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Evidence of under-ice phytoplankton blooms in the Chukchi Sea from 1998 to 2012

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ABSTRACT

The discovery in 2011 of a massive phytoplankton bloom underneath first-year sea ice in the western Arctic has prompted an investigation of the spatial and temporal distribution of under-ice phytoplankton blooms. Here, we explore the satellite record from years 1998 to 2012 for evidence of under-ice blooms on the Chukchi Sea shelf. Phytoplankton blooms were categorized as under-ice blooms, probable under-ice blooms, or marginal ice zone blooms, depending on bloom timing in relation to the timing of ice retreat. Annual bloom type maps reveal that under-ice phytoplankton blooms were present in every year of the satellite record. Averaged over all years, the combination of under-ice blooms and probable under-ice blooms covered a portion of the observable study area that was 2.5-fold higher than that of marginal ice zone blooms (71.5% and 28.5%, respectively). This finding strongly contradicts the traditional view that phytoplankton in seasonally ice-covered waters bloom only after ice retreat and instead indicates that blooms are initiated whenever light and nutrient availability is sufficient for photosynthesis, a condition often reached early in the season underneath first-year sea ice on nutrient-rich continental shelves. Spatial patterns in bloom type were distinguished relative to the date of ice retreat, with probable under-ice blooms dominating the nutrient-rich western Chukchi Sea and at higher latitudes where ice retreats later, while marginal ice zone blooms were most common in the southern and eastern Chukchi Sea where ice retreats earlier. Our results suggest that under-ice phytoplankton blooms are widespread in the Chukchi Sea and had been prevalent there for more than a decade prior to their discovery in 2011.

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1. Introduction

The seasonally ice-covered marginal shelf seas of the Arctic Ocean are highly productive ecosystems that are characterized in large part by spring phytoplankton blooms that form the base of the food web, supporting a rich array of upper trophic level organisms (Loeng et al., 2005). Until recently, phytoplankton blooms in this region were thought to begin only after the sea ice retreats and the water column stratifies, providing sufficient light for photosynthesis (Hill and Cota, 2005; Sakshaug and Skjoldal, 1989). However, the discovery in 2011 of a massive phytoplankton bloom underneath first-year sea ice in the Chukchi Sea (Arrigo et al., 2012) challenges this long-standing paradigm, revealing that substantial phytoplankton growth is possible in ice-covered seas. The exceptionally high biomass and growth rates across a spatial extent of more than 100 km (Arrigo et al., 2012; Arrigo et al., this issue) suggest that under-ice blooms are important yet overlooked features of Arctic marine ecosystems.

Concurrent with this finding, studies of the under-ice light environment also indicate that phytoplankton blooms may be a widespread phenomenon underneath the ice. In recent decades, multi-year ice over Arctic continental shelves has been largely replaced with thinner, flatter, first-year ice (Comiso, 2012; Kwok and Rothrock, 2009; Maslanik et al., 2011; Stroeve et al., 2011) with a significantly higher melt pond fraction (Polashenski et al., 2012). Because melt-ponded ice transmits 3–10 times more light than bare ice of the same thickness (Frey et al., 2011), the presence of more first-year ice with a higher melt pond fraction corresponds to an increase in the illumination of the water column beneath the sea ice (Perovich et al., 2011). In the eastern Chukchi Sea where the under-ice bloom was observed, up to 55% of the incident light was transmitted through the ice to the water column below. This high transmission paired with very high nutrient concentrations (NO_3^-: 15–20 μM) created an extremely favorable environment for under-ice phytoplankton primary production (Arrigo et al., 2012).

Considering that more than half of the Arctic Ocean consists of continental shelf waters and that pre-bloom surface nutrient concentrations are very high over 30–50% of the Arctic continental shelf (Zhang et al., 2010), Arrigo et al. (this issue) estimate that

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approximately 25% of the Arctic Ocean may be favorable for phytoplankton blooms underneath the ice. The Chukchi Sea in particular stands out as a region with extremely high pre-bloom nutrient concentrations (NO_3^-: >10 μM in non-coastal waters), due to a combination of local remineralization and brine rejection leading to convective wintertime mixing as well as the northward advection of nutrients through the Bering Strait (Zhang et al., 2010). Within the Chukchi Sea there is a nutrient gradient that increases from east to west, with the western Chukchi Sea and the East Siberian Sea filled with nutrient-rich Anadyr water that contains unutilized nutrients from the Bering Sea (Coachman et al., 1975; Hansell et al., 1993). Combined, the presence of high pre-bloom surface nutrients and increased light penetration of the thin ice cover in recent decades suggest that under-ice blooms have likely occurred throughout the region and in years prior to their discovery in 2011.

If phytoplankton blooms prior to ice retreat are indeed widespread, it will be necessary to adjust our traditional understanding of Arctic marine ecosystems. Food web and ecosystem studies in this region (Arrigo and Van Dijken, 2011; Hill and Cota, 2005; Sakshaug, 2003) currently rely on a widely accepted narrative in which, prior to bloom development, the sea ice retreats and the water column stratifies, allowing the bloom to form in well-illuminated waters trailing the ice edge. Blooms initiated in this way are termed ice-edge or marginal ice zone (MIZ) blooms and are proposed to be ubiquitous features throughout the Arctic (Perrette et al., 2011), with many upper trophic level species timing their migrations and life cycles to feed on this large biological pulse (Loeng et al., 2005). The ecological importance of MIZ blooms has been broadly recognized, with estimates that 28–33% of net primary production (NPP) in the Arctic occurs on the shelf within two weeks of ice retreat (Pabi et al., 2008). However, a comparison of satellite-based estimates of annual NPP with field observations in the region of the 2011 *in situ* under-ice bloom, which cannot be seen by ocean color satellite sensors, indicate that satellite-based estimates in some areas may be 10-fold too low (Arrigo et al., this issue). Considering that the presence of phytoplankton blooms prior to ice retreat represents a shift in the timing of peak NPP and that timing is critical for upper trophic level organisms (Kahru et al., 2010; Loeng et al., 2005), our understanding of this ecosystem crucially depends on our ability to characterize the magnitude, history, and importance of under-ice blooms.

