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Iron from melting glaciers fuels phytoplankton blooms in the Amundsen Sea (Southern Ocean): Phytoplankton characteristics and productivity

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ABSTRACT

The phytoplankton community composition and productivity in waters of the Amundsen Sea and surrounding sea ice zone were characterized with respect to iron (Fe) input from melting glaciers. High Fe input from glaciers such as the Pine Island Glacier, and the Dotson and Crosson ice shelves resulted in dense phytoplankton blooms in surface waters of Pine Island Bay, Pine Island Polynya, and Amundsen Polynya. Phytoplankton biomass distribution was the opposite of the distribution of dissolved Fe (DFe), confirming the uptake of glacial DFe in surface waters by phytoplankton. Phytoplankton biomass in the polynyas ranged from 0.6 to 14 μg Chl *a* L^{-1}, with lower biomass at glacier sites where strong upwelling of Modified Circumpolar Deep Water from beneath glacier tongues was observed. Phytoplankton blooms in the polynyas were dominated by the haptophyte *Phaeocystis antarctica*, whereas the phytoplankton community in the sea ice zone was a mix of *P. antarctica* and diatoms, resembling the species distribution in the Ross Sea. Water column productivity based on photosynthesis versus irradiance characteristics averaged 3.00 g C m^{-2} d^{-1} in polynya sites, which was approximately twice as high as in the sea ice zone. The highest water column productivity was observed in the Pine Island Polynya, where both thermally and salinity stratified waters resulted in a shallow surface mixed layer with high phytoplankton biomass. In contrast, new production based on NO_3 uptake was similar between different polynya sites, where a deeper UML in the weakly, thermally stratified Pine Island Bay resulted in deeper NO_3 removal, thereby offsetting the lower productivity at the surface. These are the first in situ observations that confirm satellite observations of high phytoplankton biomass and productivity in the Amundsen Sea. Moreover, the high phytoplankton productivity as a result of glacial input of DFe is the first evidence that melting glaciers have the potential to increase phytoplankton productivity and thereby CO_2 uptake, resulting in a small negative feedback to anthropogenic CO_2 emissions.

1. Introduction

Coastal polynyas are local areas of reduced ice cover that generally form due to offshore katabatic winds and seasonal ice melt. The reduced ice cover results in elevated irradiance in the water column in early spring. When the in situ irradiance increase coincides with a stable water column, it provides a light climate that is favorable for phytoplankton photosynthesis and growth, making Antarctic polynyas some of the most biologically productive regions of the Southern Ocean (Arrigo et al., 1999; Arrigo and van Dijken, 2003; Arrigo et al., 2008a, b). Phytoplankton primary productivity in polynyas is important for the support of biota who occupy higher trophic levels such as krill, penguins, and whales (Arrigo et al., 2003; Ainley et al., 2006). Moreover, polynyas play a disproportionally important role in sequestering anthropogenic CO_2 because of their high rates of primary production, rapid organic matter sinking fluxes (DiTullio et al., 2000), and formation of dense bottom waters (Arrigo et al., 2008a).

Phytoplankton productivity in Antarctic polynyas is generally dominated by diatoms and the haptophyte *Phaeocystis antarctica*

Abbreviations: AP, Amundsen Polynya; CDW, Circumpolar Deep Water; Chl *a*, Chlorophyll *a*; DFe, dissolved iron; E_{UML}, mean light level in the upper mixed layer; F_v/F_m, maximum efficiency of photosystem II; MCDW, Modified Circumpolar Deep Water; PAR, photosynthetically active radiation; *P–E*, photosynthesis versus irradiance; PIB, Pine Island Bay; PIG, Pine Island Glacier; PIP, Pine Island Polynya; POC, particulate organic carbon; PON, particulate organic nitrogen; z_{UML}, depth of the upper mixed layer; z_c, critical depth

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(Prymnesiophyceae), although Cryptophytes, Chlorophyceae, and Prasinophyceae may also be abundant at certain times and regions (Arrigo et al., 1999; Wright et al., 2010; Kozlowski et al., 2011). The biogeochemical characteristics of these blooms differ in important ways (Arrigo et al., 1999). Previous data suggest that *P. antarctica* draws down twice as much CO_2 per mole of PO_4 removed than do diatoms (Arrigo et al., 1999). Other evidence suggests that *P. antarctica* is not readily grazed by microzooplankton (Caron et al., 2000; Tagliabue and Arrigo, 2003; Nejstgaard et al., 2007). Therefore, *P. antarctica* is thought to form the base of a marine food web that is substantially different from that supported by diatoms.

Phytoplankton primary productivity in the Southern Ocean is often limited by the availability of iron (Fe) (Boyd et al., 2007 and references therein), although light limitation due to deep vertical mixing below the critical depth may also limit phytoplankton growth (Mitchell et al., 1991; De Baar et al., 2005). The Fe supply for phytoplankton growth in polynyas is enhanced when compared to the open ocean due to input from melting sea ice (Sedwick and DiTullio, 1997; Lannuzel et al., 2010), floating icebergs (Raiswell et al., 2008; Raiswell, 2011; Shaw et al., 2011), upwelling Circumpolar Deep Water (CDW) (Klunder et al., 2011), and melting glaciers (Raiswell et al., 2006). Despite these enhanced sources, phytoplankton growth is often still seasonally Fe-limited following blooms in polynyas such as the Ross Sea (Sedwick and DiTullio, 1997; Sedwick et al., 2000; Arrigo et al., 2003; Tagliabue and Arrigo, 2005) and the Weddell Sea (Buma et al., 1991).

