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Downward particle flux in the eastern Bransfield Strait, Antarctica

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A time-series sediment trap was deployed at a depth of 1034 m in the eastern Bransfield Strait from December 25, 1998 to December 24, 1999. Particle fluxes showed large seasonal variation; about 99% of the annual total mass flux (49 g m^{-2}) was collected during the austral summer and fall (January-March). Settling particles consisted primarily of biogenic silica, organic carbon, calcium carbonate, and lithogenic material. Biogenic silica and lithogenic material predominated settling particles, comprising 36% and 30% of the total mass flux, respectively, followed by organic carbon, 11% and calcium carbonate, merely 0.6%. The annual organic carbon flux was 5.4 g C m^{-2} at 1000 m in the eastern Bransfield Strait, which is greater than the central Strait flux. The relatively lower flux of organic carbon in the central Bransfield Strait may be caused by a stronger surface current in this region. Organic carbon flux estimates in the eastern Bransfield Strait are the highest in the Southern Ocean, perhaps because of the fast sinking of fecal pellets, which leads to less decomposition of organic material in the water column. Approximately 5.8% of the organic carbon produced on the surface in the eastern Bransfield Strait is exported down to 1000 m; this percentage exceeds the maximum EF_{1000} values observed in the Atlantic and Southern Oceans. The eastern Bransfield Strait appears to be the most important site of organic carbon export to the deep sea in the Southern Ocean.

Key words: Antarctica, Bransfield strait, Sediment trap, Particle flux

INTRODUCTION

An important mechanism in the oceanic carbon cycle is the biologically mediated export of particulate organic carbon from the surface ocean to the deep ocean and then into the surface sediments of the ocean floor (Ittekkot *et al.*, 1996). It represents a possible long-term sink of atmospheric CO_2. In addition, export of biogenic materials from the upper ocean affects nutrient regeneration, fuels benthic life, and records ecological data in the sediment record. The Southern Ocean, located south of the Subtropical Convergence (approximately 45°S), occupies a position of special interest because of its considerable role in atmospheric CO_2 budgets (Knox and McElroy 1984; Keir 1988; Robertson and Watson 1995; Bakker *et al.*, 1997); it may be important to global opal production as well (Treguer and van Bennekom, 1991; DeMaster *et al.*, 1996; Rabouille *et al.*, 1997). The Southern Ocean is also characterized by strong, dynamic links between environmental variables such as primary production and particle flux in the water column. The magnitude and composition of biogenic fluxes in the Southern Ocean vary both spatially and temporally (Fisher *et al.*, 1988; Wefer *et al.*, 1990; Karl *et al.*, 1991; Dunbar *et al.*, 1998; Collier *et al.*, 2000; Honjo *et al.*, 2000; Langone *et al.*, 2000). Particle flux in the Southern Ocean is strongly modulated by the effect of climatic factors (wind, ocean circulation, sea ice, cloud cover) on primary production (Dunbar *et al.*, 1998).

The Bransfield Strait is a semi-closed sea bounded by the South Shetland Islands and the Antarctic Peninsula. The local climate is relatively warm and humid, with high precipitation levels (Reynolds, 1981), which produces a sub-polar glacial setting that can be sensitive to changes in environmental factors that influence the growth and melt of ice sheets. Sensitivity to climate change and accessibility make the Bransfield Strait ideal for long term monitoring of particle

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fluxes. In the central Bransfield Strait, Wefer *et al.* (1990) found large seasonal and inter-annual variability in particle flux data collected from 1983 to 1986 using a time-series sediment trap. In the western Bransfield Strait, organic carbon fluxes were measured by Karl *et al.* (1991) using a free-drifting sediment trap from 1986 to 1987 and by Palanques *et al.* (2002) using a time-series sediment trap from 1995 to 1996. Although some results that describe particle flux in the Bransfield Strait exist, more data describing the magnitude and composition of particle flux are needed because of the large spatial and temporal variability.

This paper describes the initial results from data collected using a sediment trap for a year in the eastern Bransfield Strait. We aimed to determine the composition and timing of biogenic and lithogenic fluxes and to elucidate the processes controlling seasonal variation in these fluxes.

