Beaufort seas, the model resolution ranges from an average of 4 km in the Alaska coastal areas to an average of ~ 10 km for the whole region (Fig. 1b). There are 26 ocean grid cells across Bering Strait for a good connection between the Pacific Ocean and the Arctic Ocean. To better resolve the mixed layer and the pycnocline, the ocean's vertical dimension has 30 levels of different thicknesses, with 13 levels in the upper 100 m, the top six of which are 5 m thick. The model bathymetry (Fig. 1b) is obtained by merging the IBCAO