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Contrasting inherent optical properties and particle characteristics between an under-ice phytoplankton bloom and open water in the Chukchi Sea

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ABSTRACT

Variability in the inherent optical properties (IOPs) of seawater and characteristics of the particle assemblage were examined along a transect in the Chukchi Sea during July 2011. This transect encompassed samples from open waters of the marginal ice zone exhibiting low concentrations of chlorophyll-*a* (Chl*a* < 1 mg m^{-3}), as well as an extensive phytoplankton bloom (Chl*a* > 30 mg m^{-3}) beneath consolidated pack ice. Measurements included the spectral coefficients for particulate beam attenuation, backscattering, and absorption, bulk indicators of particle concentration and composition, and the particle size distribution. Within the bloom microphytoplankton contributed > 95% to the total Chl*a*, and relatively small amounts of nonalgal particles were present. This assemblage exhibited low Chl*a*-specific phytoplankton absorption coefficients (0.006 m^2 mg^{-1} at 676 nm) indicating a strong influence of pigment packaging, and a weak spectral dependence of the particulate backscattering coefficient. In contrast, the phytoplankton community in nutrient-depleted surface waters outside the sea ice had a strong contribution of picoplankton to Chl*a* (54%) and an increased abundance of nonalgal particles. The Chl*a*-specific phytoplankton absorption coefficient approached maximum values at 676 nm (0.023 m^2 mg^{-1}) and particle backscattering had much stronger spectral dependence. Additional samples from near the sea floor exhibited characteristics of either mineral-dominated assemblages or a mixture of mineral and organic particles, and also displayed optical differentiation from the surface samples. The marked contrast in absorption, attenuation, and backscattering properties of these ecological regimes suggest that they can be discriminated from optical measurements available on a variety of in situ and remote-sensing platforms.

1. Introduction

The Arctic region is warming at an average rate of 0.4 °C per decade, two to three times higher than the global average (ACIA, 2004). The seasonal extent of sea ice cover has markedly declined (Stroeve et al., 2012) with summer minimum ice extent reaching dramatic lows in 2007 and 2012 (Kerr, 2007; NSIDC, 2012). Sea ice-free summers are currently forecast to occur by 2050, or possibly sooner (Overland and Wang, 2013). The decline in sea ice extent has also been accompanied by a transition towards a thinner, younger ice cover that is more prone to melting and fragmentation (Kwok, 2007; Maslanik et al., 2007). The extended area and duration of open water along with a thinning ice cover result in increasing amounts of light penetrating the Arctic Ocean (Arrigo and van Dijken, 2011; Nicolaus et al., 2012).

Models incorporating satellite data as input indicate that the prolonged phytoplankton growing season and increased aerial extent of open water have already led to enhanced primary productivity in the Arctic, and it has been suggested that this trend will continue in the future (Arrigo et al., 2008; Arrigo and van Dijken, 2011; Brown and Arrigo, 2012). Continued thinning of the ice sheet (Comiso, 2012) and the increasing prevalence of melt ponds suggest that phytoplankton blooms beneath the sea ice may also become more widespread (Arrigo et al., 2014). However, increased light penetration in the Arctic Ocean may not necessarily lead to higher production as phytoplankton productivity is limited by nitrogen availability in many regions of the Arctic (Tremblay et al., 2006; Tremblay et al., 2008). In addition, environmental changes may alter the taxonomic composition of the phytoplankton community, which can further influence rates of primary production and have implications for food web structure and carbon cycling. As the Arctic Ocean

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stratifies from increased freshening and warming of the upper ocean, observations suggest that phytoplankton communities may be shifting towards taxonomic groups comprised of smaller species (Li et al., 2009).

Monitoring the rapidly changing biogeochemistry of the Arctic Ocean is a challenging task due to ice cover, remoteness, and extreme weather. Ship-based sampling provides only limited spatial coverage of a region at specific times. Optical measurements have the potential, however, to greatly extend sampling capabilities as they can be acquired from numerous in situ platforms including ships, moorings, and autonomous underwater vehicles, or remotely from sensors located on satellites or aircraft. Sensors capable of measuring the inherent optical properties (IOPs) of seawater at a given light wavelength λ, such as the spectral coefficients for absorption, $a(\lambda)$, scattering, $b(\lambda)$, backscattering, $b_b(\lambda)$, and beam attenuation, $c(\lambda)=a(\lambda)+b(\lambda)$, are being increasingly deployed on various in situ platforms. In the Arctic, optical sensors have recently been included on ice-tethered profilers to study seasonal dynamics of phytoplankton underneath sea ice (S. Laney, pers. comm.) and autonomous vehicles with under-ice capabilities are under development (Lee et al., 2009). Optical remote sensing from air- or space-borne platforms provide measurements of ocean color, quantified by the spectral remote-sensing reflectance, $R_{rs}(\lambda)$. To a first approximation, this quantity is proportional to the ratio of $b_b(\lambda)$ to $a(\lambda)$ (Gordon et al., 1988) and thus these coefficients can also be determined from ocean color measurements (e.g., IOCCG, 2006).

