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Assessing algal biomass and bio-optical distributions in perennially ice-covered polar ocean ecosystems

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Abstract

Under-ice observations of algal biomass and seasonality are critical for understanding better how climate-driven changes affect polar ocean ecosystems. However, seasonal and interannual variability in algal biomass has been studied sparsely in perennially ice-covered polar ocean regions. To address this gap in polar ocean observing, bio-optical sensors for measuring chlorophyll fluorescence, optical scattering, dissolved organic matter fluorescence, and incident solar radiation were integrated into Ice-Tethered Profilers (ITPs). Eight such systems have been deployed in the Arctic Ocean, with five profilers completing their deployments to date including two that observed an entire annual cycle in the central Arctic Ocean and Beaufort Sea respectively. These time series revealed basic seasonal differences in the vertical distributions of algal biomass and related bio-optical properties in these two regions of the Arctic Ocean. Because they conduct profiles on daily or sub-daily scales, ITP bio-optical data allow more accurate assessments of the timing of changes in under-ice algal biomass such as the onset of the growing season in the water column, the subsequent export of particulate organic matter at the end, and the frequency of intermittent perturbations, which in the central Arctic Ocean were observed to have time scales of between one and two weeks.

Keywords: Phytoplankton; Bio-optics; Profiler; Arctic Ocean

1. Introduction

Pelagic ecosystems in polar oceans are expected to experience significant climate-driven changes in the upcoming decades, especially the high-latitude ocean regions that currently experience perennial ice cover. In regions of the Arctic Ocean that remain ice covered year-round, both the thickness and the areal extent of perennial, multi-year ice are decreasing (Kwok and Rothrock, 2009; Laxon et al., 2013; Tucker et al., 2001). Decreasing thickness of sea ice allows more sunlight into the under-ice environment, deepening the ocean's euphotic zone and increasing the amount of light energy available for photosynthesis and primary production (Zhang et al., 2010). Decreases in the areal extent of perennial ice cover exposes more of the upper Arctic ocean to wind forcing during summer (Rainville et al., 2011), increasing the flux of kinetic energy into the surface ocean and potentially altering the nutrient supply to the euphotic zone during the time of year when light levels are sufficient to support

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photosynthesis (Carmack et al., 2004; Yang et al., 2004). These two phenomena represent significant alterations to the current photosynthetic environment in perennially ice-covered ecosystems, where the extant algal assemblages have evolved to survive in relatively quiescent, low-light conditions.

The impact of future loss and thinning of perennial ice cover on polar algae and primary production is difficult to predict. Uncertainties are exacerbated by the lack of a synoptic, comprehensive climatology showing the present spatial, seasonal, and interannual variability of phytoplankton in those Arctic marine ecosystems that currently experience year-round ice cover. Not having the observational capability for generating this much-needed climatology of under-ice algal biomass and related biogeochemical properties represents a critical gap in the nominally 'global' ocean observing infrastructure. Improved measurement of basic ecosystem parameters in perennially ice-covered ocean regions is one focus of the Arctic Observing Network (AON), whose objectives specifically include the development of autonomous systems capable of providing such observations in the central Arctic Ocean (National Science Foundation, 2007).

One of the most successful ocean observing programs developed for ice-covered regions of the Arctic Ocean is the Ice-Tethered Profiler (ITP), which since 2004 has conducted long-term, autonomous vertical sampling of the ocean's top 750 m across much of the central Arctic. The ITP was initially developed to measure basic physical properties of the water column including ocean temperature and salinity (Toole et al., 2006, 2011), and over 70 such ITPs have been deployed to date. ITP-enabled observations of the physical structure of the upper water column have considerably advanced our understanding of heat and salinity variations in the central Arctic Ocean (Timmermans et al., 2010, 2011), the distribution and seasonality of dissolved oxygen (Timmermans et al., 2010), and Arctic ice–ocean interactions, especially with respect to the role of ocean heat content on sea ice (Toole et al., 2010). ITPs are often deployed in conjunction with other autonomous systems including those that monitor ice mass (e.g., Ice Mass Balance buoys, Richter-Menge et al., 2006), atmospheric chemistry (e.g., O-buoy, Knepp et al., 2010), and ocean current structure under the ice (e.g., Autonomous Ocean Flux Buoys, Shaw et al., 2008). Such multi-platform 'Ice-Based Observatories' (IBOs, see Proshutinsky et al., 2004) are a source of vital data for building a better understanding of the Arctic climate system. *In situ* profilers like the ITP and the Polar Ocean Profiling System (Kikuchi et al., 2007) provide the necessary observations of ocean physical properties in the top half kilometer of ocean directly below.

Motivated by the ITP's contribution to understanding the spatial, seasonal, and interannual variability in the physical structure of upper Arctic Ocean, and motivated by progress in long-term use of bio-optical sensors on open-ocean profilers at lower latitudes (Bishop and Wood, 2009; Boss et al., 2008a), an effort was begun in 2009 to add bio-optical capabilities to the Arctic ITP network. The primary goal of this effort was to collect the first-ever daily and sub-daily observations of the vertical distributions of algal biomass, related bio-optical properties, and underwater irradiance in the top few hundred meters of the Arctic Ocean. These observations would provide better quantification of the spatial, seasonal, and interannual variability that algal assemblages exhibit in perennially ice-covered ecosystems in central Arctic Ocean. Ecological phenomena of interest included the timing of the onset and the end of the summer growing season, and the temporal dynamics of algal biomass under ice cover. Of equal interest was the subsequent export of organic matter to depth: its timing and magnitude during the summer growing season and also at the end of summer when photosynthetic rates are minimal. Bio-optical approaches for studying these phenomena have a long history of use in lower-latitude ocean ecosystems. Their successful integration into autonomous platforms such as the ITP could dramatically improve our understanding of seasonal and interannual variability in basic ecological properties of under-ice ecosystems in the Arctic.

2. Technology and methods: ITP-based bio-optical observations

A prototype bio-optical sensor suite was developed for use on Ice-Tethered Profilers to meet specific measurement criteria for ensuring high data quality over the expected year-plus deployments, and to meet specific operational criteria necessary for incorporating new sensors into the existing ITP system (refer to Krishfield et al., 2008 for a description of the base ITP technology). The bio-optical sensor suite included a customized 'triplet' fluorometer (*ECO* FLbb-CD, WETLabs Inc.) to measure chlorophyll fluorescence, dissolved organic matter fluorescence, and optical scatter (Table 1), as well as an irradiance detector (PAR-LOG, Satlantic Inc.) to measure the intensity of the photosynthetically active radiation (PAR) in the visible wavelengths in the water column. The