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Sinking particle flux in the sea ice zone of the Amundsen Shelf, Antarctica

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ABSTRACT

We have examined the flux, biogenic composition, and isotopic values of sinking particles collected by a time-series sediment trap deployed in the sea ice zone (SIZ) of the Amundsen Sea from January 2011 for 1 year. The major portion of the particle flux occurred during the austral summer in January and February when sea ice concentration was reduced to $<60\%$. Biogenic components, dominated by opal ($\sim$78% of the biogenic components), accounted for over 75% of particle flux during this high-flux period. The dominant source of sinking particles shifted from diatoms to soft-tissued organisms, evidenced by high particulate organic carbon (POC) content ($>30\%$) and a low bio-Si/POC ratio (<0.5) during the austral winter. $CaCO_3$ content and its contribution to total particle flux was low ($\sim$6%) throughout the study period. Aged POC likely supplied from sediment resuspension accounted for a considerable fraction only from October to December, which was evidenced by a low radiocarbon content and relatively high (30–50%) content of the non-biogenic components. When compared with POC flux inside the Amundsen Sea polynya obtained by the US Amundsen Sea Polynya International Research Expedition (ASPIRE), the POC flux integrated over the austral summer in the SIZ was virtually identical, although the maximum POC flux was approximately half that inside the Amundsen Sea polynya. This comparatively high POC flux integrated over the austral summer in the SIZ may be caused by phytoplankton blooms persisting over a longer periods and more efficient export of organic matter potentially owing to the diatom-dominant plankton community. If this observation is a general phenomenon on the Amundsen Shelf, the role of the SIZ, compared with the polynyas, need to be examined more carefully when trying to characterize the POC export in this region.

1. Introduction

The West Antarctic, especially the Bellingshausen Sea and the Amundsen Sea, is experiencing rapid decline in sea ice cover (Stammerjohn et al., 2012). Intrusion of the warm Circumpolar Deep Water (CDW) onto the Amundsen Shelf reportedly provides the necessary heat for melting of sea ice and ice shelf (Walker et al., 2007; Wåhlin et al., 2010). Physical changes accompanying the decreasing sea ice are likely to affect the biogeochemistry and biology in this region. However, our understanding of the biological carbon pump on the Amundsen Shelf is very limited because of the logistical difficulty with access (Yager et al., 2012).

Studies of the biological carbon pump of the Amundsen Sea have been based on the observations by satellites (Arrigo and van Dijken, 2003). The Amundsen Sea polynya is of particular interest because of its extremely high primary productivity during the austral summer (Arrigo and van Dijken, 2003; Arrigo et al., 2012a). Estimates of primary production based on satellite observation on the Amundsen Shelf were supported by recent *in situ* measurements (Lee et al., 2012). However, a limitation of the satellite data exists in the sense that few data are available for ice-covered regions (Arrigo et al., 2008). In addition, the process that particulate organic matter (POM) undergoes after production needs to be understood to characterize the biological pump system and the role of this region in absorption of atmospheric CO_2. Studies of

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sinking POM flux at a depth on the Amundsen Shelf can further our understanding of carbon cycling in this region.

Compared with polynyas that have attracted attention in terms of their role in the absorption of atmospheric CO_2 because of their extremely high primary production, the role of the sea ice zone (SIZ) is not well understood. The SIZ in this research is defined as the region where sea ice concentration decreases in summer but is not ice-free, unlike polynyas (National Snow and Ice Data Center, NSIDC). In the SIZ, primary production occurs not only in water but also under sea ice (Arrigo et al., 2012b) and in sea ice (Lizotte, 2001; Thomas and Dieckmann, 2002). Thomas et al. (1998) suggested the possibility of high primary production even in areas of dense pack ice in the Bellingshausen and Amundsen Seas. Dominant plankton species of a given environment, such as *Phaeocystis antarctica* (hereafter *P. antarctica*) and diatoms, and potential shift in plankton community composition may influence the biological pump efficiency in the Southern Ocean (Arrigo et al., 1999; DiTullio et al., 2000; Smith et al., 2014). Evolution of the plankton community in the SIZ may be different from that in polynyas (Lee et al., 2012; Alderkamp et al., 2012; Smith et al., 2014).

A multidisciplinary research project was launched by the Korea Polar Research Institute (KOPRI) to examine the biological carbon pump currently operating in the Amundsen Sea. As a part of this project, we designed a time-series sediment trap study to examine POM export and its major controlling factors in the SIZ and inside the Amundsen Sea polynya. Unfortunately, due to a technical failure, no samples were obtained from the sediment trap deployed in the central polynya. We describe the detailed results of the sinking particle samples in the SIZ only. Then we compare our results with those obtained from sinking particle samples collected at a 350 m depth inside the polynya by the US Amundsen Sea Polynya International Research Expedition (ASPIRE, (Ducklow et al., 2015)).

