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High particulate organic carbon export during the decline of a vast diatom bloom in the Atlantic sector of the Southern Ocean

Montserrat Roca-Martí [a,*], Viena Puigcorbé [a], Morten H. Iversen [b,c,d], Michiel Rutgers van der Loeff [b], Christine Klaas [b], Wee Cheah [b,e], Astrid Bracher [b,f], Pere Masqué [a,g,h,*]

[a] *Institut de Ciència i Tecnologia Ambientals & Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[b] *Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany*
[c] *Faculty of Geosciences and MARUM, University of Bremen, 28359 Bremen, Germany*
[d] *Helmholtz Young Investigator Group SEAPUMP, Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany*
[e] *Research Center for Environmental Changes, Academia Sinica, Taipei 115, Taiwan*
[f] *Institute of Environmental Physics, University of Bremen, 28359 Bremen, Germany*
[g] *Oceans Institute and School of Physics, The University of Western Australia, Crawley, WA 6009, Australia*
[h] *School of Natural Sciences and Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, WA 6027, Australia*

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ABSTRACT

Carbon fixation by phytoplankton plays a key role in the uptake of atmospheric CO_2 in the Southern Ocean. Yet, it still remains unclear how efficiently the particulate organic carbon (POC) is exported and transferred from ocean surface waters to depth during phytoplankton blooms. In addition, little is known about the processes that control the flux attenuation within the upper twilight zone. Here, we present results of downward POC and particulate organic nitrogen fluxes during the decline of a vast diatom bloom in the Atlantic sector of the Southern Ocean in summer 2012. We used thorium-234 (^{234}Th) as a particle tracer in combination with drifting sediment traps (ST). Their simultaneous use evidenced a sustained high export rate of ^{234}Th at 100 m depth in the weeks prior to and during the sampling period. The entire study area, of approximately 8000 km^2, showed similar vertical export fluxes in spite of the heterogeneity in phytoplankton standing stocks and productivity, indicating a decoupling between production and export. The POC fluxes at 100 m were high, averaging 26 ± 15 mmol C m^{-2} d^{-1}, although the strength of the biological pump was generally low. Only $<20\%$ of the daily primary production reached 100 m, presumably due to an active recycling of carbon and nutrients. Pigment analyses indicated that direct sinking of diatoms likely caused the high POC transfer efficiencies (~60%) observed between 100 and 300 m, although faecal pellets and transport of POC linked to zooplankton vertical migration might have also contributed to downward fluxes.

1. Introduction

The Southern Ocean is an important sink for atmospheric CO_2 accounting for about 15–20% of the global oceanic uptake (Gruber et al., 2009; Takahashi et al., 2002), with a significant contribution from phytoplankton that fix CO_2 to organic carbon (Hauck et al., 2013). However, the strength and efficiency of the biological pump (i.e. export efficiency and transfer efficiency, respectively), as well as their controlling factors are poorly understood, especially during phytoplankton blooms (Buesseler and Boyd, 2009).

The export efficiency (i.e. the fraction of production that is exported from the upper ocean, usually taken as the base of the euphotic zone or 100 m) is low in much of the global ocean (<5–10%), but it is typically about 50% for blooms at high latitudes (Buesseler, 1998). However, previous studies have reported lower export efficiencies during high-productive events in the Southern Ocean (Jacquet et al., 2011; Planchon et al., 2015; Rutgers van der Loeff et al., 1997; Savoye et al., 2008). Furthermore, iron-fertilised blooms in the Southern Ocean show high variability in the fraction of production being exported from the ocean surface. As an example, during SOFeX-South (66°S) the export efficiency was low ($<10\%$, Buesseler et al., 2005), while during EIFEX it was approximately 60%, indicating a very strong biological pump

* Corresponding authors at: Institut de Ciència i Tecnologia Ambientals & Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain. Tel.: +34 935811191.
E-mail addresses: Montserrat.Roca.Marti@uab.cat (M. Roca-Martí), pere.masque@uab.cat (P. Masqué).

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(Smetacek et al., 2012). A number of factors may explain the differences observed in export efficiencies, including phytoplankton community composition and study time frame. Diatoms are key exporters of carbon from the ocean surface to deep waters and sediments, and hence play an essential role in reducing the CO_2 content in the atmosphere (Smetacek, 1999). Previous studies have shown that very low macronutrient concentrations, specifically of silicic acid, prevent the development of diatom blooms in benefit of flagellates, resulting in low particulate organic carbon (POC) export fluxes from the ocean surface (Jacquet et al., 2011; Martin et al., 2013). Further, diatoms in the Southern Ocean contribute differently to POC export according to their life cycle strategy in which the degree of silicification is relevant (Assmy et al., 2013; Quéguiner, 2013). Moreover, since export lags production, the time scale of the studies may often be too short to quantitively estimate the strength of the biological pump during bloom events (Buesseler et al., 2004; Charette and Buesseler, 2000).