MATERIALS AND METHODS

We deployed a time-series sediment trap on a seabed-anchored mooring from December 25, 1998 to December 24, 1999 in the eastern Bransfield Strait (61°45.77S, 54°59.10W; 2134 m water depth) (Fig. 1). The mooring had two sets of instruments, placed at 1034 m and 2034 m. Each set 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 at 2034 m had a mechanical problem and thus could not be used to retrieve samples. Samples were collected at 1034 m every 10 days from November to February, every 15 days in October, and once a month in other months. Sample cups were filled with a sodium borate buffered 5% formalin solution prior to deployment to preserve trapped samples from microbial degradation.

Samples were first processed by removing recognizable swimmers by hand. The samples were then gently split into four fractions, using a Folsom plankton splitter, for chemical and microscopic analyses. One replicate was centrifuged, decanted and washed several times with distilled water. The washed sediment samples were freeze-dried for two days and then weighed for mass flux calculations. Total carbon content was measured by a Carlo-Erba CNS elemental analyzer. The precision of total carbon measurements was 3% as indicated by duplicate analyses. Inorganic carbon content was determined by a UIC Coulometrics carbon analyzer with 2% precision. Calcium carbonate content was calculated by multiplying the inorganic carbon content by 8.33 (Wefer *et al.*, 1990). Organic carbon content was measured as the difference in weight between total and inorganic carbon. Biogenic silica content was determined by time-series dissolution by 0.5N NaOH at 85°C (DeMaster, 1981), with 5% precision as indicated by duplicate analyses. Aluminum content was measured by Induced Coupled PlasmaAtomic Emission Spectroscopy (ICP-AES) at the Korea Basic Science Institute, with 5% precision. Samples were dissolved completely by total HNO_3-HF-$HClO_4$ digestion in a Teflon beaker before ICP-AES analysis (Park and Yoon, 1994).

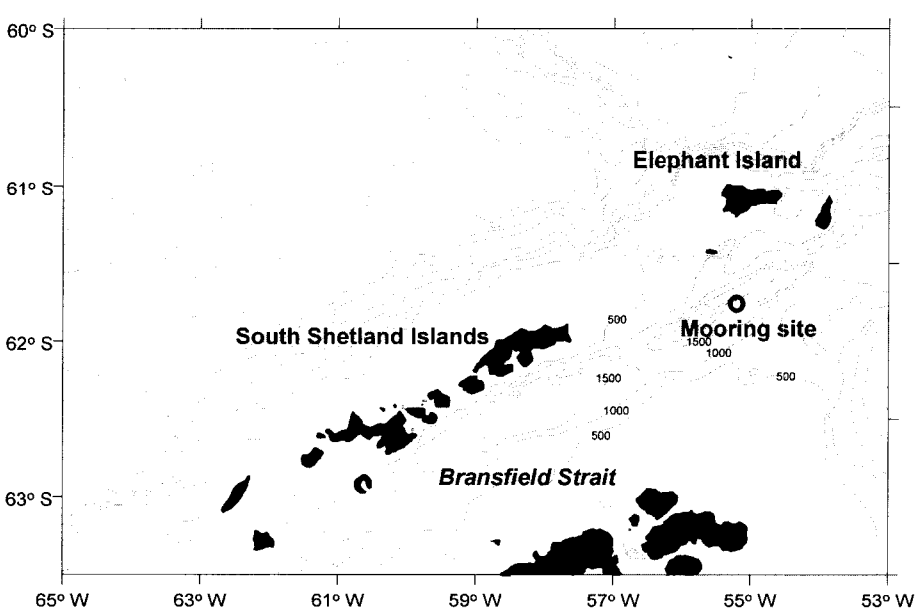

Fig. 1. Location of the sediment trap mooring site in the eastern Bransfield Strait. The mooring site is marked by an open circle.

RESULTS

Monthly mean sea ice data at the sediment trap mooring site were obtained from the DMSP F13 special sensor microwave/imager (SSM/I). In 1999, sea ice was present from June to October (Fig. 2a). Sea ice cover was less than 10% in June and October and about 40% from July to September, however, so the mooring site was never completely covered by sea ice during the study.

