

Downward fluxes of biogenic material in Bransfield Strait, Antarctica

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Abstract: Time-series sediment traps were deployed to investigate the temporal evolution of particle fluxes in eastern and central Bransfield Strait, from December 1999–December 2000. Particle fluxes showed large seasonal variation at both trap sites. In eastern Bransfield Strait, summer mass fluxes were two orders of magnitude higher than winter mass fluxes, while in central Bransfield Strait, almost 99% of the annual mass flux (33 g m⁻²) was collected in a 40-day period from December–January. Export flux also exhibited a high regional variability. This regional variability is probably due to central Bransfield Strait's strong surface current, which carries most settling particles produced in the surface waters away from the mooring site during the low summer flux period. The relatively low biogenic silica to organic carbon ratios (a range of 0.29–1.4) and high lithogenic fluxes (41% of total mass flux) indicate that the growth of phytoplankton is not limited by the micronutrient iron in eastern Bransfield Strait. The annual flux of organic carbon in eastern Bransfield Strait was 6.8 g C m⁻², which is three times higher than the flux measured in central Bransfield Strait (2.2 g C m⁻²). Organic carbon flux in eastern Bransfield Strait is relatively high for the Southern Ocean, possibly due to fast-sinking faecal pellets that lead to less decomposition of organic material in the water column. Calculations suggest that approximately 7.2% of the organic carbon produced at the surface in eastern Bransfield Strait is exported to a depth of 678 m. This exceeds the maximum calculated export of primary production to a depth of 1000 m in the Atlantic and Southern oceans.

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Introduction

The production of biogenic particles in surface waters and their removal to deep waters restricts the distribution of biogeochemical elements in seawater. Particle flux controls nutrient regeneration, the delivery of food to benthic communities, and the preservation of climate change records in the sediment (Ittekkot *et al.* 1996 and references therein). In terms of the global carbon cycle, particle flux in the ocean is an important mechanism for the transfer of carbon derived from atmospheric CO₂ to the deep sea.

The Southern Ocean, located south of the Subtropical Convergence (*c.* 45°S), is of special interest because of its significant role in the atmospheric CO₂ cycle (Knox & McElroy 1984, Keir 1988, Robertson & Watson 1995, Bakker *et al.* 1997). It may also play an important role in the global opal cycle (Treguer & van Bennekom 1991, DeMaster *et al.* 1996, Rabouille *et al.* 1997). The Southern Ocean is characterized by strong and dynamic links between environmental forcing variables, primary production and particle fluxes in the water column. The magnitude and composition of biogenic fluxes in the Southern Ocean have large spatial and temporal variability, due to short-lived phytoplankton blooms occurring when the ice cover opens. This supplies a large amount of the annual production of biogenic material (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 affected by climate, with winds, ocean circulation, sea ice, and cloud cover influencing primary production (Dunbar *et al.* 1998). The role of the Southern Ocean in climate change can be examined by monitoring the long-term variation of particle flux.

The Southern Ocean is characterized by high concentrations of surface macronutrients and relatively low chlorophyll levels. The question of why marine ecosystems are unable to make more efficient use of the available nutrients is still a matter of considerable debate. Possible explanations are physical effects including strong vertical mixing and weak vertical stratification, grazing pressure, and the unavailability of the micronutrient iron (Martin *et al.* 1990, Frost 1991, de Baar *et al.* 1995, Bakker *et al.* 2001). Recently, substantial evidence has accumulated that the limited availability of iron constrains primary productivity in the Southern Ocean (Boyd 2002, Sosik & Olson 2002, Coale *et al.* 2003). Iron limitation also leads to more silicified, faster sinking diatom biomass, and thus the Si:C ratios are 2–3 times higher under iron limitation (Hutchins & Bruland 1998, Takeda 1998). Such changes in the stoichiometry of nutrient consumption and particle composition may eventually alter the elemental

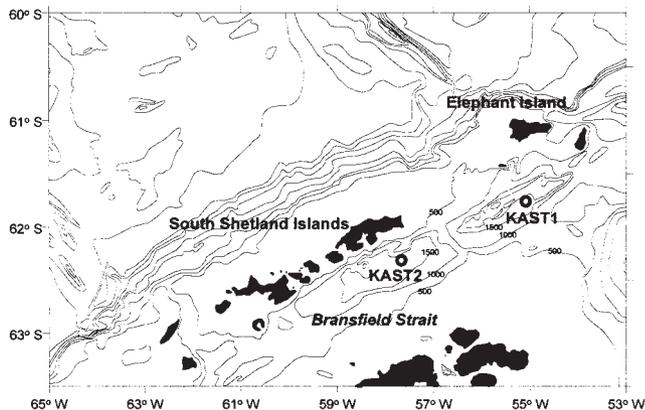


Fig. 1. Location of the sediment trap mooring sites in Bransfield Strait. The mooring sites are marked by open circles.

composition of exported material.

