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The influence of air–sea–ice interactions on an anomalous phytoplankton bloom in the Indian Ocean sector of the Antarctic Zone of the Southern Ocean during the austral summer, 2011

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Abstract

An anomalous phytoplankton bloom was recorded in the Indian Ocean sector of the Antarctic Zone (AZ) of the Southern Ocean (SO) during the austral summer, 2011. Possible mechanisms for the triggering of such a large bloom were analyzed with the help of *in situ* and satellite data. The bloom, which formed in January 2011, intensified during February and weakened by March. High surface chlorophyll (Chl) concentrations (0.76 mg m^{-3}) were observed in the area of the bloom (60°S, 47°E) with a Deep Chlorophyll Maximum (DCM) of 1.15 mg m^{-3} at a depth of 40–60 m. During 2011, both the concentration and spatial extent of sea ice were high on the western side of the bloom, between 0°E and 40°E, and enhanced freshwater influx was observed in the study area as a result of melting ice. A positive Southern Annular Mode (SAM) (with a resultant northward horizontal advection) and an intense La Niña during 2010–2011 are possible reasons for the high sea-ice concentrations. The enhanced Chl *a* observed in the study region, which can be attributed to the phytoplankton bloom, likely resulted from the influx of nutrient-laden freshwater derived from melting sea ice.

Keywords: Phytoplankton bloom; Advection; Southern annular mode; Antarctic zone

1. Introduction

Surficial and deep waters of the Southern Ocean (SO) are among the largest sinks of anthropogenic atmospheric carbon dioxide (CO_2) in the world (Takahashi et al., 2012). These properties make the SO a potential site for enhanced carbon sequestration. A major fraction of the CO_2 that enters the deep ocean does so through phytoplankton input pathways, and hence 'biological pumps' play a major role in the process of oceanic sequestration of atmospheric CO_2 (Smith and Comiso, 2008; Arrigo et al., 2008). However, the SO is one of the largest regions of the world ocean in which phytoplankton growth is nutrient limited, specifically by lack of the micronutrient iron (Fe), despite high loadings of macronutrients (De Baar et al., 1995; Van Leeuwe et al., 1997; Hutchins et al., 2001). As compared with other Fe-limited regions,

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the flux of Fe-enriched dust to the SO is the lowest in the world's oceans (Duce and Tindale, 1991), particularly at higher latitudes; as a result, oceanic sources of Fe, such as by upwelling of deep water, resuspension of sediments, remineralization of sinking materials, and diffusion of Fe through the water column have been proposed as likely supply pathways of Fe to surficial waters of the SO (De Baar et al., 1995; Loscher et al., 1997). Strong zooplankton grazing pressure, as well as light and silicate limitations have also been suggested as supplementary factors contributing to low phytoplankton production in the SO (Banse, 1996); however, the relative importance of each of these factors has remained a contentious issue. Nonetheless, phytoplankton blooms have been reported in several regions of the SO, including in areas associated with marginal ice zones (Moore and Doney, 2006), shallow coastal and shelf waters (Sullivan et al., 1993), near fronts of the Antarctic Circumpolar Current (Moore et al., 1999), near polynyas (Arrigo et al., 2008), and in areas of upwelling associated with large bathymetric features (Moore et al., 1999; Moore and Abbott, 2000). These blooms play a key role in drawing down atmospheric CO_2, exporting carbon to the ocean interior, enhancing annual biological productivity, and influencing trophic dynamics and biogeochemical cycles of the entire SO (Smith and Nelson, 1986; Arrigo et al., 1998).

The SO comprises several oceanic frontal systems (Orsi et al., 1995; Belkin and Gordon, 1996), and these fronts subdivide the SO into zones with different biogeochemical characteristics (Deacon, 1984). The Antarctic Zone (AZ), which lies between the Polar Front (PF) and the Southern Boundary of the Antarctic Circumpolar Current Front (SB), is characterized by cold winter water in the uppermost ~150 m of the water column during the winter, and is overlain by fresher and warmer Antarctic Surface Water (AASW) during the summer (Orsi et al., 1995). The typical upper layer in the AZ during summer is characterized by a well-developed subsurface temperature minimum (T_{min}) layer (or winter water, WW, layer), capped by a relatively warm fresh well-mixed surface layer (Park et al., 1998; Sokolov and Rintoul, 2007). The T_{min} layer is the result of surface freshening during the austral summer, mainly as a result of ice melting and subsequent warming of the surface layer (Park et al., 1998). The warmer Circumpolar Deep Water (CDW) lies at depth, below the T_{min} layer (Toole, 1981). In contrast to temperature, salinity increases with depth throughout the T_{min}, thus providing vertical stability to the water column. Therefore, salinity is more important than temperature in controlling the stratification of the AZ. Furthermore, large-scale zonal and meridional ocean circulation patterns (Bindoff et al., 2000), the annual formation and dissipation of sea ice (Gloersen et al., 1992), and distinct seasonal surface water mass transformations (Williams et al., 2008) make the AZ a physically dynamic region.

In general, surface waters of the AZ are characterized by low temperatures (4 °C to −2 °C) and a large repository of available macronutrients (El-Sayed, 1978). Although phytoplankton production in the AZ is generally low (Holm-Hansen et al., 1989; Moore and Abbott, 2000), occasional high-productivity events have been reported in the seasonal ice zone during summer–autumn (Hirawake et al., 2003) and spring (Hirawake et al., 2005). However, occurrences of phytoplankton blooms during summer in the Indian Ocean sector of the AZ have not been previously reported. In this study, evidence for the occurrence of an anomalous phytoplankton bloom in the Indian Ocean sector of the AZ during the austral summer of 2011 is presented, based on an analysis of *in situ* data and ocean color imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS). A clear understanding of the physical processes that control phytoplankton production, particularly in a high-nutrient and low-chlorophyll environment like the AZ, is of vital importance in understanding the role of the SO in carbon sequestration and cycling. Hence, the physical mechanisms for the evolution of the phytoplankton bloom are also examined.

2. Materials and methods

As part of the Indian Scientific Expedition to the Southern Ocean (SOE), hydrographic and biological measurements were obtained at six stations along 60°S, at 2°-longitudinal intervals between 47°E and 57°30′E, during the austral summer (January–February) of 2011. From these, two stations (at 47°E and 49°E) were chosen to investigate *in situ* chlorophyll *a* (Chl *a*) distributions in the vicinity of the bloom (Fig. 1). Sea-water samples were collected at standard depths (0, 10, 30, 50, 75, 100, and 120 m) using General Oceanics Niskin samplers (5 L) fitted on a carousel unit that also included a conductivity–temperature–depth (CTD) device (Sea-Bird Electronics, Washington, USA). For measurement of Chl *a*, 1 L of water was immediately filtered through a glass fiber filter (GF/F) (Whatman, 47 mm diameter) under low suction pressure; the filter was folded in half and placed in a glass centrifuge tube with 10 ml 90% acetone, and subject to extraction overnight in the dark at