Current meters were placed 20 m below each sediment trap to evaluate flow conditions during sampling. Five-day mean current data were collected at 1054 m (Fig. 2b). Current velocity was 0.3 to 7.6 cm s^{-1} with an overall mean of 3.8 cm s^{-1}. Currents flowed southwest from January to September and then northeast or northwest for the remainder of the study. Current speeds did not vary much seasonally but were slightly faster during the austral winter.

Total mass flux showed extremely large seasonal variation (Fig. 3). Almost all flux occurred over three months (January-March); measurements were 306 to 904 mg m^{-2} d^{-1}, with the maximum flux in February

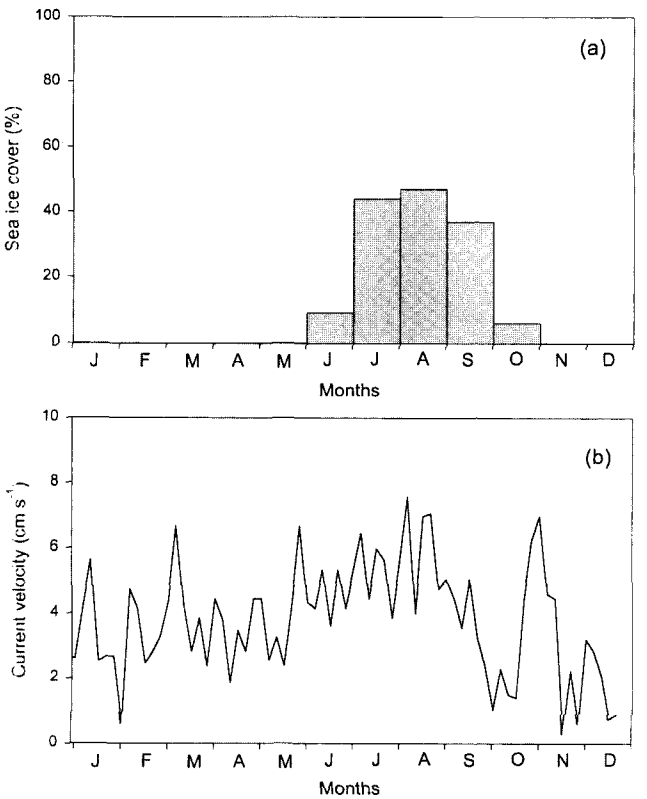

Fig. 2. Monthly averaged sea ice coverage at the mooring site (a) and current velocity (5-day means) at 1054 m depth of the mooring site (b).

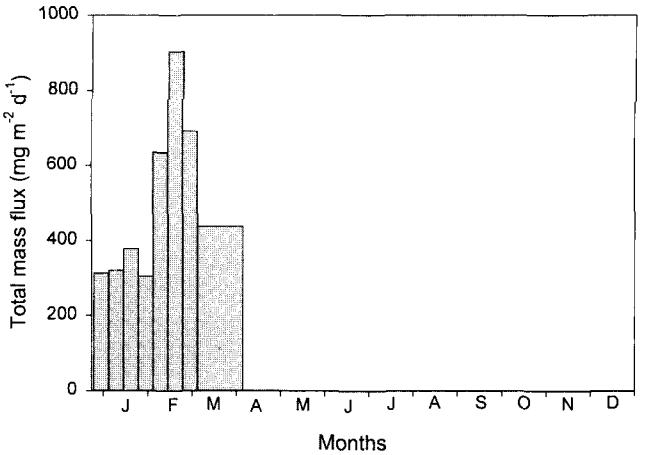

Fig. 3. Total mass fluxes in the eastern Bransfield Strait from December 25, 1998 to December 24, 1999.

(Table 1). During all other months, flux was lower by at least two orders of magnitude (0.01 to 1.2 mg m^{-2} d^{-1}) (Table 1). The annual total mass flux was 49 g m^{-2}.

Total mass flux comprised mostly biogenic silica, organic carbon, and lithogenic particles (Table 1). Biogenic silica was the most dominant component, comprising about 36% of the total mass flux (Table 1). Biogenic silica fluxes were 86 to 299 mg-SiO_2 m^{-2} d^{-1} (Fig. 4a). The annual biogenic silica flux was 18 g-SiO_2 m^{-2} (Table 1), which is comparable to the typical biogenic silica accumulation rate in the central Circumpolar Ocean, 10 g-SiO_2 m^{-2} yr^{-1} (Lisitzin 1985).