Bransfield Strait is a semi-closed sea bounded by the South Shetland Islands and the Antarctic Peninsula. It is relatively warm and humid, with high precipitation (Reynolds 1981). This climate produces a sub-polar glacial region that can be sensitive to changes in the environmental factors that influence the advance and retreat of ice sheets. Thus, its accessibility and sensitivity to climate change make Bransfield Strait an ideal site for the long-term monitoring of particle fluxes. Wefer *et al.* (1988, 1990) measured particle fluxes using time-series sediment traps in central Bransfield Strait from 1983 to 1986. They found considerable seasonal and interannual variability in particle fluxes. Palanques *et al.* (2002) measured organic carbon fluxes in western Bransfield Strait from 1995–96, which were one order of magnitude lower than those in central Bransfield Strait. The seasonal sedimentation pattern was also somewhat different at both areas. However, long-term studies of particle flux have never been conducted in eastern Bransfield Strait. To build on these studies, and because of the large spatial and temporal variability, further data are needed on the magnitude and composition of particle fluxes in Bransfield Strait.

In this paper, we examine particle fluxes measured at mid-water depths in central and eastern Bransfield Strait over a one-year period. The objectives of this research are to determine the composition and timing of biogenic fluxes at both sites, to elucidate the processes controlling seasonal and regional variations of these fluxes, and to evaluate the efficiency of the biological pump in Bransfield Strait.

Materials and methods

We deployed time-series sediment traps on moorings anchored to the seabed. In eastern Bransfield Strait (KAST 1; 61°45.77'S, 54°59.10'W, a water depth of 1778 m), the trap was deployed from 27 December 1999–24 December 2000 (Fig. 1). In central Bransfield Strait (KAST 2; 62°15.25'S,

57°38.02'W, a water depth of 1960 m), the traps were set from 27 December 1999–27 December 2000. The mooring had a set of instruments attached; this was deployed at 678 m in eastern Bransfield Strait and 960 m in central Bransfield Strait. The instruments included a McLane PARFLUX Mark 7G time-series sediment trap with 21 rotary sample cups and an Aanderaa RCM8 current meter. Samples were collected at intervals of ten days in November, December, January and February, 15 days in October, and once in each of the remaining months. Sediment trap samples were preserved by filling the sample cups with a Na-borate buffered 5% formalin solution prior to deployment.

Upon recovery, the 250-ml trap sample bottles were removed and refrigerated at 4°C prior to analysis. Before samples were split, recognizable swimmers were removed by hand. The samples were then gently split, using a Folsom plankton splitter, into four 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.

The total carbon and nitrogen contents were measured by a Carlo-Erba CNS elemental analyser. The precision of total carbon and nitrogen analyses was 3% based on the duplicate samples. The inorganic carbon content was determined by a UIC coulometrics carbon analyser with 2% precision. Calcium carbonate was calculated by multiplying inorganic carbon by 8.33. Organic carbon was calculated by the difference between total and inorganic carbon. The biogenic silica content was determined by a time-series dissolution using 0.5 N NaOH at 85°C (DeMaster 1981). The precision of the biogenic silica analyses was 5% based on the duplicate samples. The aluminium content was measured with 5% precision by induced coupled plasma-atomic emission spectroscopy (ICP-AES) at the Korean Basic Science Institute. Complete sample dissolution prior to its introduction into ICP-AES was achieved by HNO₃-HF-HClO₄ total digestion in a Teflon beaker (Park & Yoon 1994). The lithogenic fractions were estimated by multiplying the aluminium content (wt%) by 12.15 (Honjo *et al.* 2000).

