Characterizing the subsurface chlorophyll *a* maximum in the Chukchi Sea and Canada Basin

Zachary W. Brown [a,*], Kate E. Lowry [a], Molly A. Palmer [a,b], Gert L. van Dijken [a], Matthew M. Mills [a], Robert S. Pickart [c], Kevin R. Arrigo [a]

[a] Stanford University, 473 Via Ortega, Room 140, Stanford, CA 94305, United States
[b] ExxonMobil Research and Engineering, 1545 Route 22 East, Annandale, NJ 08867, United States
[c] Woods Hole Oceanographic Institution, United States

ABSTRACT

Throughout the Arctic Ocean, subsurface chlorophyll *a* (Chl *a*) maxima (SCM) develop every summer after the water column stratifies and surface nutrients have been exhausted. Despite its ubiquity, the SCM's distribution, seasonal dynamics, and productivity remain uncertain. Here we present the first in-depth analysis of the SCM in the Chukchi Sea and adjacent Canada Basin, drawing on data collected during the field program Impacts of Climate on the EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE). The SCM was significantly shallower on the Chukchi shelf (30 m) than in the Canada Basin (56 m), and in both regions was correlated with the euphotic and nitracline depths, suggesting an actively growing community maintaining its optimal position within the water column, consistent with previous work. The SCM was located significantly deeper than the net primary productivity (NPP) maximum, which averaged 15 m depth. The development of the SCM on the Chukchi shelf appears tightly linked to under-ice blooms, beginning ∼1 month prior to sea-ice retreat and reaching ∼15 m depth by the time ice retreats, beyond the range of satellite ocean-color sensors. A seasonal analysis of historical data from the region shows that the SCM deepens to ∼30 m by July and remains there throughout the summer, a depth that is consistent with previous studies across the pan-Arctic shelves. We employed a spectral model of light propagation through the water column to demonstrate that surface Chl *a* and CDOM play approximately equal roles in attenuating light, limiting euphotic depth, and therefore SCM depth, to ∼30 m, thus greatly limiting new production. If surface Chl *a* and CDOM were reduced, allowing greater light penetration, new production on Arctic shelves could potentially be 40% greater.

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1. Introduction

In the Arctic summer, after the water column stratifies and spring phytoplankton blooms have depleted inorganic nitrogen (N) in surface waters, a subsurface chlorophyll *a* (Chl *a*) maximum (SCM) commonly develops (e.g. Carmack et al., 2004; Martin et al., 2010). Dominated by large diatoms (such as *Chaetoceros* and *Thalassiosira*), this subsurface phytoplankton community is a pervasive feature of the Arctic marine environment throughout the summer and early fall. SCM have been observed on the continental shelves of the Chukchi (Cota et al., 1996; Codispoti et al., 2005), Beaufort (Carmack et al., 2004), Greenland (Cherkasheva et al., 2013), Barents (Kristiansen and Lund, 1989), Laptev (Heiskanen and Keck, 1996), and East Siberian seas

(Codispoti and Richards, 1971), as well as in the Canadian Arctic Archipelago (Martin et al., 2010; Booth et al., 2002), North Water Polynya (Klein et al., 2002) and Canada Basin (Lee and Whitledge, 2005; Nishino et al., 2008).

Despite its ubiquity, the ecological significance of the SCM remains uncertain for several reasons. First, it is unclear to what extent the SCM represents the sinking remains of a surface bloom versus an actively growing phytoplankton community maintaining its optimal position in the water column with respect to the opposing gradients of light (higher above) and nitrate (higher below). Several studies have noted a high fraction of diatom resting spores within the SCM, suggesting a moribund community (Heiskanen and Keck, 1996; Booth et al., 2002; Sukhanova et al., 2009). On the other hand, recent research points to active photosynthesis and new production within the SCM (Hill and Cota, 2005; Tremblay et al., 2008; Martin et al., 2010; Palmer et al., 2013).

Second, despite its ease of measurement, Chl *a* is an imperfect metric of phytoplankton abundance (Cullen, 1982). Because

phytoplankton growing at low light may produce 5–10 times as much Chl *a* per cell as those growing at high light (Falkowski and Raven, 2007), the SCM may partially represent the effect of photoacclimation rather than a true maximum in phytoplankton biomass. For example, Lee and Whitledge (2005) observed that the ratio of Chl *a* to organic carbon in the Canada Basin was nearly 20 times higher at the SCM than at the surface.

Third, the productivity of the SCM remains in question. Because of the exponential decay of photosynthetically active radiation (PAR) within the water column, the SCM is consistently exposed to very low light levels, placing an upper threshold on maximum productivity regardless of the extent of shade-adaptation of Arctic phytoplankton species (e.g., Palmer et al., 2013). Thus, although Chl *a* concentrations may be very high at the SCM, primary productivity is not necessarily at its maximum level at that depth within the water column. For example, Cota et al. (1996) observed that productivity maxima in the north Chukchi Sea were significantly shallower than the depth of the SCM.

