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Article

Particle Flux in the Eastern Bransfield Strait in 1999, Antarctica

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Abstract : A time-series sediment trap was deployed at 1,034 m water depth in the eastern Bransfield Strait from December 25, 1998 to December 24, 1999. About 99 % of total mass fluxes were observed during the austral summer and fall (January, February, and March). The annual total mass flux was 49.2 g m^{-2}. Biogenic materials including biogenic silica, organic matter, and carbonate accounted for about 67 % of total particle flux, and lithogenic materials contributed about 29 %. Biogenic silica was the most dominant (42 % of the total flux) in these components. The next most important biogenic component was organic matter, comprising 24 % of total mass flux. Calcium carbonate contributed a small fraction of total mass flux, only 0.6 %. The annual organic carbon flux was 5.2 g C m^{-2} at 1,034 m water depth. The annual primary production was estimated to be 21.6 g C m^{-2} at the sediment trap site, which seems to be highly underestimated. About 5.5 % of the surface water production of organic carbon sinks below 1,034 m water depth.

Key words : particle flux, biogenic opal, organic carbon, lithogenic flux, Bransfield Strait.

1. Introduction

The production of biogenic particles in the surface waters and their removal to the deep waters constraints the distribution of the biogeochemical elements in seawater. Particle flux controls nutrient regeneration, delivery of food to benthic communities, and preservation of sediment records of climate changes (Ittekkot *et al*. 1996 and references therein). With regard to the global carbon cycle, particle flux in the ocean is an important mechanism for the transfer of carbon derived from atmospheric CO_2 to the deep sea.

The Southern Ocean, located south of the Subtropical Convergence (ca 45°S), occupies a position of special interest because of its considerable role in atmospheric CO_2 cycle (Knox and McElroy 1984; Keir 1988; Robertson and Watson 1995; Bakker *et al.* 1997) and may play an important role as in the global opal cycle as well (Treguer and van Bennekom 1991; DeMaster *et al*. 1996; Rabouille *et al*. 1997). It is also characterized by strong dynamic links between environmental forcing variables, primary production and particle fluxes through the water column. There is large spatial and temporal variability in the magnitude and composition of biogenic fluxes in the Southern Ocean (Fisher *et al*. 1988; Wefer *et al*. 1988, 1990; Karl *et al*. 1991; Dunbar *et al.* 1998; Honjo *et al.* 2000). Particle flux in the Southern Ocean is strongly modulated by climate, via the influence of wind, ocean circulation, sea ice, and cloud cover on primary production (Dunbar *et al*. 1998). Therefore, it is possible to elucidate climate changes in the Southern Ocean by monitoring the long-term variation of particle flux.

The Bransfield Strait is a semi-closed sea, which is bounded by the South Shetland Islands and the Antarctic Peninsula. It belongs to relatively warm and humid regime with high precipitation (Reynolds 1981). These climatic conditions produce a sub-polar glacial setting which can be sensitive to change in environmental factors that influence the waxing and waning of ice sheets. Thus, the Bransfield Strait is an optimum site for the long-term monitoring of particle flux due to the high sensitivity on climate change and the easy accessibility. Wefer *et al.* (1990) measured particle fluxes using time-series sediment traps in the central Bransfield Strait from 1983 to 1986 for

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three years. They found huge seasonal and inter-annual variability in particle fluxes. Karl *et al*. (1991) measured organic carbon fluxes using the free-drifting sediment trap in the western Bransfield Strait from 1986 to 1987. Although there are some results on particle fluxes in the Bransfield Strait, we need more data on the magnitude and compositions of particle fluxes because of their large special and temporal variability.

In this paper, we examine particle fluxes measured over a 1-year period in the eastern Bransfield Strait. The objectives of this research are 1) to determine fluxes of total mass, organic matter, biogenic opal, calcium carbonate, and lithogenic material, 2) to estimate seasonal variations of these fluxes, and 3) to estimate how much the organic carbon produced at the surface waters sinks into the deep waters.

2. Materials and methods

We deployed time-series sediment traps on seabed-anchored mooring from Dec. 25, 1998 to Dec. 24, 1999 in the eastern Bransfield Strait (Fig. 1), at 61°45.77'S, 54°59.10'W (2,134 m water depth). The mooring contained two sets of instrument, which were deployed at 1,034 m and at 2,034 m water depths. Each set of instruments consisted of a McLane PARFLUX Mark 7G time-series sediment trap with 21 rotary sample cups and an Aanderaa RCM8 current meter. The sediment trap deployed at 2,034 m had a mechanical problem, and thereby we could not get any sediment trap samples. Sample collection intervals were 10 days on November, December, January, and February, 15 days on October, and 30/31 days on other months. Sediment trap samples were preserved by filling sample cups with a Na-borate buffered 5 % formalin solution prior to deployment.

