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Seasonal dynamics in diatom and particulate export fluxes to the deep sea in the Australian sector of the southern Antarctic Zone

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ABSTRACT

Particle fluxes were recorded over a one-year period (2001-02) in the southern Antarctic Zone in the Australian Sector of the Southern Ocean. Here, we present the results on the seasonal and vertical variability of biogenic particle and diatom valve fluxes. Total mass and diatom fluxes were highly seasonal, with maxima registered during the austral summer and minima during winter. Biogenic opal dominated sedimentation, followed by carbonate, and very low levels of organic carbon (annual average 1.4%). The strong correlation between opal and organic carbon at both depth levels suggests that a significant fraction of organic matter exported to the deep sea was associated with diatom sedimentation events. Seasonal diatom fluxes appear driven principally by changes in the flux of *Fragilariopsis kerguelensis*. The occurrence of the sea-ice affiliated diatoms *Fragilariopsis cylindrus* and *Fragilariopsis curta* in both sediment traps is considered to correspond to the sedimentation of a diatom bloom advected from an area under the influence of sea ice. Highest fluxes of the subsurface-dwelling species *Thalassiothrix antarctica* registered at the end of the summer bloom were linked to a drop of the light levels during the summer-autumn transition. This study provides the first annual observation on seasonal succession of diatom species in the Australian sector of the Antarctic Zone, and corresponds, in terms of magnitude and seasonality of diatom fluxes, to those in neighbouring sectors (Pacific and eastern Atlantic).

1. Introduction

Diatoms are unicellular algae with an absolute requirement for silicic acid to form their frustules. They constitute a major component of phytoplankton communities, being responsible for ~40% of all marine carbon fixation (Nelson et al., 1995). Diatoms are the main contributors to the silica-rich deposits in deep-sea sediments and are thought to influence the present and past global climate via their influence on the biological pump of CO_2 from the atmosphere into the ocean interior (Matsumoto et al., 2002; Nelson et al., 1995; Sarmiento et al., 1998). The composition of phytoplankton communities and abundance of diatoms within them are related to specific ecological parameters of the water masses where they live (e.g., temperature, sea-ice cover and nutrient availability), and hence in the case of diatoms, their frustules can be used as biotic proxies for palaeoenvironmental and palaeoceanographic reconstructions.

In order to evaluate the role of diatoms in the biological pump and the cycling of silicon, it is essential to thoroughly understand their ecology and the processes that the living biocoenoses undergo from their initial production in the euphotic zone to their eventual preservation in the ocean sediments (e.g. Grigorov et al., 2014; Varela et al., 2004). This knowledge is also required to validate paleorecontructions based on the diatom sedimentary record (e.g. Armand and Leventer, 2010; Leventer et al., 1993; Taylor and Sjunneskog, 2002).

The Southern Ocean is regarded as having one of the highest diatom biomasses of the global ocean. Despite its high-nutrient low chlorophyll (HNLC) regime, massive diatom blooms occur every year during spring and summer associated with specific areas, such as oceanographic fronts (e.g. Honjo et al., 2000; Moore and Abbott, 2000), coastal areas of Antarctica (e.g. Arrigo et al., 1999; Bathmann et al., 1991; Wefer et al., 1988) and the retreating sea ice edge (e.g. Smith and Nelson, 1986; Sullivan et al., 1988). As a result of this relatively high diatom productivity (Pondaven et al., 2000), large amounts of biogenic silica accumulate in the Southern Ocean sediments, mainly south of the Antarctic Polar Front (APF), where about 30% of the global opal marine accumulation occurs (Tréguer and De la Rocha, 2013).

Moored sediment traps are one of the few available tools for monitoring particle fluxes in the open ocean over extended periods of time. They provide a means to determine the magnitude and timing of phytoplankton blooms, document species succession and estimate the remineralization of labile components throughout the water column. The use of sediment traps has contributed significantly to our understanding of diatom ecology in the Southern Ocean and coastal Antarctic systems (e.g. Leventer and Dunbar, 1987, 1996; Fischer et al., 1988;

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Abelmann and Gersonde, 1991; Ishikawa et al., 2001; Suzuki et al., 2001; Pilskaln et al., 2004; Ichinomiya et al., 2008; Romero and Armand, 2010). However, these studies are scattered in space and time, and large regions of the Southern Ocean, including the Australian Sector, remain undocumented.

During the Australian multidisciplinary ACE CRC SAZ Project (Trull et al., 2001a), the main hydrological zones of the Australian sector of the Southern Ocean were instrumented with sediment trap mooring lines. The central goal of this experiment was to determine the origin, composition and fate of particulate matter transported to the ocean interior. This research yielded important results, including the demonstration that particulate organic carbon (POC) export in the Southern Ocean is similar to the global ocean median (Bray et al., 2000; Trull et al., 2001b).

Here, as part of the ACE CRC SAZ project, we report on the biogenic particle fluxes registered by two sediment traps deployed in the southern Antarctic Zone (60° 44.43´S; 139°E 53.97´S) over a year (November 2001 to September 2002) in order to (1) document the magnitude, composition and seasonal distribution patterns of the settling particle fluxes, with particular focus on diatoms and their specific composition; and (2) assess the effects of dissolution and physical processes in the water column on the diatom assemblage composition by comparing the assemblages registered by the 2000 and 3700 m sediment traps. An improved understanding of diatom ecology and changes that the diatom assemblages undergo during their sinking through the water column should lead to a better interpretation of proxy records in the Southern Ocean.

