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Impacts of sea ice retreat, thinning, and melt-pond proliferation on the summer phytoplankton bloom in the Chukchi Sea, Arctic Ocean

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ABSTRACT

In 2011, a massive phytoplankton bloom was observed in the Chukchi Sea under first-year sea ice (FYI), an environment in which primary productivity (PP) has historically been low. In this paper, we use a 1-D biological model of the Chukchi shelf ecosystem, in conjunction with in situ chemical and physiological data, to better understand the conditions that facilitated the development of such an unprecedented bloom. In addition, to assess the effects of changing Arctic environmental conditions on net PP (NPP), we perform model runs with varying sea ice and snow thickness, timing of melt, melt ponds, and biological parameters. Results from model runs with conditions similar to 2011 indicate that first-year ice (FYI) with at least 10% melt pond coverage transmits sufficient light to support the growth of shade-adapted Arctic phytoplankton. Increasing pond fraction by 20% enhanced peak under-ice NPP by 26% and produced rates more comparable to those measured during the 2011 bloom, but there was no effect of further increasing pond fraction. One of the important consequences of large under-ice blooms is that they consume a substantial fraction of surface nutrients such that NPP is greatly diminished in the marginal ice zone (MIZ) following ice retreat, where NPP has historically been the highest. In contrast, in model runs with < 10% ponds, no under-ice bloom formed, and although peak MIZ NPP increased by 18–30%, this did not result in higher total annual NPP. This suggests that under-ice blooms contribute importantly to total annual NPP. Indeed, in all runs exhibiting under-ice blooms, total annual NPP was higher than in runs with the majority of NPP based in open water. Consistent with this, in model runs where ice melted one month earlier, peak under-ice NPP decreased 30%, and annual NPP was lower as well. The only exception was the case with no sea ice in the region: a weak bloom in early May was followed by low but sustained NPP throughout the entire growth season (almost all of which occurred in deep, subsurface layers), resulting in higher total annual NPP than in cases with sea ice present. Our results also show that both ultraviolet radiation and zooplankton grazers reduce peak open water NPP but have little impact on under-ice NPP, which has important implications for the relative proportion of NPP concentrated in pelagic vs. benthic food webs. Finally, the shift in the relative amount of NPP occurring in under-ice vs. open-water environments may affect total ecosystem productivity.

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1. Introduction

The Arctic Ocean has undergone unprecedented changes in sea ice extent and thickness in recent decades, with old, stable multi-year ice (MYI) being largely replaced by young, thinner first-year ice (FYI) (Maslanik et al., 2011; Stroeve et al., 2012). These changes, which have been particularly pronounced in the Beaufort and Chukchi seas (Meier et al., 2007; Douglas, 2010; Maslanik et al., 2011), are predicted to affect marine primary productivity (PP)

because the timing and intensity of the summer phytoplankton bloom are strongly controlled by the dynamics of sea ice and water column stabilization (Arrigo and van Dijken, 2004; Carmack et al., 2004; Wang et al., 2005). In this region, the summer phytoplankton bloom typically begins in surface waters adjacent to the ice edge where melting and retreating sea ice create a shallow, stable mixed layer (10–20 m over the continental shelf) that is conducive for algal growth (Sakshaug, 2004; Hill and Cota, 2005; Tremblay et al., 2008). This bloom grows rapidly, fueled by high light and abundant nutrients that have been remineralized in place or carried in from outside the region during the long winter months (Carmack et al., 2006; Codispoti et al., 2005, 2009).

Phytoplankton growth in waters beneath the ice has typically been considered minimal (Grebmeier et al., 1995; Sakshaug, 2004)

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because sea ice and snow strongly reflect and attenuate incoming solar radiation (Perovich, 1998; Perovich and Polashenski, 2012), one of the key requirements for phytoplankton growth. However, in 2011, one of the most intense phytoplankton blooms ever recorded was observed under sea ice over the 50 m-deep Chukchi Sea shelf (Arrigo et al., 2012, this issue). This bloom was composed primarily of pelagic diatoms and reached biomass levels of 1291 mg m^{-2} Chl *a* as far as 100 km into the main ice pack under 100% FYI cover 0.8–1.2 m thick (Arrigo et al., 2012). Data indicate that the areas surveyed in open water southeast of the main ice edge likely had previously experienced an under-ice bloom as well (Palmer et al., 2013; Arrigo et al., this issue).

In trying to explain this massive bloom, studies have shown that the thinner sea ice, in combination with ~30% melt pond coverage, increased light transmission to the underlying water column by > 40% compared to unponded bare ice (Frey et al., 2011; Arrigo et al., 2012). As a result, light levels below the ponded ice exceeded the threshold needed for net growth of shade-adapted Arctic phytoplankton (Palmer et al., 2013). However, due to very limited observations, it is still unknown exactly how changing ice conditions relate to the formation of under-ice blooms, including what factors (ice type/thickness, ponds, snow, timing, etc.) promote the development of under-ice blooms, how prevalent these phenomena may be, and/or how under-ice blooms impact both the seasonal pattern of PP as well as total annual net PP (NPP). In fact, although satellite-based studies have suggested that NPP may be increasing in the Arctic due to increased open water area and length of the growing season, none of these studies have considered under-ice NPP (Pabi et al., 2008; Arrigo and van Dijken, 2011; Bélanger et al., 2013).

