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Phytoplankton blooms beneath the sea ice in the Chukchi sea

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ABSTRACT

In the Arctic Ocean, phytoplankton blooms on continental shelves are often limited by light availability, and are therefore thought to be restricted to waters free of sea ice. During July 2011 in the Chukchi Sea, a large phytoplankton bloom was observed beneath fully consolidated pack ice and extended from the ice edge to >100 km into the pack. The bloom was composed primarily of diatoms, with biomass reaching 1291 mg chlorophyll *a* m^{-2} and rates of carbon fixation as high as 3.7 g C m^{-2} d^{-1}. Although the sea ice where the bloom was observed was near 100% concentration and 0.8–1.2 m thick, 30–40% of its surface was covered by melt ponds that transmitted 4-fold more light than adjacent areas of bare ice, providing sufficient light for phytoplankton to bloom. Phytoplankton growth rates associated with the under-ice bloom averaged 0.9 d^{-1} and were as high as 1.6 d^{-1}. We argue that a thinning sea ice cover with more numerous melt ponds over the past decade has enhanced light penetration through the sea ice into the upper water column, favoring the development of these blooms. These observations, coupled with additional biogeochemical evidence, suggest that phytoplankton blooms are currently widespread on nutrient-rich Arctic continental shelves and that satellite-based estimates of annual primary production in waters where under-ice blooms develop are ~10-fold too low. These massive phytoplankton blooms represent a marked shift in our understanding of Arctic marine ecosystems.

1. Introduction

Over the last several decades, the Arctic Ocean has undergone unprecedented changes in sea ice, with summer minimum ice extent declining $>40\%$ since 1979 (Comiso et al., 2008) and first-year ice largely replacing the once prevalent multi-year pack ice (Maslanik et al., 2011; Nghiem et al., 2007). This has produced an ice cover that is substantially thinner and more prone to melting and transport, leading to a markedly extended period of open water, particularly over the last decade (Arrigo and van Dijken, 2011).

Associated with the loss in sea ice on these shelves has been an increase in the amount of light penetrating the surface ocean and a dramatic rise in the productivity of phytoplankton (Arrigo and van Dijken, 2011), the organisms responsible for the bulk of Arctic Ocean primary production and constitute the base of the marine food web. This is particularly true for the Pacific sector of the

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Arctic Ocean where annual production increased by 130% in the East Siberian Sea and 48% in the Chukchi Sea between 1997 and 2009 (Arrigo and van Dijken, 2011). Because sea ice and snow strongly reflect and attenuate incident solar radiation (Perovich, 1998; Perovich and Polashenski, 2012), the growth of phytoplankton at high latitudes is generally thought to begin in the open waters of the marginal ice zone (MIZ) once sea ice retreats in spring, as solar elevation increases and surface waters become stratified by the addition of sea ice melt water (Alexander and Niebauer, 1981; Loeng et al., 2005; Sakshaug, 1997; Hill and Cota, 2005; Perrette et al., 2011). In fact, all current large-scale estimates of primary production in the Arctic Ocean assume that phytoplankton production in the water column under sea ice is negligible (Subba Rao and Platt, 1984; Sakshaug, 2003; Pabi et al., 2008; Arrigo and van Dijken, 2011). However, an intense phytoplankton bloom was recently observed in the Chukchi Sea growing beneath fully consolidated sea ice ranging in thickness from 0.8 to 1.3 m (Arrigo et al., 2012). The development of this bloom has been attributed to increased light transmission through sea ice (Frey et al., 2011) as well as high nutrient concentrations on the Chukchi shelf.

The Chukchi Sea is an inflow shelf (Carmack and Wassmann, 2006) that ventilates the upper halocline of the Arctic Ocean (Woodgate et al., 2005). Water flows northward through the Bering Strait due to the sea surface height differential that results from the salinity difference between the Pacific and Arctic Oceans (Coachman et al., 1975), with the volume flux increasing by 50% between 2001 and 2011 (Woodgate et al., 2012). Upon reaching the Chukchi Sea, the Pacific-origin water separates into three branches that flow around or between Herald and Hanna Shoals (Fig. 1). Although these branches are identified based on water mass properties set within the Bering Sea (Coachman et al., 1975; Overland and Roach, 1987; Weingartner et al., 2005), they also differ significantly with respect to nutrient concentrations (Walsh et al., 1989; Cooper et al., 1997; Codispoti et al., 2005, 2013). The easternmost Alaska Coastal Water (ACW) is relatively warm (1–6 °C), fresh ($S<31.8$), and nutrient-poor ($NO_3^- < 10$ μM) due to the input of river runoff and the biological drawdown of nutrients in the eastern Bering Sea. The Central Channel pathway consists of Bering Shelf Water with moderate nutrients ($NO_3^- \sim 15$ μM) and salinity (31.8–32.5). The westernmost Herald Canyon pathway, containing mostly Anadyr Water, has the highest salinity (32.5–33) and nutrient concentrations (pre-bloom $NO_3^- > 25$ μM) due to the under-utilization of nutrients in the western Bering Sea (Hansell et al., 1993). Upon reaching the shelf break, some of this water turns eastward and flows toward the Beaufort Sea in a relatively swift shelf break jet (Weingartner et al., 2005).