1.1. Oceanographic setting

The Antarctic Circumpolar Current (ACC) flows eastward around Antarctica driven by strong westerly winds connecting the Pacific, Atlantic and Indian Oceans. Several circumpolar jets or fronts divide the ACC into distinct zones (Fig. 1a), each one characterized by specific hydrological and biochemical properties (Orsi et al., 1995). The fronts coincide with strong current cores of the ACC defined by contours of sea surface height (SSH). Each of these fronts consists of multiple branches or filaments, where their position varies rapidly over time (Sokolov and Rintoul, 2002, 2007, 2009a,b). From north to south, these fronts and zones are the Subtropical Front (STF), the Subantarctic Zone (SAZ), the Subantarctic Front (SAF), the Polar Frontal Zone (PFZ), the Polar Front (PF), the Antarctic Zone (AZ) and the Southern ACC Front (SACCF) (Sokolov and Rintoul, 2009a, b).

The surface waters of the Australian sector of the Southern Ocean are nitrate and phosphate rich and their concentrations remain fairly uniform across the ACC (Bostock et al., 2013). In contrast, silicic acid (Si) content shows a marked south to north gradient. Highest Si concentrations are reached south of the Polar Front Zone (up to 70 μM), whereas the Subantarctic Zone waters exhibits low Si values (1 to 5 μM) (Bostock et al., 2013; Coale et al., 2004). Despite the relatively high macronutrient concentrations, Southern Ocean surface waters are often characterized by relatively low phytoplankton biomass. Light limitation related to deep mixing (Sakshaug and Holm-Hansen, 1984) and extremely low concentrations of trace metals such as iron (Boyd et al., 2000; De Baar et al., 1995; Fitzwater et al., 2000; Johnson et al., 1997; Martin et al., 1990) seem to be the main causes for this “high-nitrate, low-chlorophyll” (HNLC) regime.

Sea ice seasonality off East Antarctica is considered linked to patterns of oceanic currents, which in turn are related to sea floor topography (Massom et al., 2013). Seasonal sea-ice advance occurs from early autumn through early spring followed by retreat from late spring through summer (Kimura and Wakatsuchi, 2011; Massom et al., 2013).

Our study site, station 61 S (60° 44.43´S; 139° 53.97´E), is located within the southern Antarctic Zone (AZ-S; Parslow et al., 2001), between the southern branch of the PF (59°S) and the southern front of the SAACF (Rintoul and Bullister, 1999; Rintoul and Sokolov, 2001). The mooring site is within the same region where the first open-ocean iron enrichment experiment in the Southern Ocean (Southern Ocean Iron Release Experiment - SOIREE) was conducted (Boyd et al., 2000) and can be considered representative of the region between the PF and the SACCF (between 54°S and 62°S) (Trull et al., 2001c). Despite surface waters rich in macronutrients (i.e. silicate, phosphate and nitrate), the algal biomass accumulation is considered low (<0.5 μg/L) (Parslow et al., 2001; Popp et al., 1999; Trull et al., 2001c). Copepods, mainly large calanoid copepodites, dominate the zooplankton community at the study site. Grazing pressure is considered low (<1% of the phytoplankton standing stock removed per day) and is thought not to greatly influence the development of the annual bloom (Zeldis, 2001). Very low iron concentrations (0.1-0.2 nM; Sohrin et al., 2000; Boyd et al., 2000) appear to be responsible for the low primary production. The study area is far from the influence of coastal waters and just north of the maximum winter sea-ice extent (Fig. 1b; Massom et al., 2013).

2. Material and Methods

2.1. Field experiment

Site 61 S was instrumented with a mooring line equipped with three McLane Parflux time series sediment traps (Honjo and Doherty, 1988) placed at 1000, 2000 and 3700 m depth in a water column of 4393 m (Fig. 1c). Each trap was paired with an Aanderaa current meter and temperature sensor. The trap sampling cups were filled with a buffered solution of sodium tetraborate (1 g L^{-1}), sodium chloride (5 g L^{-1}), strontium chloride (0.22 g L^{-1}), and mercury chloride (3 g L^{-1}). Cup rotation intervals were synchronized between traps and were established based on anticipated mass fluxes. The shortest sampling intervals were 8 days and correspond with the austral summer and autumn, whereas the longest interval was 55 days corresponding with austral winter (Table 1). No samples were recovered from the shallowest trap owing to equipment malfunction. The two deeper traps completed their collection sequence as programmed without any instrumental failures providing a continuous time-series for 317 days (November 30, 2001 to September 29, 2002) divided into 21 collecting intervals. Owing to the low particle fluxes registered at the onset and end of the experiment insufficient material remained for diatom analysis of cup 1 of the 2000 m trap and cups 1, 2, 19, 20 and 21 of the 3700 m trap (Table 1). After recovery, sediment trap cups were removed, capped on board and stored at 4 °C in the dark until they were processed. The original samples were sieved through a 1 mm nylon mesh in order to remove the largest swimmers, and only the fraction <1 mm was analyzed. Then, they were split into 10 equal fractions using a McLane WSD-10 wet-sample divider. One complete split was used for microplankton analysis. A detailed description of the geochemical analytical procedures is given by Trull et al. (2001b); Bray et al. (2000). Component fluxes are reported for individual cups along with average values over the collection or deployment period for each component (Table 1). As the collection period was shorter than a calendar year, annual mean estimates were determined and are presented in Table 1. These annual estimates take into account the fact that the unobserved days occurred in winter when fluxes were low, and were obtained by using the flux for the last winter cup (#21 in 2002) to represent mean daily fluxes during the unobserved period.

In order to investigate the correlation between time series, a correlation matrix was calculated (Table 2).

2.2. Siliceous microplankton sample preparation and analysis

Each diatom fraction sample was refilled with distilled water to 40 ml, from which 10 ml was subsampled and buffered with a solution of sodium carbonate and sodium hydrogen carbonate (pH 8) and kept refrigerated for future calcareous nannoplankton analysis. The remaining