Satellite data revealed that the polynyas with highest productivity per surface area of Antarctica are found in the Amundsen Sea (Arrigo and van Dijken, 2003). The Amundsen Sea contains two polynyas, the Pine Island Polynya with a mean area of 17, 632 km^2 in the east and Amundsen Polynya with a mean area of 27,333 km^2 in the west. The Amundsen Sea is located in the western Antarctic, where rates of ice sheet thinning are the highest in all of Antarctica (Pritchard et al., 2009) and are a potential Fe source for phytoplankton blooms (Raiswell et al., 2006, 2008). Several fast-flowing glaciers that are thinning rapidly drain into the Amundsen Sea, most notably the Pine Island Glacier (PIG), the Smith Glacier, and the Thwaites Glacier (Pritchard et al., 2009). The thinning of the ice sheets is mainly attributed to the regional bathymetry and oceanography. As the Antarctic Circumpolar Current (ACC) flows close to the continent, Circumpolar Deep Water (CDW) intrudes southward through deep troughs onto the Antarctic continental shelf as modified CDW (MCDW) (Jacobs et al., 1996, 2011; Jenkins et al., 1997; Hellmer et al., 1998; Walker et al., 2007; Nitsche et al., 2007). This relatively warm ($\sim$1.2 °C) and salty MCDW is able to enter the cavity beneath the floating terminus of the PIG and drive basal melting (Jenkins et al., 2010; Jacobs et al., 2011). The resulting seawater dilution by the glacial melt initiates a circulation pattern whereby fresher and cooler meltwater MCDW flows up the underside of the floating ice sheets and returns to the open sea higher in the water column (Hellmer et al., 1998).

During the 2009 DynaLiFe program, an international collaboration that was part of the International Polar Year, we found that meltwater MCDW from the PIG and other glaciers draining into the Amundsen Sea polynyas is the major source of Fe for the phytoplankton blooms in these polynyas (Gerringa et al., 2012). Here, we describe the characteristics of the phytoplankton bloom that was fueled by this Fe input, including phytoplankton community composition, photo-physiological characteristics, and primary productivity of this highly productive area.

2. Methods

2.1. Sampling

Seawater samples were collected during the NBP 09-01 cruise on the RVIB *Nathaniel B. Palmer* in the Amundsen Sea area during the austral summer, 12 January–17 February 2009 (Figs. 1 and 2). We entered a band of multi- and first-year ice to the north of Pine Island Polynya (PIP) on 12 January and followed a depression in the continental shelf through the sea ice (Sta 2, 3, 5, 7, 10) into the PIP. We transected the PIP on 15 and 16 January (Sta 11, 12, 13, 14) and subsequently sampled the PIB (Sta 36, 37, 46, 47, 86, 88, 89, 90, 94, 99) and stations in proximity to the PIG tongue (Sta 16,

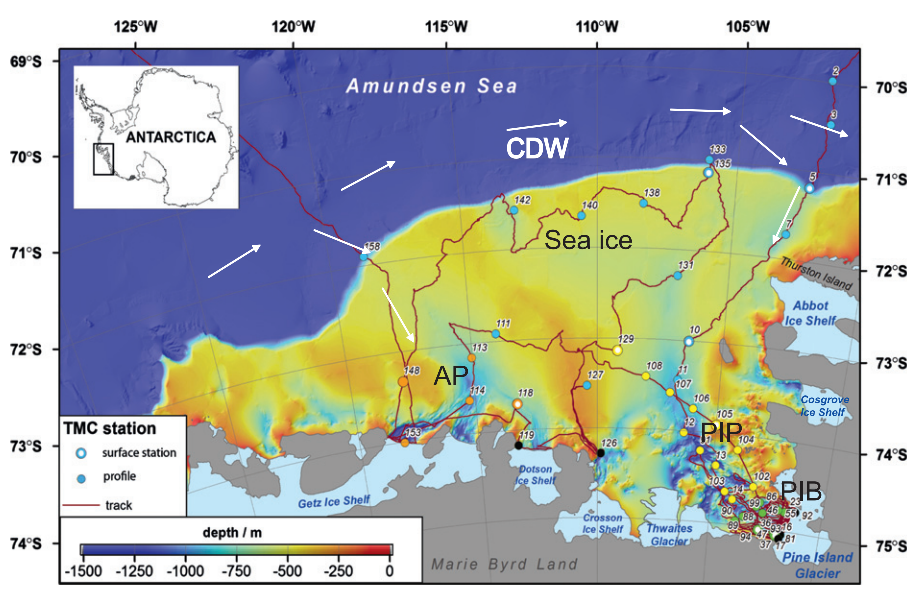

Fig. 1. DynaLiFe cruise track and stations superimposed on the bathymetry of the Amundsen Sea by Nitsche et al. (2007). White arrows indicate the flow of Circumpolar Deep Water (CDW) to the east in the Antarctic Circumpolar Current and south, where it flows onto the continental shelf through troughs in the shelf as modified CDW (MCDW). Blue stations were located in the sea ice zone, yellow stations in the Pine Island Polynya (PIP), green stations in the Pine Island Bay (PIB), orange stations in the Amundsen Polynya (AP), and black stations were influenced by outflow of meltwater MCDW from under glacier tongues. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)