In this study, we investigate the temporal and spatial distributions of under-ice blooms in the Chukchi Sea to provide context for the massive bloom observed in 2011 and to gain a more comprehensive understanding of phytoplankton bloom dynamics in this rapidly changing ecosystem. The remote location of this region combined with the difficulty of sampling in ice-covered waters necessitates the use of new approaches to assess the importance of phytoplankton growth beneath the ice. Using satellite data, we identify phytoplankton blooms within two weeks of sea ice retreat and distinguish blooms that were initiated prior to ice retreat (i.e. under-ice blooms) from those that began after ice retreat (i.e. MIZ blooms) based on the amount of phytoplankton biomass present at the time of sea ice retreat. We assume that high chlorophyll *a* (Chl *a*) concentrations at the time of ice retreat indicate a phytoplankton bloom that had developed under the ice, while low initial Chl *a* concentrations that increase following ice retreat indicate a MIZ bloom. Furthermore, considering that non-coastal waters of the Chukchi Sea shelf are characterized by high surface nutrient availability, we assume that areas without a bloom in the two weeks following ice retreat likely supported a bloom that depleted surface nutrients prior to ice retreat (i.e. a probable under-ice bloom), preventing the onset of a subsequent MIZ bloom in open water. Combined, this approach enables an evaluation of the prevalence of under-ice phytoplankton blooms throughout the Chukchi Sea over a 15-year period from 1998 to 2012.

2. Methods

2.1. Study region

The study region for this analysis consists of non-coastal (>50 km from land) continental shelf waters (<200 m) within the Chukchi Sea and a portion of the East Siberian Sea (Fig. 1A). The total area included in the analysis was approximately 425,000 km^2. For comparison, the total area of the Chukchi Sea, including off-shelf waters, is 620,000 km^2 (Jakobsson, 2002). Coastal waters were excluded from the analysis due to the high concentrations of colored dissolved organic matter (CDOM) in this region, which can bias satellite retrievals of Chl *a* (Matsuoka et al., 2011).

2.2. Satellite data

2.2.1. Sea ice cover

Daily sea ice concentrations were obtained for the study region for years 1998–2012 from the Special Sensor Microwave/Imager (SSM/I) at 25 km resolution. Maps of the date of sea ice retreat

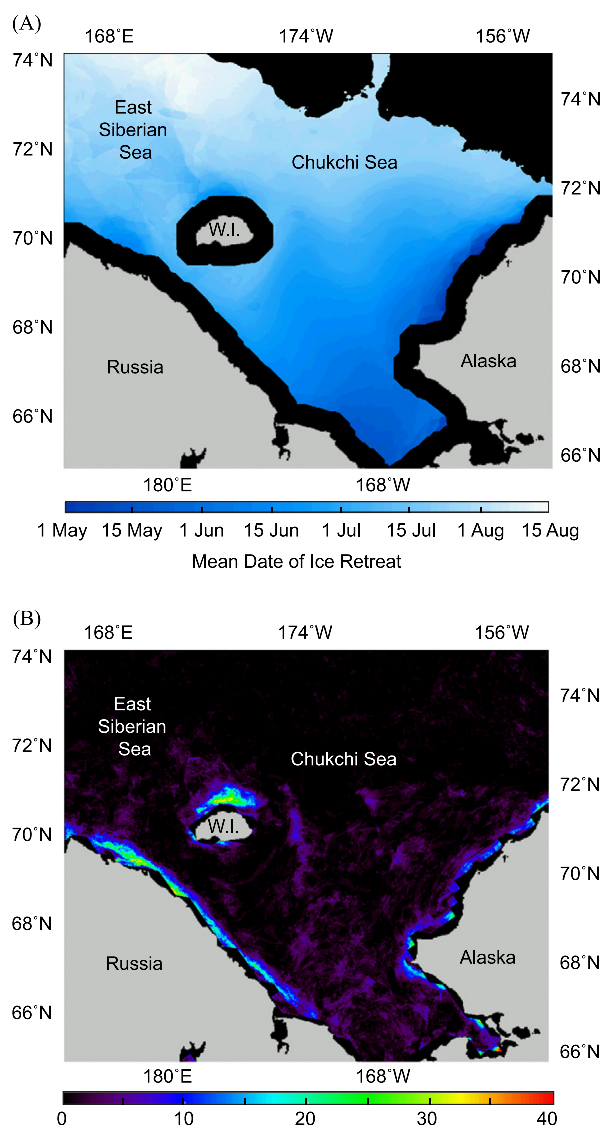

Fig. 1. Maps of the study region displaying (A) the mean date of ice retreat and (B) the cumulative number of Chl *a* retrievals over the 15-year time series within one week prior to the date of sea ice retreat. W.I.=Wrangel Island.

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