The second important biogenic component was organic carbon, accounting for 11% of the total mass flux (Table 1). Organic carbon fluxes were 23 to 90 mg m^{-2} d^{-1}, peaking in February (Fig. 4b). The annual organic carbon flux was 5.2 g m^{-2} (Table 1).

Less than 1% of total mass flux contained calcium carbonate (Table 1). These fluxes were 1.8 to 5.5 mg m^{-2} d^{-1} (Fig. 4c), one to two orders of magnitudes lower than those of biogenic silica and organic carbon.

Lithogenic particles made up the remainder of the sediment samples; the relative fraction of this material can be estimated using an elemental proxy such as Al. Lithogenic fractions were estimated to contribute 30% of the total mass flux (Table 1) by multiplying the Al content (% weight) by 12.15 (Honjo *et al.*, 2000). Lithogenic fluxes were 59 to 296 mg m^{-2} d^{-1}, with the highest flux in February (Fig. 4d). The annual lithogenic flux was 14 g m^{-2} (Table 1).

DISCUSSION

Particle fluxes showed considerable seasonal vari-

Table 1. Fluxes and composition of biogenic and lithogenic components at 1034 m depth of the eastern Bransfield Strait

Cup	Date open	Days	Total mass fluxes ($mg\ m^{-2}\ d^{-1}$)	Organic carbon fluxes ($mg\ m^{-2}\ d^{-1}$)	Organic carbon contents (%)	Biogenic Si fluxes ($mg\ m^{-2}\ d^{-1}$)	Biogenic Si contents (%)	$CaCO_3$ fluxes ($mg\ m^{-2}\ d^{-1}$)	$CaCO_3$ contents (%)	Lithogenic fluxes ($mg\ m^{-2}\ d^{-1}$)	Lithogenic contents (%)
1	12/25/98	10	314	23	7.2	146	46	2.1	0.68	59	19
2	01/04/99	10	322	38	12	108	34	2.2	0.70	108	34
3	01/14/99	10	379	65	17	114	30	1.8	0.48	101	27
4	01/24/99	10	306	39	13	86	28	1.8	0.58	117	38
5	02/03/99	10	635	58	9.1	217	34	3.8	0.59	251	40
6	02/13/99	10	904	90	10	299	33	5.5	0.60	296	33
7	02/23/99	10	690	72	10	254	37	4.1	0.59	200	29
8	03/05/99	31	437	43	9.8	192	44	1.8	0.41	89	20
9	04/05/99	30	1.17	–	–	–	–	–	–	–	–
10	05/05/99	31	0.04	–	–	–	–	–	–	–	–
11	06/05/99	30	0.01	–	–	–	–	–	–	–	–
12	07/05/99	31	0.01	–	–	–	–	–	–	–	–
13	08/05/99	31	0.01	–	–	–	–	–	–	–	–
14	09/07/00	30	0.02	–	–	–	–	–	–	–	–
15	10/05/99	15	0.03	–	–	–	–	–	–	–	–
16	10/20/99	15	0.02	–	–	–	–	–	–	–	–
17	11/04/99	10	0.23	–	–	–	–	–	–	–	–
18	11/14/99	10	0.06	–	–	–	–	–	–	–	–
19	11/24/99	10	0.12	–	–	–	–	–	–	–	–
20	12/04/99	10	0.04	–	–	–	–	–	–	–	–
21	12/14/99	10	0.04	–	–	–	–	–	–	–	–
Annual flux ($g\ m^{-2}\ yr^{-1}$)			49	5.2		18		0.27		14.1	