2. Methods

A bottom-tethered hydrographic mooring with a sediment trap was deployed on the 530 m isobath (72.40 °S, 117.72 °W) on the western side of a glacier-carved trough (Dotson Trough) connecting the shelf break and the Dotson and Getz Ice Shelves (Fig. 1). Current meters (RCM-11) were attached at 253 m and 409 m depths on the same mooring (detailed design of the mooring line is available in Ha et al. (2014)). Less saline (salinity <34.2) and colder (potential temperature <-1 °C) water occupied the upper layer shallower than ~400 m above more saline and warmer water at the mooring site (Ha et al., 2014). Northward flow was observed more frequently in this upper layer (Ha et al., 2014). The vertical gradient in potential temperature and salinity in the upper water column above ~400 m was much smaller than that below this depth to the bottom, where a southward inflow of warm CDW was prevalent (Ha et al., 2014). The current speed measured at 409 m for a year was 5 cm s^{-1} on average. The current speed was higher in January and February (7.5 ± 3.3 cm s^{-1} on average) than in the other months (4.4 ± 2.4 cm s^{-1}). The pressure registered by a MicroCAT (Sea-Bird Electronics) moored at 409 m fluctuated daily with an amplitude of <1.7 dbar due to the tide and did not show any out-of-phase signal caused by tilting of the mooring line.

In this study, we used daily sea ice concentration data derived from SSMIS F-17 microwave remote sensor, retrieved from the University of Bremen (http://www.iup.uni-bremen.de:8084/ssmis/). The data were processed using a Bootstrap algorithm with 25 km^2 grid resolution. The sea ice concentration at the mooring site varied seasonally with high interannual variability. For example, the minimum sea ice concentration was 0, 37, and 56% in January and February 2010, January 2011, and March 2012, respectively. A reduced sea ice concentration below ~70% was observed from late December 2009 to late March 2010, from December 2010 to late February 2011, and from late January to early March 2012.

Sinking particle samples were collected by deploying a time-series sediment trap (McLane, conical type, aperture diameter=80 cm, and height/diameter=2.5) at 400 m from January 2011 to January 2012 in the SIZ of the Amundsen Shelf (K1 trap). The sample cup opening interval was set between 9 and 31 days depending on the expected particle flux at the study site (Table 1). Sampling bottles were filled with filtered seawater (45 mm GF/F filter; 0.7 μm nominal pore size), collected at a 400 m depth at the sediment trap mooring site, containing 5% formalin solution buffered with sodium borate. Recovered particle samples were stored in the refrigerator at 4 °C until further treatment. Recovered samples were not fortified with fresh formalin. The pH of the solution in the sampling bottles was not determined upon recovery. The US ASPIRE sediment trap (Technicap, cylindrical type) was deployed at a 350 m depth inside the polynya (73.82°S, 113.07°W; 785 m water depth (Ducklow et al., 2015)).

Any conspicuous swimmers were removed by tweezers before dividing the samples into 10 equal aliquots using a wet-sample divider (McLane Research Laboratories). Seven aliquots of each sample were combined, rinsed with ultrapure (Millipore) water, and freeze-dried for total mass and biogenic component analyses. Total dry mass was determined gravimetrically. Details of the analyses for the biogenic components of the particles have been published elsewhere (Kim et al., 2012). Briefly, total carbon content was determined using an elemental analyzer (Carlo-Erba 1110 CNS EA) on ~10 mg samples with an uncertainty of 2% relative standard deviation (RSD). Particulate inorganic carbon (PIC) content was determined by coulometric titration (UIC Coulometrics carbon analyzer) on ~15 mg samples with an RSD of 0.2% based on repeated analyses of a $CaCO_3$ standard. Organic carbon content was estimated as the difference between the total and particulate inorganic carbon contents. Organic matter content was estimated by multiplying the particulate organic carbon (POC) content by 2.5 (Thunell, 1998). $CaCO_3$ content was estimated by multiplying the PIC content by 8.33. Opal content was estimated by multiplying the biogenic Si (Bio-Si) content by 2.4, determined by a sequential dissolution method using 0.5 N NaOH solution at 85 °C (DeMaster, 1981; Mortlock and Froelich, 1989). The precision based on 10 duplicate analyses was 15% (RSD). The difference between the total amount and the sum of the three biogenic components was defined as non-biogenic components. The error associated with this estimation was 52 ± 41% (RSD; see Table 1).

One aliquot of each sample was used for isotopic analyses. The effect of formalin as a preservative on radiocarbon analysis was determined to be insignificant in a previous study (Otosaka et al., 2008). Each sample with a sizeable amount upon visual inspection (samples #1–#9) was filtered on a pre-cleaned Nuclepore filter (Whatman membrane, 47 mm, 1.0 μm pore size) rinsing three times with ultrapure (Millipore) water. Samples were dried at 45 °C in an oven, and particles were recovered from the filter pads. Each sample was ground using a mortar and pestle, then ~20 mg dry sample was weighed in a silver cup and fumigated with concentrated HCl in a desiccator for ~20 h (Hedges and Stern, 1984; Komada et al., 2008). Small samples were filtered on pre-combusted 47 mm GF/F filters. These particle samples were not separated from the filter pads. Each pair of samples (#13 and #14, #15 and #16, #17 and #18, and #20 and #21) was combined together to obtain enough carbon for radiocarbon measurements. HCl-fumed samples were then placed on a hot plate at ~45 °C for 4 h to remove HCl vapor. The sample cup was placed in a quartz tube with CuO. The sample tube was evacuated on a vacuum line and flame-sealed, then combusted at 850 °C for 4 h. Particle samples on GF/F filters were treated in the same way except that silver wire was added instead of a silver cup.