The transfer efficiency (i.e. the fraction of shallow export that is transferred to depth) indicates the attenuation of the flux that takes place within a certain depth range. While it is known that the attenuation of POC fluxes is sharpest in the upper twilight zone, i.e. 100–300 m below the euphotic zone depth, our understanding of the processes affecting sinking particles throughout this layer is still poor (Buesseler and Boyd, 2009). The vertical flux of organic matter throughout the water column is dominated by large particles such as marine snow and faecal pellets (Ebersbach et al., 2011; Fowler and Knauer, 1986; Laurenceau-Cornec et al., 2015) that can be attenuated to a large extent by zooplankton and microbial degradation (Giering et al., 2014; Iversen et al., 2010; Kiørbe, 2000; Smith et al., 1992). However, packaging of slowly sinking phytoplankton cells into large faecal pellets may play a key role in increasing the export and transfer efficiencies in the Southern Ocean (Cavan et al., 2015; Le Moigne et al., 2014). Mineral ballasting also appears to alter the efficiency by which POC is transported to depth (e.g. Iversen and Robert, 2015; Klaas and Archer, 2002).

Thorium-234 (^{234}Th, half-life=24.1 d) is widely used as a particle tracer, mainly of POC, since it is particle reactive and its half-life allows studying events occurring over short time scales, ranging from days to weeks, such as phytoplankton blooms (e.g. Buesseler et al., 1992; Rutgers van der Loeff et al., 1997). A deficit of ^{234}Th with respect to its parent ^{238}U is typically found in the upper ocean. Once the ^{234}Th downward flux at a specific depth is quantified, this flux can be converted to POC and particulate organic nitrogen (PON) fluxes by determining the POC/^{234}Th and PON/^{234}Th ratios, respectively, in sinking particles (Buesseler et al., 2006; Cochran and Masqué, 2003).

This study focuses on the decline of a vast diatom bloom that occurred in the Antarctic Circumpolar Current (ACC) region of the Southern Ocean (around 51°S 13°W) during the late austral summer in 2012. Our objectives were to evaluate the export efficiency and transfer efficiency of POC between 100 and 300 m, as well as identify the main mechanisms that had an influence on particle fluxes. Particle fluxes were quantified by means of two different techniques, as highly recommended given the uncertainties associated with each collection method (e.g. Puigcorbé et al., 2015; Turner, 2015). We used the disequilibrium between the natural radionuclides ^{234}Th and ^{238}U to determine the export fluxes of POC and PON in parallel with the use of surface-tethered drifting sediment traps. Export fluxes were related to the evolution of chlorophyll *a* (Chl-a) and POC concentrations in the water column, as well as to pigments in sinking particles, following the decline of the bloom during three weeks. Net primary production (NPP) measured during the same cruise (Hoppe et al., this issue) was used to assess the export efficiency.

2. Methods

2.1. Study area

Samples were collected from 29 January to 17 February 2012 during the ANT-XXVIII/3 expedition in the Atlantic sector of the Southern Ocean (7 January–11 March, 2012; R/V Polarstern; Wolf-Gladrow, 2013). The sampling was carried out to study a massive bloom with high spatial and temporal resolution over an area of about 8000 km^2 located between the Antarctic Polar Front (APF) and the Southern Polar Front (SPF; Leach et al., this issue and Strass et al., this issue). Time-series measurements of ^{234}Th, POC, PON, Chl-a, other pigments and NPP were carried out at a station located in the centre of the study area at 51.21°S 12.67°W (hereafter "central station", indicated by a 'C' in front of the station number). The location and sampling dates of the stations sampled for ^{234}Th, POC and PON fluxes are given in Fig. 1 and Table 1.

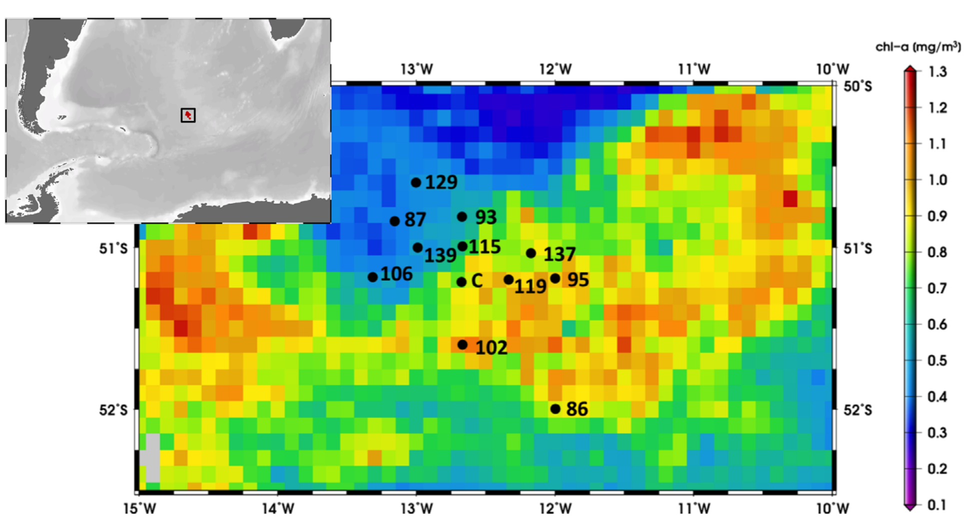

Fig. 1. Study area and sampled stations for ^{234}Th, POC and PON analyses. C represents the central station, which was occupied 7 times: C91, C98, C99, C114, C128, C136, C140. See Table 1 for further details regarding sampling dates. The satellite plot represents the mean Chl-a concentration from the OC-CCI Chl-a product version-2 during the sampling period (29 January to 17 February 2012).

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