Indeed, ice conditions corresponding to the 2011 bloom may not be totally unique, as FYI has largely replaced MYI in the entire Arctic Ocean, and well more than half of all Arctic sea ice is now FYI (e.g., 64% of spring ice in 2010 was FYI; Maslanik et al., 2011; NSIDC, 2012). Furthermore, climate models have shown that ice loss may accelerate in the future due to complex feedback loops (Loeng et al., 2006; Comiso et al., 2008; Stroeve et al., 2012). A 2011 report investigating light transmission through various sea ice types all over the Arctic confirmed that on average, (non-deformed) FYI transmits 3-fold more light than MYI largely because of its higher fraction of melt-ponds (Nicolaus et al., 2012). Accordingly, thinner sea ice and the Arctic-wide proliferation of melt ponds may be affecting primary productivity not just in the Chukchi Sea, but wherever these ice conditions prevail, highlighting the need to better understand the factors responsible for initiating, sustaining, and controlling under-ice blooms.

In addition to changes in sea ice and ponds, one factor certain to affect the formation of under-ice blooms is snow depth, as the distribution of snow determines light penetration and controls spatial variability of under-ice light (Perovich, 1996). Grebmeier et al. (1995) showed that snow depth accounted for 70–85% of the variance of under-ice biomass, and that the loss of snow could increase light penetration by > 10-fold. This was confirmed by Apollonio and Matrai (2010), who showed that maximum under-ice PP in the Canadian Archipelago was correlated with snow depths in spring. Importantly, late spring snow cover in the Beaufort–Chukchi region has severely declined in recent years, with a new record low set in 2012 (NSIDC, 2012).

Other potential factors that may aid in the formation of under-ice blooms include ultraviolet radiation (UVR, 280–400 nm), or lack thereof: sea ice and snow strongly attenuate UVR. UVR inhibits photosynthesis and can severely damage genetic material (Holm-Hansen et al., 1993; Holm-Hansen, 1997; de Mora et al., 2000; Helbling et al., 1992; Helbling and Villafañe, 2002; Leu et al., 2007). Thus, thin ice may protect under-ice phytoplankton from harmful UVR while still transmitting sufficient light to support net

photosynthesis, potentially creating an “ideal” habitat for algae to grow. Similarly, reduced grazing rates by zooplankton in cold under-ice waters may allow phytoplankton reach higher biomass levels (e.g., Grebmeier et al., 1995; Hunt et al., 2011). This has been proposed to explain why the consumption of phytoplankton by micro- and mesozooplankton in the cold but highly productive Chukchi Sea is a small fraction of total biomass, resulting in a rich benthos and high rates of export (Grebmeier et al., 1995).

Here, we utilize a one-dimensional (vertical column) nitrogen (N)-based biological model with realistic under-ice light profiles to investigate how changing environmental conditions affect PP in the Chukchi Sea, Arctic Ocean. In particular, our study focuses on understanding what conditions help initiate under-ice blooms, what is needed to sustain and drive massive under-ice blooms, and the impact of under-ice blooms on NPP. Model experiments include variable sea ice (both FYI and MYI) and snow thickness, melt pond fraction, the timing of melt, phytoplankton sensitivity to UVR, and zooplankton grazing.

2. Methods

2.1. General model description

The annual cycle of sea ice, snow, and melt ponds were specified using a combination of satellite and in situ data (Perovich et al., 2003; Druckenmiller et al., 2009; Arrigo et al., this issue). A spectral atmospheric radiative transfer model (Gregg and Carder, 1990, as modified by Arrigo et al., 1998) was used to calculate surface fluxes of UVR and photosynthetically active radiation (PAR, 400–700 nm). This light was propagated through ice, snow, or water based on the two-stream multiple-scattering radiative transfer model described by Saenz (2011) and Saenz and Arrigo (2012). The biological model is a modified version of the ecosystem model for the Ross Sea, Antarctica (Arrigo et al., 2003) and the N-based model of Fasham et al. (1990).

2.2. Model domain

The 1-D model is designed to simulate a 50 m deep water column (1 m vertical resolution) at 72°N, 169°W in the Chukchi Sea, the location of the under-ice phytoplankton bloom observed in 2011 (Arrigo et al., 2012). Sea ice, snow, and melt ponds overlying the water column are represented by a maximum of 10 vertical layers of varying thicknesses (described below), with the minimum thickness of any layer set at 0.02 m. All model runs are from April 15 to October 15, so initial conditions are specified based on the pre-melt time period.

2.3. Seasonal cycles of ice, snow, and water

2.3.1. Standard model run

For the standard model run (described in this section; see Table 1 and Fig. 1A), we used an initial sea ice thickness of 1.6 m based on regional averages of April FYI (Perovich et al., 2003; Druckenmiller et al., 2009). Similarly, we set initial snow depth at 0.32 m, which is an average regional value (April range: 0.22–0.56 m; Perovich et al., 2003; Druckenmiller et al., 2009). Two different types of snow cover were modeled: dry snow, which is new, cold and highly reflective; and wet snow, which is older, melting snow with a lower albedo (Perovich et al., 2003). For snow transitions and melting, the first key date is when dry snow converts to wet snow; we set this date as May 10 based on a regional climatology (Perovich et al., 2003; Druckenmiller et al., 2009). The second key date is when large amounts of wet snow begin to melt. The climatological range for this spans a ~1-month

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