Study area

Bransfield Strait is *c.* 50 000 km² in area, located between the northern tip of the Antarctic Peninsula and the South Shetland Islands (Fig. 1). It has three basins, commonly referred to as the western, central and eastern basins, which are connected by sills less than 1000 m deep. The western basin is connected to the Bellingshausen Sea through the Gerlache Strait and other gaps between the most westerly South Shetland Islands, while the eastern basin is open to the Weddell and Scotia seas. The depth of the basins increases to the north-east, with a maximum axial depth of

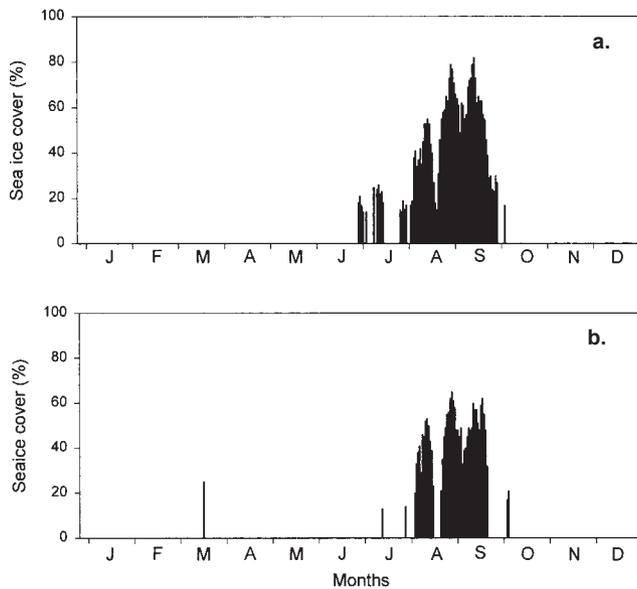


Fig. 2. Percent sea ice cover at **a.** KAST 1, and **b.** KAST 2 derived from daily DMSP F13 Special Sensor Microwave/Imager (SSM/I).

1100 m in the western basin, 1900 m in the central basin, and 2700 m in the eastern basin. The central basin is separated from the western basin by a sill of 1000 m and from the eastern basin by a sill of 1100 m.

Bransfield Strait itself is entirely encircled by sills shallower than 500 m; these restrict deep water from flowing in from the adjacent Drake Passage and Weddell Sea. However, water from Drake Passage enters Bransfield Strait from a deep gap between Brabant and Smith islands (Niiler *et al.* 1991, Capella *et al.* 1992b). This inflowing water remains near the vicinity of the South Shetland Islands. The relatively saline and cold water in Bransfield Strait originates on the Weddell Sea shelf and flows westward around the tip of the Antarctic Peninsula and into Bransfield Strait. In the upper 300 m of the strait, water that originates in the Bellingshausen Sea (fresh and warm; 33.50‰ and 2.25°C) comes in contact with water that can be traced to the Weddell Sea (saline and cold; 34.40‰ and 0.75°C). The Bransfield Strait current flows along the deep channel of the Gerlache Strait, following the 750 m isobath north-east to the southern continental margin of the South Shetland Islands (Zhou *et al.* 2002). The strongest daily mean current is *c.* 40 m s⁻¹ and is confined to the shelf break south of the South Shetland Islands.

Bransfield Strait has an important impact on biological processes in Antarctica because it is a breeding ground for krill (Capella *et al.* 1992a). Since zooplankton feed in the upper water column, the near-surface circulation affects the residence time and dispersion of krill in the area. Primary production during the summer is highly variable in Bransfield Strait; waters can vary from oligotrophic to productive upwelling systems with high chlorophyll

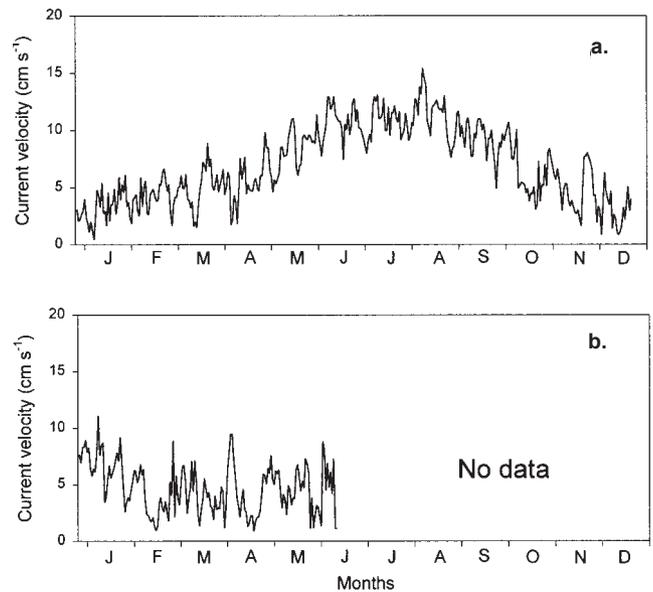


Fig. 3. Daily averaged current velocity at **a.** KAST 1, and **b.** KAST 2. At KAST 2, current data were not available after mid-June due to malfunctioning current meter.