The IOPs of seawater result from the additive contributions of water molecules and the various dissolved and particulate components of seawater, thus providing a bridge between measurements of bulk optical properties and the concentrations of optically-significant seawater constituents such as suspended particulate matter (SPM) and colored dissolved organic matter (CDOM). Particles in seawater are an ubiquitous and important component of the marine environment, and play a fundamental role in the biogeochemical cycling of elements and compounds within the marine ecosystem. The suspended particle assemblage in seawater includes living biological organisms (viruses, bacteria, phytoplankton, and zooplankton) and non-living matter (detritus and inorganic particles) which span a broad size range from a few tens of nanometers to a few millimeters. The concentration, composition, and size distribution of these particles impact a wide range of physical and biological phenomena, and also directly influence the optical properties of seawater and the propagation of light within the ocean.

The relationships between characteristics of the particle assemblage and the optical properties of seawater have not been extensively studied in the Arctic Ocean. Previous studies provided evidence that relationships between seawater optical properties and seawater constituents such as chlorophyll-*a* concentration (Chl*a*) differ in the Arctic from relationships observed in lower-latitude waters, and result largely from a reduced Chl*a*-specific absorption coefficient of phytoplankton and a large contribution to total absorption by CDOM (Matsuoka et al., 2007; Mitchell, 1992). To better understand bio-optical variability in Arctic waters, we collected an extensive dataset of in situ optical properties and characteristics of seawater constituents during two ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment) project cruises in the western Arctic Ocean. In this study, we examine the absorption and scattering of light by particles in seawater and relationships with characteristics of the particle assemblage along a 250 km long transect from ice-free to ice-covered waters collected within the Chukchi Sea during the 2011 cruise. This transect included a transition from low Chl*a* (<0.5 mg m^{-3}) surface waters adjacent to the ice edge to an extensive phytoplankton bloom (Chl*a* >30 mg m^{-3}) occurring beneath the sea ice near the shelf break. Our specific objective is to compare and contrast particle characteristics and seawater IOPs of four distinct particle assemblages occurring along this transect, which can be considered representative of various ecological regimes commonly observed in Arctic waters.

2. Materials and methods

2.1. Study area and sampling

The Chukchi Sea has a shallow shelf with water depths generally less than 50 m (Fig. 1). Owing to efficient export of organic matter from surface waters, it is one of the most productive regions in the world supporting large numbers of consumers in the benthic and pelagic environments (e.g., Feder et al., 2005; Grebmeier et al., 1988). This region was recently proposed as a long-term study site for an international distributed biological observatory aimed at a better understanding of the effects of climatic change on Arctic biology (Grebmeier et al., 2010).

As part of the NASA ICESCAPE study in this region, 172 stations were sampled during a research cruise on the USCGC *Healy* over the period of 25 June–20 July 2011. An extensive phytoplankton bloom, with Chl*a* in the surface layer exceeding 1000 mg m^{-3}, was observed on the Chukchi continental shelf occurring beneath a continual sea ice cover of approximately 1 m thickness. This under-ice phytoplankton bloom was composed primarily of pelagic diatoms of the genera *Chaetoceros*, *Thalassiosira*, and *Fragilariopsis* (Arrigo et al., 2012, 2014).

In this study, we focus on a subset of 12 stations along a 250 km long transect from open water into the ice pack (stations 46–57, Fig. 1) sampled between 3 and 7 July 2011. These stations encompass the transition from nutrient-depleted, low Chl*a* surface water outside the marginal ice zone to the under-ice bloom located near the shelf break. Standard hydrographic measurements at every station included vertical profiles of water temperature, salinity, chlorophyll-*a* fluorescence, and optical beam attenuation in two spectral bands (488 and 660 nm) obtained using a CTD-Rosette equipped with an SBE43 conductivity, temperature, and depth sensor package (Sea-Bird Electronics), a Chelsea Aqua 3 fluorometer (Sea-Bird Electronics), and two

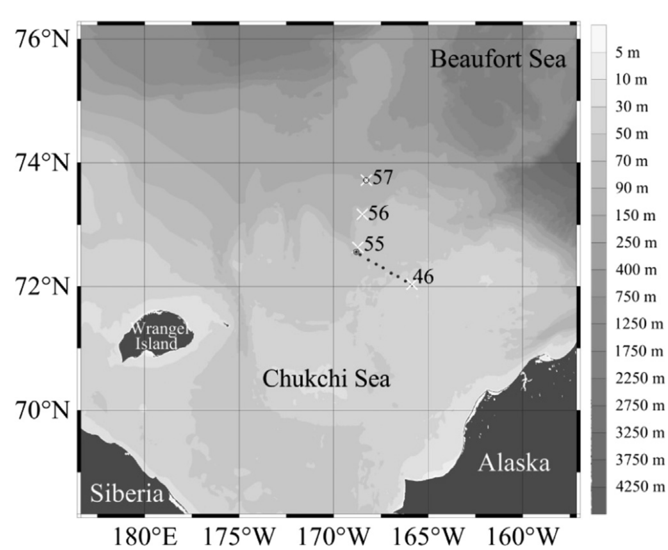

Fig. 1. Map of the Chukchi Sea showing the location of stations along a transect from ice-free to ice-covered waters during the ICESCAPE 2011 campaign. White crosses indicate stations where additional sampling for seawater optical properties and particle characterization was performed. Bathymetry data from Jakobsson et al. (2012).