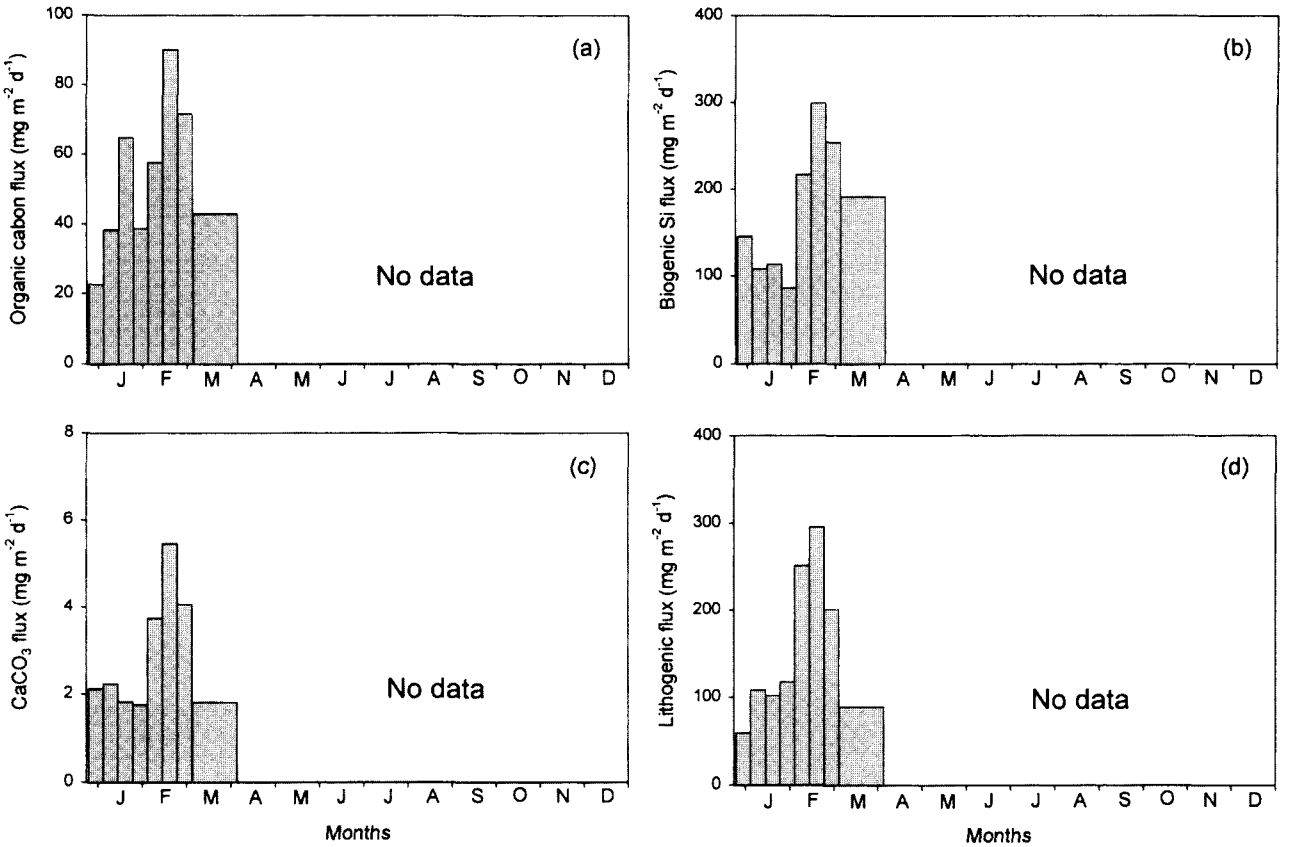

Fig. 4. Organic carbon fluxes (a), biogenic Si fluxes (b), calcium carbonate fluxes (c), and lithogenic fluxes (d) in the eastern Bransfield Strait.

ation (Fig. 3), occurring only in austral summer and early fall (January, February, and March). Particle flux was at least 100 times lower, less than 2.0 mg m^{-2} d^{-1}, in the other months. These extremely small fluxes could be artificial anomalies caused by either mechanical problems or hydrodynamic bias. The rotor of the sediment trap must be perfectly aligned with the hole of the funnel to collect sinking particles. We checked the rotor alignment immediately after recovering the sediment trap array, however, and found no sign of malfunctioning. Hydrodynamic bias concerns the fact that when current speeds exceed 15 cm s^{-1}, particle fluxes are significantly underestimated (Gust *et al.*, 1994; Gardner, 2000). Current speeds measured in this study were always less than 10 cm s^{-1} (Fig. 2a), which are low enough to expect maximal trapping efficiency. It is therefore unlikely that the sediment trap failed to record particle fluxes during the period of small flux. Wefer *et al.* (1990) measured particle fluxes in the central Bransfield Strait for three years. They also observed that 97% of particle flux occurred over two months (December and January) and during all other months flux was typically between 10 and 100 times lower.