Prior to sample splitting, recognizable swimmers were removed by handpicking. Samples were gently split using a Folsom plankton splitter into 4 fractions for chemical and microscopic analyses. One replicate split was centrifuged, decanted, and washed several times with distilled water. The washed sediment samples were freeze-dried for two days and weighed for mass flux calculations.

Total carbon content was measured by a Carlo-Erba CNS elemental analyzer. The precision of total carbon was 3 % based on the duplicate analyses. Inorganic carbon content was determined by a UIC coulometrics carbon analyzer with 2 % of precision. Calcium carbonate was calculated by multiplying inorganic carbon by 8.33. Organic carbon was calculated by difference between total and inorganic carbon. Organic matter was calculated by multiplying organic carbon by a factor of 2.27 (Martin and

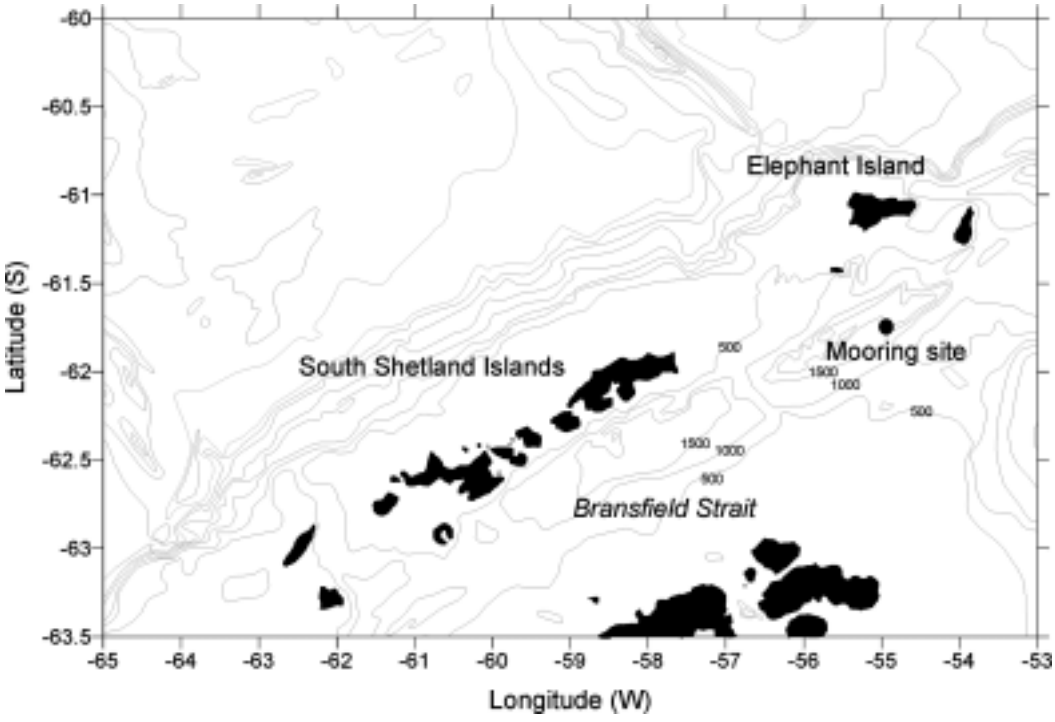

Fig. 1. Location of the sediment trap mooring site. The mooring site is marked by a closed circle.

Knauer 1973). Biogenic silica content was determined by time-series dissolution using 0.5 N NaOH at 85 °C (DeMaster 1981). The precision of biogenic silica was 2 % based on the duplicate analyses. Biogenic opal was calculated by multiplying biogenic Si by a factor of 1.12 (Mortlock and Froelich 1989). Aluminum content was measured by the Induced Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) in the Korea Basic Science Institute with 5 % of precision. Complete sample dissolution prior to introduction into the ICP-AES was achieved by HNO_3-HF-$HClO_4$ total digestion in Teflon beaker. Lithogenic content was estimated from Al content (wt.%) × 12.15 (Honjo *et al.* 2000). Primary production was measured by the ^{14}C incubation on deck for 3 hours (Holm-Hansen and Mitchell 1991).

