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The influence of winter water on phytoplankton blooms in the Chukchi Sea

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ABSTRACT

The flow of nutrient-rich winter water (WW) through the Chukchi Sea plays an important and previously uncharacterized role in sustaining summer phytoplankton blooms. Using hydrographic and biogeochemical data collected as part of the ICESCAPE program (June–July 2010–11), we examined phytoplankton bloom dynamics in relation to the distribution and circulation of WW (defined as water with potential temperature ≤ -1.6 °C) across the Chukchi shelf. Characterized by high concentrations of nitrate (mean: 12.3 ± 5.13 μmol L^{-1}) that typically limits primary production in this region, WW was correlated with extremely high phytoplankton biomass, with mean chlorophyll *a* concentrations that were 3-fold higher in WW (8.64 ± 9.75 μg L^{-1}) than in adjacent warmer water (2.79 ± 5.58 μg L^{-1}). Maximum chlorophyll *a* concentrations (~30 μg L^{-1}) were typically positioned at the interface between nutrient-rich WW and shallower, warmer water with more light availability. Comparing satellite-based calculations of open water duration to phytoplankton biomass, nutrient concentrations, and oxygen saturation revealed widespread evidence of under-ice blooms prior to our sampling, with biogeochemical properties indicating that blooms had already terminated in many places where WW was no longer present. Our results suggest that summer phytoplankton blooms are sustained for a longer duration along the pathways of nutrient-rich WW and that biological hotspots in this region (e.g. the mouth of Barrow Canyon) are largely driven by the flow and confluence of these extremely productive pathways of WW that flow across the Chukchi shelf.

1. Introduction

Located north of the Bering Strait between Alaska and Far East Russia, the Chukchi Sea is the gateway of the Pacific Ocean to the Arctic. With a total area of 620,000 km^2 and a median depth of approximately 50 m (Jakobsson, 2002), the Chukchi Sea contains a wide and shallow continental shelf that comprises 10% of the total Arctic Ocean shelf area (Jakobsson et al., 2004; Carmack and Wassmann, 2006). The importance of the Chukchi Sea as an inflow shelf sea (Carmack and Wassmann, 2006) that ventilates the upper halocline of the Arctic Ocean (Woodgate and Aagaard, 2005b; Woodgate et al., 2005a) motivates a thorough understanding of the physical and biogeochemical processes that modify Pacific-origin water masses as they transit the shelf en route to the basin.

The Chukchi Sea is a region of intense summer biological activity with a rich benthic community that supports abundant populations of marine mammals and seabirds (Loeng et al., 2005; Dunton et al., 2005; Grebmeier et al., 2006). In recent decades, the Arctic Ocean has experienced unprecedented reductions in sea ice cover and thickness (Kwok and Rothrock, 2009; Serreze et al., 2007; Stroeve et al., 2011), accompanied by an increased heat and freshwater flux through the Bering Strait (Woodgate et al., 2012). The impacts of these changes on the global carbon cycle (Bates et al., 2011) and the marine ecosystem of the Chukchi Sea (Grebmeier, 2012) are only beginning to be understood. Of particular interest is how the primary producers that form the base of the food web are being affected by the pronounced changes in the physical environment. Previous work suggests that phytoplankton are already responding to reduced sea ice cover and thickness, with evidence for increased primary production in open water (Arrigo and Van Dijken, 2011) and beneath the thinning sea ice cover (Arrigo et al., 2012, 2014; Palmer et al., 2014, 2013; Lowry et al., 2014). To fully comprehend the significance of these

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changes, it is necessary to further our understanding of bloom dynamics in this region.

Pacific-origin water flows northward through the Bering Strait due to the sea surface height differential resulting from the salinity difference between the Arctic and Pacific Oceans (Coachman et al., 1975). Upon entering the Chukchi Sea, the flow is steered primarily by shelf bathymetry into three branches, which to some degree are distinguished by water mass properties set within the Bering Sea (Coachman et al., 1975; Overland and Roach, 1987; Weingartner et al., 2005). Differences in temperature, salinity (S), and nutrient concentrations between these pathways result in significant variations in biogeochemical properties across the shelf (Walsh et al., 1989; Cooper et al., 1997; Codispoti et al., 2005, 2013). In summertime, the easternmost pathway advects Alaskan Coastal Water, which is relatively warm (>2 °C), fresh ($S<32$), and nutrient-poor (pre-bloom $\mathrm{NO_3^-} < 10\ \mu\mathrm{mol\ L^{-1}}$) due to the input of river runoff and the biological utilization of nutrients in the eastern Bering Sea. The middle flow branch, which progresses through the Central Channel between Hanna and Herald Shoals, consists largely of colder and saltier Bering Shelf Water (BSW) with moderate nutrient concentrations (pre-bloom $\mathrm{NO_3^-} > 10\ \mu\mathrm{mol\ L^{-1}}$). The westernmost branch follows Hope Valley into Herald Canyon and transports a large amount of Anadyr Water (AW), which is the saltiest of the three Chukchi Sea water masses and has the highest nutrient concentration (pre-bloom $\mathrm{NO_3^-} > 15\ \mu\mathrm{mol\ L^{-1}}$), owing to the upwelling of nutrient-rich waters in the Northern Bering Sea (Hansell et al., 1993; Lee et al., 2007). The precise division of transport between the branches is currently unknown. Using relatively sparse mooring data, Woodgate et al. (2005b) estimated a roughly even split between the branches, but recent shipboard surveys suggest that, in summer, the majority of the flow is contained in the two eastern branches (Gong and Pickart, this issue; Itoh et al., 2015).