Total mass flux decreased rapidly from 437 mg m^{-2} d^{-1} in March to 1.2 mg m^{-2} d^{-1} in April (Fig. 3). This sharp drop was probably not due to sea ice cover; typically, less than half the study area was covered by packed ice from June through October (Fig. 2a). In the Ross Sea, however, ice cover is responsible for the large seasonal variability in particle flux (Langone *et al.*, 2000). Primary production tends to decrease suddenly in the Southern Ocean after March because of low irradiation, a deep mixed layer, and sea ice (Smith *et al.*, 1996; Arrigo *et al.*, 1998). In the Bransfield Strait, primary production in late March is an order of magnitude lower than that in austral summer (Holm-Hansen and Mitchell, 1991). Air temperature measured at the King Sejong Station located at the King George Island drops below 0°C in April (Lee *et al.*, 1997) and thereby, input of lithogenic material in the Bransfield Strait must be significantly reduced by stop of ice melting on land. Therefore, the sharp drop in total mass flux after

March in this study could have been caused by sudden decreases in primary production and input of lithogenic material.

Organic carbon fluxes generally give an approximate indication of primary production in surface waters. Primary production in the Southern Ocean is usually very low throughout austral fall and winter, and increases in austral spring as solar radiation increases and the surface mixed layer becomes shallower (Smith *et al.*, 1996; Arrigo *et al.*, 1998). In the Bransfield Strait, primary production increases rapidly in November and remains high throughout the summer (December to February) (Holm-Hansen and Mitchell, 1991). In the western Antarctic Peninsula region, primary production is greater in November and December than in February and March (Smith *et al.*, 1996). However, total mass fluxes measured in this study were still very small (less than 1.0 mg m^{-2} d^{-1}) in November and December (Fig. 3). Even though primary production increases rapidly in those months, particle flux did not change significantly. Such uncoupling of primary production and particle flux may have two explanations. One is that most primary production in November and December is built up in phytoplankton stock since environmental conditions in spring are favorable for phytoplankton growth and therefore only a few organic particles sink into the deep ocean. In the Ross Sea, the average phytoplankton growth rate (0.60 d^{-1}) is much higher than the average mortality rate (0.14 d^{-1}); thus most primary production in the spring was held in phytoplankton (Caron *et al.*, 2000; Smith *et al.*, 2000). The other explanation is that zooplankton appear in the study area only after December, such that zooplankton fecal pellets, the most important vehicle of sinking particles in the Bransfield Strait (Bodungen *et al.*, 1987), are too few in November and December to drive large fluxes in particles. During the initial peak in primary production in the Bransfield Strait in December and January, few krill are caught, whereas many are caught later in the austral summer (February to March) (Brinton, 1991). Both of these explanations probably act to reduce particle flux in November and December.

The annual flux in organic carbon was estimated as 5.2 g C m^{-2} at a depth of 1034 m in the eastern Bransfield Strait (Table 2). Wefer and Fisher (1991) reported that annual organic carbon fluxes in the central Strait varied greatly between years (0.35 to 7.7 g C m^{-2}) from 1983 to 1986 (Table 2), as did annual fluxes measured from 1987 to 1990 west of the Maud Rise (0.16 to 2.3 g C m^{-2}) (Table 2). In the Ross Sea, annual organic carbon fluxes are measured at three different sites; these values vary considerably by site, from 0.35 to 5.9 g C m^{-2} (Table 2). Annual organic carbon fluxes do not differ spatially, however, in the Polar Frontal and Antarctic zones (Table 2).