The question of SCM productivity is particularly relevant to recent pan-Arctic satellite-based studies, which have shown a significant increase in Arctic marine net primary production (NPP) coincident with sea ice decline (e.g. Arrigo et al., 2008). Because ocean color sensors only capture the first optical depth of the water column, they often miss the SCM and potentially significantly underestimate water column NPP (e.g. Uitz et al., 2006; Tremblay et al., 2008). For example, the recent study of Hill et al. (2013) reports that correcting for subsurface production doubles estimates of pan-Arctic NPP. On the other hand, in a separate analysis using the same dataset, Arrigo et al. (2011) showed that the error in satellite-derived NPP estimates associated with removing the SCM averages only 7.6%. They attribute this surprisingly small error to two main factors: (1) the largest errors occur when surface Chl *a* is low and the SCM is located very deep (≥ 40 m), a situation that is rare in Arctic waters, and (2) satellite-based productivity algorithms do not assume negligible NPP at the depth of the SCM as is commonly believed, but rather calculate NPP at all depths using a parameterization of Chl *a* that does not include a SCM – therefore, satellite algorithms do not miss the entire NPP contribution of the SCM layer, but only a fraction thereof. Consistent with this, Ardyna et al. (2013) recently showed that vertical variations in Chl *a* have limited impact on annual depth-integrated Arctic Ocean NPP. Thus, although ubiquitous in nature and having been the subject of numerous studies in recent years, many important questions about the Arctic summer SCM (including its development (sinking vs. active growth), its biomass, and its contribution to Arctic primary production) remain unanswered.

The most comprehensive studies of the Arctic SCM to date were conducted in the Beaufort Sea and Canadian Arctic Archipelago (CAA) (Tremblay et al., 2008; Martin et al., 2010, 2012, 2013; Palmer et al., 2011; Ardyna et al., 2011; Ardyna et al., 2013). These studies clearly show that in these regions, phytoplankton within the SCM can rapidly acclimate to the attenuated light habitat of the subsurface (Tremblay et al., 2008; Palmer et al., 2011). The SCM maintains its vertical position near the nitracline (the depth at which nitrate (NO_3^-) concentrations rapidly increase to deep values), and therefore grows with a relatively high *f*-ratio (indicating substantial new production potentially available for export) compared to the surface community (Martin et al., 2012). Moreover, the SCM in these regions supplies a large fraction of the total annual new production (Martin et al., 2013). Thus, in the Beaufort Sea and CAA, the paradigm of the SCM as an actively growing, dynamic phytoplankton community that maintains its optimal water column position and contributes substantially to annual production has been well demonstrated (e.g. Martin et al., 2010).

In-depth studies of the SCM have yet to be undertaken in other regions of the Arctic Ocean, including the Chukchi Sea. The Beaufort Sea and CAA are very different from the Chukchi Sea due to their perennial freshwater stratification. Whereas the Beaufort Sea and CAA experience very limited surface nutrient renewal, even in winter, precluding intense surface spring blooms (hence the rapid development of the SCM in this region), the water column over the shallow Chukchi Sea shelf is thoroughly mixed at the start of the phytoplankton growing season, with surface NO_3^- concentrations of 10–15 μmol L^{-1} (Mills et al., 2015). This allows the Chukchi Sea to support the longest-lived surface bloom of any Arctic region (Arrigo and van Dijken, 2011). Furthermore, Arrigo et al. (2012) recently showed that these intense Chukchi Sea surface blooms can occur underneath the consolidated ice pack far from the ice edge. Similarly, Palmer et al. (2013) suggested that changing sea ice conditions may be resulting in a new pattern of seasonal productivity for the region. It is crucial to understand how these very different spring bloom dynamics affect the development of the SCM in the Chukchi Sea, and whether the emerging paradigm of an active, photosynthetically competent subsurface diatom community holds in this region as in the Beaufort Sea and CAA.

Here we present the first in-depth analysis of the distribution and seasonal dynamics of the SCM in the seasonally ice-free Chukchi Sea and Canada Basin. We draw on data from the recent NASA field program Impacts of Climate on the EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE), as well as historical cruise data from this region. Our goals are: (1) to map the distribution of the SCM and quantify its correlation to key physical and chemical variables of the Chukchi Sea and Canada Basin; (2) to assess the relationship of the SCM to NPP and export production; and (3) to use historical data to quantify and elucidate the seasonal development of the SCM.

2. Methods

2.1. Field sampling and analysis

We collected water samples for nutrients, dissolved gases, and particulate measurements on two cruises aboard the USCGC *Healy* to the Chukchi and Beaufort seas, HLY1001 (June 15–July 22, 2010) and HLY1101 (June 25–July 29, 2011), comprising the field portion of the NASA program ICESCAPE (Fig. 1).

At each station, water column profiles of temperature and salinity were measured using a conductivity–temperature–depth system (CTD; SBE 911+ Sea-Bird Electronics, Inc.) attached to a rosette. Additional instruments on the rosette included an oxygen (O_2) sensor (SBE43, Sea-Bird Electronics, Inc.), two transmissometers (C-Star red and blue, WET labs), a photosynthetically active radiation (PAR) sensor (QSP2300 PAR, Biospherical Instruments, Inc.), and a fluorometer (AQIII, Chelsea Technologies Group, Ltd.). In this study, we use only measurements made during the downcast. Seawater was collected into twelve 30 L Niskin bottles at discrete depths, typically the surface and bottom depths, as well as 10 m, 25 m, 50 m, 100 m, 150 m, and 200 m. When present, we also collected seawater from the depth of the fluorescence maximum.

2.2. Analytical methods

Concentrations of nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), silicate ($Si(OH)_4$), and phosphate $\left(PO_4^{3-} \right)$ in discrete water samples were analyzed on-board with a Seal Analytical continuous-flow AutoAnalyzer 3 (AA3) using standard methods (Armstrong et al., 1967; Bernhardt and Wilhelms, 1967; Kerouel and Aminot, 1997).