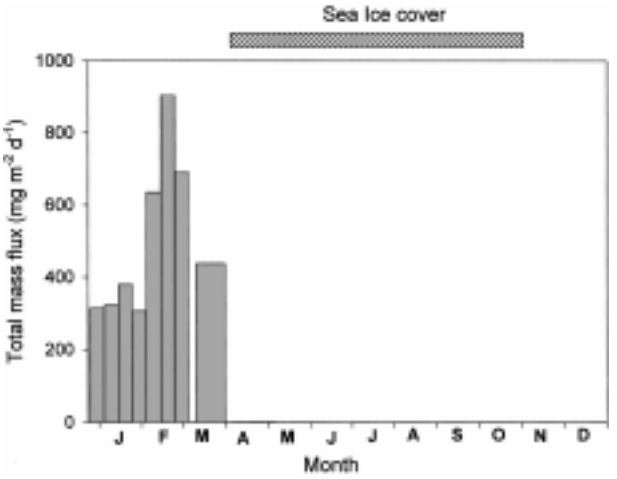

Fig. 2. Total mass flux in the eastern Bransfield Strait from December 25 th, 1998 to December 24 th, 1999. The hatched bar indicates the period of sea ice cover in the Bransfield Strait.

3. Results

Total mass fluxes showed an extremely large seasonal variation (Fig. 2). They concentrated only in three months (January, February, and March), reaching values between 306 and 904 mg m^{-2} d^{-1} (Table 1). During all the other months, they were at least three orders of magnitude lower, ranging from 0.01 to 1.2 mg m^{-2} d^{-1} (Table 1). The annual total mass flux was 49.1 g m^{-2}, of which 99 % occurred during the three most productive months.

Total mass flux was mostly composed of biogenic opal, organic matter, and terrestrial matter. Among them, biogenic opal was the most dominant component, comprising about 42 % of total mass flux (Table 1). Biogenic opal fluxes were 128 g m^{-2} d^{-1} on January, 288 g

Table 1. Fluxes of individual biogenic and lithogenic components.

Sampling interval	Total flux (mg m^{-2} d^{-1})	Opal flux (mg m^{-2} d^{-1})	Organic flux (mg m^{-2} d^{-1})	Carbonate flux (mg m^{-2} d^{-1})	Lithogenic flux (mg m^{-2} d^{-1})
98/12/25-99/01/04	314.0	163.6	51.4	2.1	59.1
99/01/04-99/01/14	321.7	121.4	87.2	2.2	108.0
99/01/14-99/01/24	379.0	127.7	147.1	1.8	101.3
99/01/24-99/02/03	305.8	96.6	87.8	1.8	117.1
99/02/03-99/02/13	635.4	243.7	131.0	3.8	251.2
99/02/13-99/02/23	903.8	335.8	204.7	5.5	295.3
99/02/23-99/03/05	690.0	284.6	162.4	4.1	200.2
99/03/05-99/04/05	437.5	215.0	97.5	1.8	88.8
99/04/05-99/05/05	1.165	n.d.	n.d.	n.d.	n.d
99/05/05-99/06/05	0.036	n.d.	n.d.	n.d.	n.d.
99/06/05-99/07/05	0.015	n.d.	n.d.	n.d.	n.d.
99/07/05-99/08/05	0.012	n.d.	n.d.	n.d.	n.d.
99/08/05-99/09/05	0.011	n.d.	n.d.	n.d.	n.d.
99/09/05-99/10/05	0.016	n.d.	n.d.	n.d.	n.d.
99/10/05-99/10/20	0.028	n.d.	n.d.	n.d.	n.d.
99/10/20-99/11/04	0.024	n.d.	n.d.	n.d.	n.d.
99/11/04-99/11/14	0.234	n.d.	n.d.	n.d.	n.d.
99/11/14-99/11/24	0.058	n.d.	n.d.	n.d.	n.d.
99/11/24-99/12/04	0.118	n.d.	n.d.	n.d.	n.d.
99/12/04-99/12/14	0.036	n.d.	n.d.	n.d.	n.d.
99/12/14-99/12/24	0.038	n.d.	n.d.	n.d.	n.d.
Annual estimate (g m^{-2} yr^{-1})	49.1	20.4	11.7	0.3	14.1