The water mass properties in the Chukchi Sea are heavily influenced by the seasonal cycle of sea ice, both locally on the Chukchi shelf and to the south in the Bering Sea. In the winter, sea ice formation causes brine rejection that can mix the entire water column and cool it to the freezing point (approximately -1.9 °C) (e.g. Woodgate et al., 2005b). When the convection reaches the bottom it suspends regenerated nutrients from the sediments into the water column. The resulting water mass, known as winter water (WW), is cold, dense, and high in nutrients. The water so formed in the Bering Sea flows northward through Bering Strait during the winter months and into the spring (Woodgate et al., 2005b). However, the occurrence of leads and polynyas on the Chukchi shelf during the winter can lead to further re-freezing and the formation of “hyper-saline” WW (Weingartner et al., 1998; Itoh et al., 2012).

Although there are few winter and spring measurements in the Chukchi Sea, modeling results (Zhang et al., 2010) and field studies (e.g. Codispoti et al., 2005) indicate that surface waters are nutrient-replete in the Chukchi Sea, with $\mathrm{NO_3^-}$ concentrations as high as 10–20 $\mu\mathrm{mol\ L^{-1}}$ in non-coastal shelf waters. As sea ice retreats in the summer, the water column becomes re-stratified as surface waters freshen and warm due to a combination of ice melt, solar heating, and the influx of Pacific summer waters from the Bering Sea (Woodgate and Aagaard, 2005a; Gong and Pickart, this issue). The WW remaining on the Chukchi shelf is gradually modified by mixing with these waters and/or by direct solar heating (Weingartner et al., 2005; Gong and Pickart, 2012). As a result, the presence of WW on the shelf in summer is spatially variable, with residence times determined by the bathymetry and circulation of the Chukchi Sea (Pickart et al., submitted for publication). By the end of summer, all of the WW gets flushed from the shelf, largely through Herald Canyon in the west (Pickart et al., 2010) and Barrow Canyon in the east (Pickart et al., 2005; Woodgate et al., 2005b; Itoh et al., 2015).

The high nutrient content and persistence of WW on the Chukchi shelf through the spring and summer suggests that this water mass plays an important, yet previously uncharacterized, role in influencing phytoplankton blooms. In this study, we examine the relationship between the early-summer hydrographic conditions in the Chukchi Sea and the phytoplankton blooms that occur on the shelf, with specific focus on the role of the nutrient-rich WW in initiating and sustaining phytoplankton blooms both before and after sea ice retreat. We assess the biological significance of WW in the summer as it drains across the Chukchi shelf by relating the location of WW to biogeochemical properties such as phytoplankton biomass, oxygen ($\mathrm{O_2}$) saturation, and concentrations of nutrients and dissolved inorganic carbon (DIC). To fully elucidate the relationship between WW and phytoplankton blooms in this seasonally ice-free ecosystem, we incorporate field results from both under the sea ice and in open water, and use satellite imagery of sea ice to provide further environmental context.

2. Methods

2.1. Study region

As part of the NASA-funded Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) program, two field campaigns were carried out in the Chukchi Sea aboard USCGC Healy, from 18 June to 16 July 2010 (HLY1001) and from 28 June to 24 July 2011 (HLY1101). The present analysis focuses on the continental shelf of the northeastern Chukchi Sea, using data from seven transects that together span the shallow shelf waters of this region (Fig. 1). Six of the seven transects considered here were occupied in 2011, while the southernmost transect (the Central Channel line) was sampled in 2010. The Chukchi North and Hanna Shoal North transects were occupied on both cruises, providing an opportunity to compare hydrographic conditions between 2010 and 2011. Except where otherwise noted, data presented for these two transects were collected in 2011 when the sampling was more comprehensive.

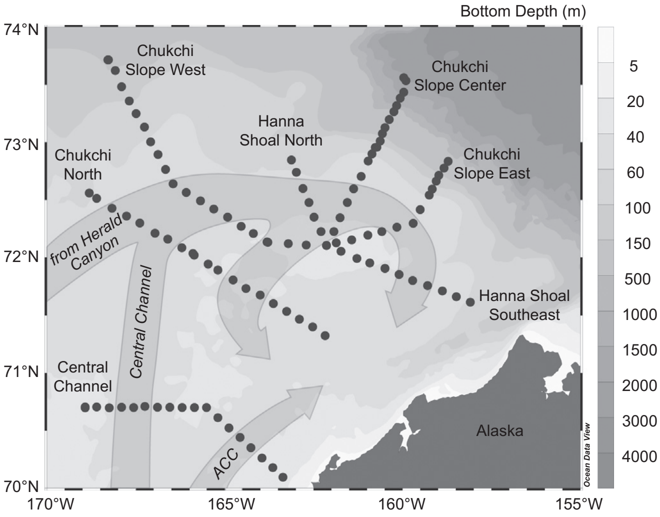

Fig. 1. Map of the northeastern Chukchi Sea illustrating bathymetry, the seven transects sampled as part of our field campaign in 2010–2011 that we focus on in this study, and the main pathway of winter water (WW) as it flowed across the Chukchi shelf during our sampling period (as identified and described in more detail by Pickart et al. (submitted for publication)).

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