Organic carbon flux generally decreases with water depth (Martin *et al.*, 1987). For comparison with other measurements, we normalized the measured organic carbon fluxes to a depth of 1000 m using the equation proposed by Martin *et al.* (1987):

$$F_{1000}=F_{trap}/(Z_{trap}/1000)^{-0.858},$$

where F_{1000} is the organic carbon flux at 1000 m, F_{trap}, the measured organic carbon flux, and Z_{trap}, the sediment trap depth. The highest annual flux of organic carbon (normalized) in the Southern Ocean, 5.4 g C m^{-2}, occurred in the eastern Bransfield Strait (Table 2); annual organic carbon fluxes at 1000 m were smaller in the central Strait (0.26 to 4.2 g C m^{-2}). Organic carbon fluxes are closely coupled with primary production in surface waters. The fluxes measured in the eastern and central Bransfield Strait suggest that primary production is much higher in the eastern region. However, primary productivities measured during austral summer do not differ considerably between the two; data from both sites range from 500 to 1500 mg C m^{-2} d^{-1} (Helbling *et al.*, 1995; Basterretxea and Aristegui, 1999; Figueiras *et al.*, 1999). Organic carbon fluxes in the Bransfield Strait therefore seem to be strongly influenced by environmental factors other than primary productivity.

The hydrography of the Bransfield Strait is very complex, a result of two interacting inflows: the relatively cold and salty Weddell Sea and the relatively warm and fresh Bellingshausen Sea (Holm-Hansen *et al.*, 1997; Lopez *et al.*, 1999). The Bransfield Current is also highly variable on a spatial scale; surface currents are faster than 15 cm s^{-1} at the mooring site in the central Bransfield Strait but less than 5 cm s^{-1} at the mooring site of the eastern Strait (Lopez *et al.*, 1999). Therefore, the relatively small organic carbon fluxes in the central Bransfield Strait may be due to the strong surface current, which could carry away a substantial amount of locally produced organic material.

The organic carbon flux measured in this study includes the highest value in the Southern Ocean, more than two times greater than fluxes measured in the Polar Front and Antarctic zone and almost one

Table 2. Compilation of annual organic carbon fluxes and 1000 m-normalized organic carbon fluxes in the eastern Bransfield Strait and in other areas of the Southern Ocean.

Area	Position	Year	Water depth (m)	Trap depth (m)	Organic carbon fluxes ($g\ m^{-2}\ yr^{-1}$)	Organic carbon fluxes at 1000 m ($g\ m^{-2}\ yr^{-1}$)	Sources
Bransfield Strait	61°46'S, 54°59'W	1999	2034	1034	5.2	5.4	Present study
Bransfield Strait	62°15'S, 57°32'W	1983-1984	1952	494	7.7	4.2	Wefer and Fisher (1991)
Bransfield Strait	62°20'S, 57°28'W	1984-1985	1659	693	0.35	0.26	Wefer and Fisher (1991)
Bransfield Strait	62°22'S, 57°50'W	1985-1986	1992	687	1.1	0.80	Wefer and Fisher (1991)
Northern Weddell Sea	62°27'S, 34°46'W	1985-1986	3880	863	0.021	0.019	Wefer and Fisher (1991)
Maud Rise	64°55'S, 02°30'W	1987	5000	4456	0.17	0.61	Wefer and Fisher (1991)
Maud Rise	64°54'S, 02°34'W	1988-1989	5053	360	2.3	0.96	Wefer and Fisher (1991)
Maud Rise	64°56'S, 02°36'W	1989-1990	5044	352	0.16	0.065	Wefer and Fisher (1991)
Ross Sea	74°02'S, 175°06'E	1994-1995	588	211	0.35	0.092	Langone *et al.* (2000)
Ross Sea	73°33'S, 176°53'E	1996-1998	565	200	2.2	0.55	Collier *et al.* (2000)
Ross Sea	76°30'S, 178°10'E	1996-1998	581	206	5.9	1.5	Collier *et al.* (2000)
Polar Front	50°09'S, 05°46'W	1987-1988	3750	700	2.9	2.1	Wefer and Fisher (1991)
Polar Frontal zone	56°54'S, 170°10'W	1997	4924	982	1.7	1.7	Honjo *et al.* (2000)
Polar Front	60°17'S, 170°03'W	1997	3957	1003	2.3	2.3	Honjo *et al.* (2000)
Antarctic zone	63°09'S, 169°54'W	1997	2885	1031	2.2	2.3	Honjo *et al.* (2000)
Antarctic zone	66°10'S, 169°40'W	1997	3015	937	1.9	1.8	Honjo *et al.* (2000)