Water mass properties in the Chukchi Sea are further influenced by the seasonal cycle of sea ice. In the winter, brine rejection during sea ice formation mixes the entire water column to extremely cold temperatures (−1.8 °C) (Woodgate et al., 2006). Sea ice formation in polynyas and leads continue to convectively form cold and dense winter water (WW) on the Chukchi shelf throughout the winter. A large fraction of this becomes nutrient-rich Pacific Winter Water that drains through the Chukchi Sea in the spring and eventually fills the Arctic Ocean halocline. As sea ice retreats in spring and summer, the water column becomes re-stratified as surface waters freshen and warm (Woodgate and Aagaard, 2005). WW remaining on the Chukchi shelf in the summer is gradually replaced by relatively warm Pacific Summer Water (Weingartner et al., 2005).

Because of its high nutrient content, the Chukchi Sea is a region of intense summer biological activity with a rich benthic

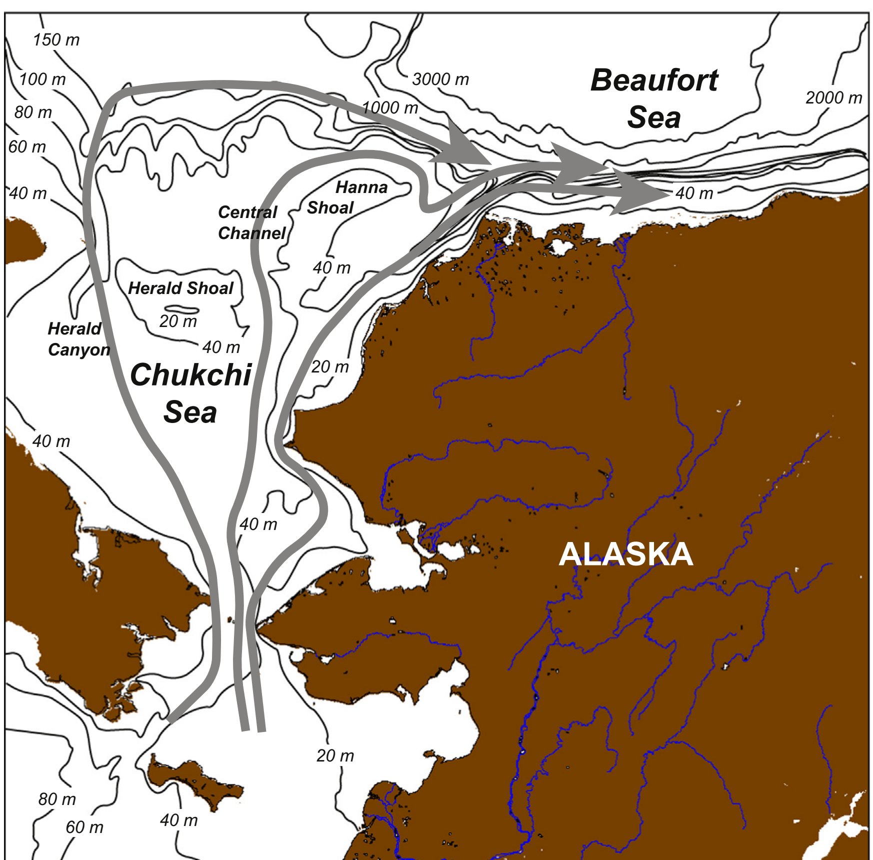

Fig. 1. Map of the Chukchi Sea showing the major bathymetric features and the predominant flow paths from the Bering Sea. Currents modified from Weingartner et al. (2005).

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