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Seasonal variability of phytoplankton biomass and composition in the major water masses of the Indian Ocean sector of the Southern Ocean

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Abstract

Long-term changes in phytoplankton biomass and community composition are important in the ecosystem and biogeochemical cycle in the Southern Ocean. We aim to ultimately evaluate changes in phytoplankton assemblages in this region on a decadal scale. However, yearly continuous data are lacking, and long-term datasets often include seasonal variability. We evaluated the seasonal changes in phytoplankton abundance/composition across latitudes in the Indian Ocean sector of the Southern Ocean via multi-ship observations along the 110°E meridian from 2011 to 2013. The chlorophyll *a* concentration was 0.3−0.5 mg m^{-3} in the Subantarctic Zone (40−50°S) and 0.4−0.6 mg m^{-3} in the Polar Frontal Zone (50−60°S); pico-sized phytoplankton (<10 µm), mainly haptophytes, were dominant in both zones. In the Antarctic Divergence area (60−65°S), the chlorophyll *a* concentration was 0.6−0.8 mg m^{-3}, and nano-sized phytoplankton (>10 µm), mainly diatoms, dominated. Chlorophyll *a* concentrations and phytoplankton community compositions were the same within a latitudinal zone at different times, except during a small but distinct spring bloom that occurred north of 45°S and south of 60°S. This small seasonal variation means that this part of the Southern Ocean is an ideal site to monitor the long-term effects of climate change.

Keywords: Phytoplankton; Size fraction; Seasonal variability; Pigment analysis; CHEMTAX

1. Introduction

The Southern Ocean is very important to the global carbon cycle. One reason is that it occupies approximately 20% of the world's ocean area, and another is its very high primary productivity (Arrigo et al., 1998a). This area is a critical CO_2 sink globally, with the region south of 50°S accounting for about 20% of the global ocean CO_2 sink (Takahashi et al., 2009). Its carbon absorption rate is approximately 1.5×10^{15} g C yr^{-1} (McNeil et al., 2007).

The Southern Ocean is also one of the largest high-nutrient low-chlorophyll (HNLC) areas. Iron availability may control the biomass and productivity of phytoplankton (Martin et al., 1990). However,

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phytoplankton blooms often have been observed in several regions near fronts and in sea ice retreat areas (Comiso et al., 1993; Moore and Abbott, 2000). Large phytoplankton blooms transport particulate organic carbon in the frustules of diatoms from the surface layer of deep oceans. Diatoms are the main component of the phytoplankton community in blooms around fronts (Brzezinski et al., 2001); therefore, diatom blooms are very important for carbon cycling in these areas. Diatom blooms mainly occur in polar front areas, while blooms in seasonal ice areas are dominated by non-calcifying haptophytes, e.g. *Phaeocystis antarctica* (Arrigo et al., 1998b). Large carbon exports occur in haptophyte bloom areas as well (DiTullio et al., 2000). Therefore, phytoplankton blooms and variability in their compositions affect the carbon cycle in the Southern Ocean.

The Southern Ocean also has one of the highest biological productivities in the world. In particular, the Antarctic krill *Euphausia superba* is a key species in this area, and most of the sea mammals, sea birds, and fishes depend on it for survival (e.g. Hempel, 1985). Consequently, the biomass of phytoplankton, the food source for krill, is an important factor in this ecosystem, and changes in primary productivity have large effects on the community and the carbon cycle in this region.

The most unique hydrographic feature in the Southern Ocean is the circumpolar current, which strongly affects the global carbon cycle and ecosystem dynamics. The Antarctic Circumpolar Current (ACC), a major current in the Southern Ocean, is induced by strong westerly winds between 45°S and 55°S (Nowlin and Klinck, 1986). The ACC flows through the Atlantic, Indian, and Pacific oceans without continental barriers. Therefore, the ACC is the most important factor affecting biogeochemical cycles, including the iron cycle, in the Southern Ocean (e.g. Nowlin and Klinck, 1986; Tynan, 1998; Boyd and Ellwood, 2010). The ACC is also associated with several oceanic fronts: the Subtropical Front (STF), the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF), and the Southern Boundary (SB) of the ACC (Orsi et al., 1995; Belkin and Gordon, 1996). These frontal regions are characterized by sharp horizontal gradients in hydrographic properties that represent the boundaries of distinct water masses (Orsi et al., 1995; Belkin and Gordon, 1996; Rintoul and Bullister, 1999; Sokolov and Rintoul, 2002).

Seasonal sea ice cover also affects phytoplankton dynamics in the Southern Ocean. The sea ice is distributed zonally by latitude, and it affects the habitats of phytoplankton and zooplankton in these areas (Massom and Stammerjohn, 2010). Antarctic zooplankton communities can be divided into three ice-associated zones: 1) the permanent ice-free area, dominated by copepods and salps; 2) the seasonal sea ice zone, dominated by *E. superba*; and 3) the permanent sea ice area, dominated by ice krill (*Euphausia crystallorophias*) (Loeb, 2007). The distributions of phytoplankton communities are closely related to these fronts and to the distribution of sea ice.

Interannual variations in phytoplankton distribution and primary productivity affect ecosystems and carbon cycles in the Southern Ocean. The changes in carbon cycling in the Southern Ocean can have global effects because of thermodynamic circulation. Several studies have examined the variations in phytoplankton distribution and primary productivity in the Indian Sector of the Southern Ocean (e.g. Strutton et al., 2000; Wright et al., 2010). In particular, Johnston and Gabric (2010) revealed that the Southern Annual Mode (SAM) and sea surface temperatures (SST) produced conditions that were favorable for phytoplankton growth, based on analyses of satellite remote sensing datasets. Interannual variations in annual productivity were most closely linked to changes in sea ice cover, although sea surface temperature also played a role, and only 31% of the variation in annual production was explained by the SAM.

Annual primary production could increase in the future as stronger winds increase nutrient upwelling (Arrigo et al., 2008). However, although the satellite chlorophyll (chl) *a* dataset has been available since 1996, continuous datasets based on direct observations are scarce for the Southern Ocean. The only monitoring station datasets were collected in the Antarctic Peninsula region (Montes-Hugo et al., 2009), and very limited data are available for other areas of the Southern Ocean. The Japanese Antarctic Research Expedition (JARE) has conducted monitoring since 1965 in the Indian Ocean Sector of Southern Ocean using the icebreakers *Fuji* (1965–1983) and *Shirase* (1983–present) to discover long-term trends in the oceanic environment. All hydrographic and biological data have been published by the National Institute of Polar Research (NIPR) (http://ci.nii.ac.jp/vol_issue/nels/AA10457766_en.html). However, because these data were sometime collected in different seasons and at different positions and depths, long-term variations in primary productivity are difficult to evaluate directly. Therefore, we must identify seasonal changes in phytoplankton distribution and composition before