order of magnitude higher than fluxes in the Maud Rise and Ross Sea (Table 2). Organic carbon flux is usually coupled tightly with primary production in surface waters. Arrigo *et al.* (1998) estimated primary productivity in the Southern Ocean from algal pigments using a coastal zone color scanner (CZCS). They divided the Southern Ocean into five geographic sectors and three open-water ecological provinces and estimated the daily primary productivity of each region throughout the year. Their estimates suggest that primary productivity in the Bransfield Strait does not differ significantly from that estimated in other Antarctic areas (the Polar front, Antarctic zone, Maud Rise, and Ross Sea); the Ross Sea showed the highest primary productivity in that study. Thus, the largest flux of organic carbon observed in this study in the Bransfield Strait may not be due to high primary productivity.

Antarctic krill and salp are the most important filter-feeding metazoans in the Southern Ocean (Voronina, 1998). These two microphage species can efficiently repackage small particles into large, fast-sinking feces, thus playing an important role in transporting organic carbon from the euphotic zone to the deep ocean (Le Fevre *et al.*, 1998; Perissinotto and Pakhomov, 1998). In the Southern Ocean, krill and salp occur at the highest densities in the Antarctic Peninsula region, which includes the Bransfield Strait (Pakhomov *et al.*, 2002). Thus, most sediment trap samples collected in this and other studies in the Bransfield Strait are composed of krill feces (Bodungen *et al.*, 1987; Wefer *et al.*, 1990). Their sinking velocity is relatively high due to their large size, and the sinking velocity of salp fecal pellets can reach 2700 m d^{-1} (Bruland and Silver, 1981). High sinking velocity may mean this fecal material is less digested by microbes in the water column. The large organic carbon flux measured at 1000 m in the Bransfield Strait may be caused by fast sinking of krill and salp fecal pellets, which leads less decompostion of organic material in the water column.

Annual primary production in the Bransfield Strait was estimated at 94 g C m^{-2} yr^{-1} between 1978 and 1986, from composite monthly mean CZCS chlorophyll images (Fisher *et al.*, 2000). This annual production is somewhat lower than the Southern Ocean average (Arrigo *et al.*, 1998). In this study, the organic carbon flux at 1000 m was estimated at 5.4 g C m^{-2} yr^{-1}. Thus, about 5.8% of the surface water production of organic carbon is exported to 1000 m in the eastern Bransfield Strait. Fisher *et al.* (2000) calculated the export fractions of primary production to 1000 m (=EF_{1000}) as 0.4 to 2.9% in the Atlantic Ocean and 0.01 to 3.9% in the Southern Ocean. The EF_{1000} value calculated in the eastern Bransfield Strait exceeds these values. Therefore, the eastern Bransfield Strait appears to be the most important site in the Southern Ocean for the export of organic carbon to the deep sea.

CONCLUSIONS

We have presented particle flux data from the eastern Bransfield Strait measured over one year. Our major findings are:

1) Particle fluxes showed extremely large seasonal variation; almost all flux occurred over three months (January-March).

2) Total mass flux decreased rapidly, from 437 mg m^{-2} d^{-1} in March to 1.2 mg m^{-2} d^{-1} in April, probably because primary production and input of lithogenic material decrease sharply after March.

3) Primary production and particle flux became uncoupled in November and December, probably due to a build-up of phytoplankton and a dearth of fecal pellets.

4) Annual organic carbon flux was 5.4 g C m^{-2} at a depth of 1000 m in the eastern Bransfield Strait, greater than in the central Strait. This difference in flux may be due to the stronger surface current in the central Bransfield Strait.

5) Organic carbon flux estimated in the eastern Bransfield Strait is the highest in the Southern Ocean, probably because fecal pellets sink quickly and are therefore less decomposed in the water column.

6) About 5.8% of primary production in surface waters is exported down to 1000 m in the Bransfield Strait, exceeding the EF_{1000} values for the Atlantic and Southern Oceans.

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