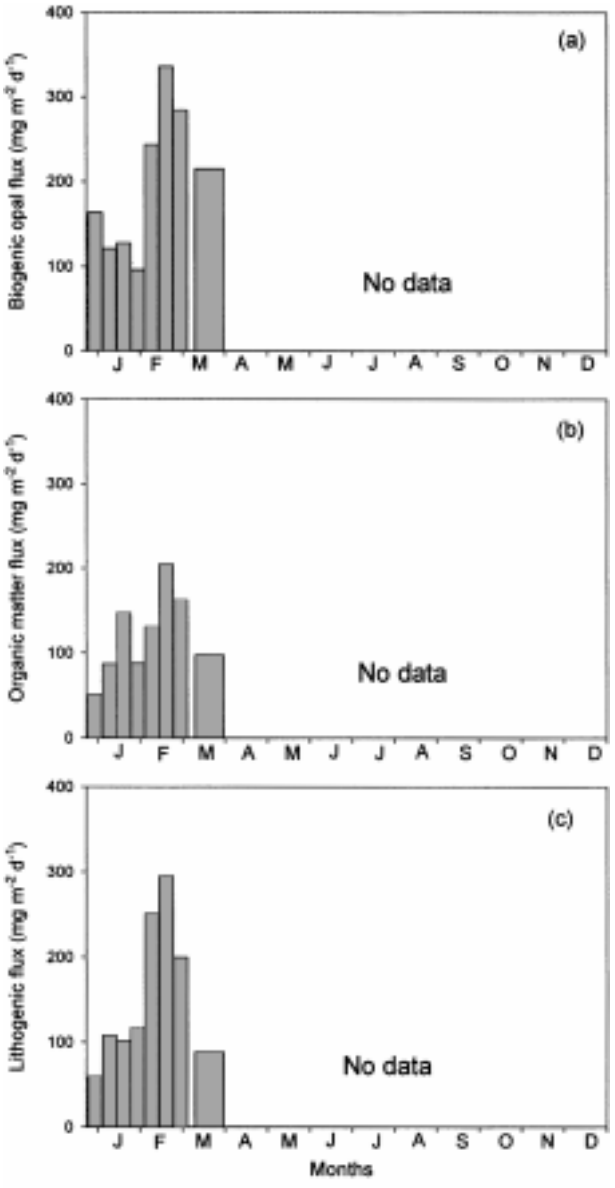

Fig. 3. (a) Biogenic opal flux, (b) organic matter flux, and (c) lithogenic flux in the eastern Bransfield Strait.

m^{-2} d^{-1} on February, 215 g m^{-2} d^{-1} on March and negligible on all the other months (Fig. 3a). The highest biogenic opal flux was observed on February. The annual biogenic opal flux was 20.4 g m^{-2} (Table 1), which was two times higher than the typical biogenic opal accumulation rate of 10 g m^{-2} yr^{-1} in the central Circumpolar Ocean (Lisitzin 1985).

The next most important biogenic component is organic matter, with 24 % of total mass flux (Table 1). Organic matter fluxes ranged from 51-205 g m^{-2} d^{-1}, with the highest flux on February (Fig. 3b). The annual organic

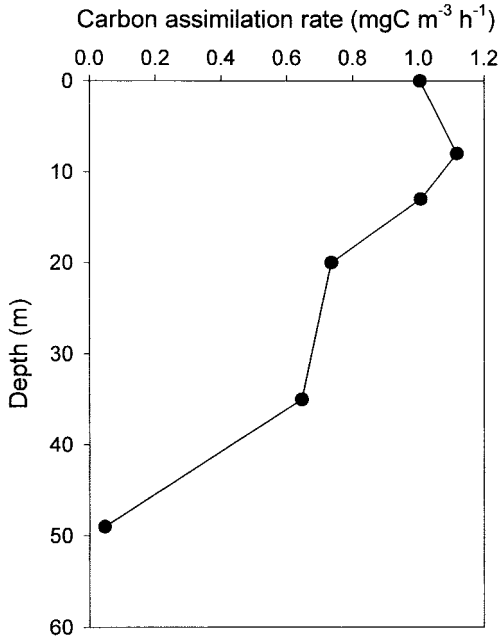

Fig. 4. Vertical profile of primary production (^{14}C) at the sediment trap mooring site in January 2000.

matter flux was 11.7 g m^{-2} (Table 1), which was converted to an annual organic carbon flux of 4.2 g C m^{-2}.

Calcium carbonate flux was negligible on all months, which contributes only 0.6 % of total mass flux (Table 1). The small carbonate flux seems to be due to dissolution of calcium carbonate during settling through the water column since carbonate compensation depth is only several hundred meters in the Antarctic Ocean.

The remaining portion of the material collected consists of lithogenic particles, contributing 29 % of total mass flux (Table 1). Lithogenic fluxes were 96 g m^{-2} d^{-1} on January, 249 g m^{-2} d^{-1} on February, 89 g m^{-2} d^{-1} on March and negligible on all the other months (Fig. 3c). The annual lithogenic flux was 14.1 g m^{-2} (Table 1).