concentrations (Holm-Hansen & Mitchell 1991, Basterretxea & Aristegui 1999, Figueiras *et al.* 1999). The highest primary production (more than 2000 mg C m⁻² d⁻¹) is found in the stratified waters influenced by the Bellingshausen Sea and in the coastal waters close to d'Urville Island. Basterretxea & Aristegui (1999) suggested that major phytoplankton blooms in Bransfield Strait are transported from the nearby Gerlache Strait or Bellingshausen Sea by north-east surface currents. The spatial distribution of chlorophyll in Bransfield Strait is patchy and generally associated with the influence of different water masses. Wefer *et al.* (1988, 1990) documented very high fluxes of settling material associated with episodic high-production events in Bransfield Strait.

Sea ice and current speed

Sea ice data at the mooring sites were obtained daily from the DMSP F13 Special Sensor Microwave/Imager (SSM/I). The sea ice appeared at KAST 1 for several days in late June, mid-July, and late July, and persisted for two months from August to September (Fig. 2a). The maximum cover of sea ice at KAST 1 was about 80% and occurred in mid-August and mid-September. At KAST 2, the sea ice first appeared in mid-March for one day, and then for two days in July and for several days in early August. It then persisted for one month, from late August to late September (Fig. 2b). The maximum extent of sea ice at KAST 2 was about 60% and occurred in late August and mid-September. The mooring sites were never completely covered by sea ice during the sediment trap deployment.

Current meters were deployed 20 m below each sediment

Table I. Fluxes and composition of biogenic and lithogenic components in eastern and central Bransfield Strait.

Cup	Date open	Days	Mass flux (mg m ⁻² d ⁻¹)	Organic C flux (mg m ⁻² d ⁻¹)	Organic C content (%)	BSi flux (mg m ⁻² d ⁻¹)	BSi content (%)	CaCO ₃ flux (mg m ⁻² d ⁻¹)	CaCO ₃ content (%)	Litho flux (mg m ⁻² d ⁻¹)	Litho content (%)	OC/TN molar ratio	BSi/OC molar ratio
a. 678 m water depth of eastern Bransfield Strait (KAST 1)													
1	27/12/99	10	374	33	8.7	115	31	2.8	0.75	159	42	8.1	0.70
2	06/01/00	10	516	62	12	179	35	5.9	1.1	160	31	7.8	0.58
3	16/01/00	10	385	45	12	135	35	2.9	0.74	130	34	7.9	0.61
4	26/01/00	10	539	49	9.0	191	36	3.9	0.72	212	39	8.2	0.79
5	05/02/00	10	902	96	11	384	43	5.7	0.63	240	27	8.0	0.80
6	15/02/00	10	538	54	10	188	35	3.7	0.69	184	34	7.7	0.70
7	25/02/00	10	720	79	11	309	43	4.3	0.60	168	23	7.6	0.78
8	07/03/00	31	456	46	10	168	37	3.0	0.66	144	32	7.2	0.74
9	07/04/00	30	86	8.3	9.6	23	27	0.67	0.78	44	51	7.2	0.56
10	07/05/00	31	16	1.8	11	3.9	24	0.16	0.97	-	-	6.5	0.43
11	07/06/00	30	6.3	0.68	11	1.0	16	0.14	2.2	-	-	7.2	0.29
12	07/07/00	31	8.3	0.58	7.0	1.0	12	0.11	1.4	-	-	6.3	0.34
13	07/08/00	31	42	2.3	5.5	4.9	12	0.56	1.3	31	76	6.7	0.43
14	07/09/00	30	50	4.7	9.4	8.9	18	0.58	1.2	33	66	7.8	0.38
15	07/10/00	15	32	4.6	14	5.8	18	0.34	1.1	-	-	5.9	0.26
16	22/10/00	15	27	5.3	20	3.9	15	0.37	1.4	-	-	5.8	0.15
17	06/11/00	10	65	10	15	17	26	0.57	0.88	-	-	6.5	0.33
18	16/11/00	10	129	10	7.9	53	41	1.0	0.80	47	36	5.8	1.0
19	26/11/00	10	107	8.3	7.8	60	56	0.59	0.55	-	-	6.4	1.4
20	06/12/00	10	83	11	14	37	44	0.66	0.79	-	-	6.2	0.65
21	16/12/00	11	62	11	17	20	33	0.41	0.67	-	-	6.1	0.39
Annual flux (g m ⁻² yr ⁻¹)			66	6.8		24		0.49		21			
Average value (%)					11		30		0.95		41	7.0	0.59
b. 960 m water depth of central Bransfield Strait (KAST 2)													
1	27/12/99	10	521	50	9.6	136	26	3.2	0.62	265	51	6.9	0.54
2	06/01/00	10	1129	59	5.3	210	19	8.1	0.72	778	69	7.6	0.71
3	16/01/00	10	1104	66	6.0	234	21	7.7	0.70	619	56	7.7	0.71
4	26/01/00	10	500	40	7.9	148	30	3.6	0.72	258	52	7.1	0.75
5	05/02/00	10	0.02	-	-	-	-	-	-	-	-	-	-
6	15/02/00	10	1.8	-	-	-	-	-	-	-	-	-	-
7	25/02/00	10	6.8	-	-	-	-	-	-	-	-	-	-
8	07/03/00	31	0.01	-	-	-	-	-	-	-	-	-	-
9	07/04/00	30	0.02	-	-	-	-	-	-	-	-	-	-
10	07/05/00	31	0.01	-	-	-	-	-	-	-	-	-	-
11	07/06/00	30	0.56	-	-	-	-	-	-	-	-	-	-
12	07/07/00	31	0.02	-	-	-	-	-	-	-	-	-	-
13	07/08/00	31	0.02	-	-	-	-	-	-	-	-	-	-
14	07/09/00	30	0.03	-	-	-	-	-	-	-	-	-	-
15	07/10/00	15	0.01	-	-	-	-	-	-	-	-	-	-
16	22/10/00	15	0.02	-	-	-	-	-	-	-	-	-	-
17	06/11/00	10	0.03	-	-	-	-	-	-	-	-	-	-
18	16/11/00	10	2.5	-	-	-	-	-	-	-	-	-	-
19	26/11/00	10	0.03	-	-	-	-	-	-	-	-	-	-
20	06/12/00	10	0.02	-	-	-	-	-	-	-	-	-	-
21	16/12/00	8	0.01	-	-	-	-	-	-	-	-	-	-
Annual flux (g m ⁻² yr ⁻¹)			33	2.2		7.3		0.23		19			
Average value (%)					7.2		24		0.69		57	7.3	0.68