Primary productivity was measured by the ^{14}C method at the sediment trap site in January 2000 (Fig. 4). Carbon assimilation rate did not change significantly within the 15 m water depth and then decreased rapidly below it, reaching almost zero at 50 m water depth. Primary productivity was estimated to be 243 mg C m^{-2} d^{-1}.

4. Discussion

Particle flux showed large seasonal variations, with flux only in January, February, and March. On an annual average, the particle flux estimated at our sediment trap are not out of the ordinary. Our annual particle flux of

49.1 g m^{-2} is comparable with the previous results (11.9 120 g m^{-2} yr^{-1}) obtained by Wefer *et al*. (1988, 1990) in the central Bransfield Strait. The Bransfield Strait is usually covered with sea ice from April to October (http://geochange.er.usgs.gov). Thus, the minimal particle fluxes from April to October are probably due to sea ice cover at the sediment trap site during these months. Despite of disappearance of sea ice, however, particle flux was still very low (less than 1.0 mg m^{-2} d^{-1}) on November and December, which may be explained by two possibilities. One possibility is that most of primary production occurred on November and December is built up in phytoplankton stock and thereby only few particles sink into the deep ocean. Smith *et al*. (2000) suggested that most of initial production was going into phytoplankton stock through early February in the Ross Sea. The other possibility is that zooplankton appeared in the study area after December so that zooplankton fecal pellets, the most important carrier of sinking particles in the Bransfield Strait (Bodungen *et al*. 1987), were not produced sufficiently to record high particle fluxes on November and December. During an initial (December to January) peak in primary production in the Bransfield Strait, few krills were caught, but many krills were caught later in the austral summer (February to March) (Brinton 1991). It is difficult to determine which possibility prevails at this stage, but we think that the both may act similarly to reduce particle fluxes on November and December.

The average organic carbon flux at 1,034 m water depth was 53 mg C m^{-2} d^{-1} in the eastern Bransfield Strait during the most productive period (January, February, and March) (Table 1). Karl *et al*. (1991) measured organic carbon flux at 100 m water depth using the free-drifting sediment trap in the western Bransfield Strait from December to March, which ranged from 36 to 373 mg C m^{-2} d^{-1}, with an average of 132 mg C m^{-2} d^{-1}. Thus, the organic carbon flux measured in the eastern Bransfield Strait is about an half of that in the western Bransfield Strait. The annual organic carbon flux of 5.2 g C m^{-2} measured in our sediment trap is larger than that (3.1 g C m^{-2}) in the central Bransfield Strait (Wefer *et al*. 1990). Dunbar *et al*. (1998) and Wefer *et al*. (1982) measured annual organic carbon fluxes in the continental shelf of the Ross Sea and the Drake Passage using the time-series sediment traps, which were 5.0 and 5.4 g C m^{-2}, respectively. These annual organic carbon fluxes are fairly similar to our estimate.

Primary production measured at the sediment trap site in January 2000 was 243 mg C m^{-2} d^{-1}. We also measured primary production at several stations in the eastern Bransfield Strait, which ranged from 121 to 298 mg C m^{-2} d^{-1}, with an average of 209 mg C m^{-2} d^{-1}. Thus, the primary production measured at the sediment trap site is similar to the average primary production in the eastern Bransfield Strait. Assuming that the primary production was sustained at the same rate for the most productive months (January, February, and March) and was negligible on the other months, the annual primary production would be 21.6 g C m^{-2} yr^{-1}. Fisher *et al*. (2000) estimated the annual primary production in the Bransfield Strait using the Coastal Zone Colour Scanner (CZCS) data, which was 93.7 g C m^{-2}. Thus, our estimate was extremely underestimated. Considering that the annual primary production is 93.7 g C m^{-2}, and the annual organic carbon flux at 1,034 m water depth was 5.2 g C m^{-2} in the eastern Bransfield Strait, therefore, about 5.5 % of organic carbon produced at the surface waters sinks below 1,034 m water depth.

5. Conclusions

1. Particle fluxes showed huge seasonal variations, which concentrated on three months (January, February, and March). The annual total mass flux was estimated to be 49.1 g m^{-2}, which is comparable with the previous estimate in the central Bransfield Strait.

2. About 42 % of total mass flux was composed of biogenic opal. Organic matter contributed 24 % of total mass flux, calcium carbonate 0.6 %, and lithogenic particles 29 %.

3. The annual organic carbon flux was 5.2 g C m^{-2}, which is fairly similar to those measured in the continental shelf of the Ross Sea and the Drake Passage.

4. About 5.5 % of the surface water production of organic carbon sinks below the 1,034 m water depth.

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