- Not determined

trap to evaluate water flow conditions during sampling. The daily mean current records at each mooring site are shown in Fig. 3. Current data were available only from January to mid-June at KAST 2 due to a malfunctioning current meter. At KAST 1, the current generally flowed to the south-west at speeds of 1 to 15 cm s⁻¹ (Fig. 3a). Current speeds showed

a distinct seasonal variation, with high values in the winter (June–August) and low values in the summer (December–February). At KAST 2, the currents flowed to the north-east at speeds of less than 10 cm s⁻¹ (Fig. 3b). Because the current speeds were less than 15 cm s⁻¹ at both sites, they would have had minimal effects on trapping

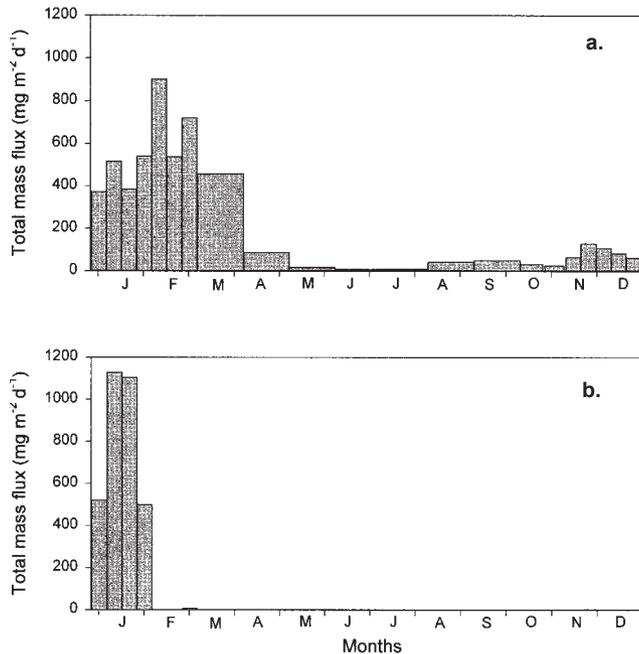


Fig. 4. Temporal evolution of mass fluxes at **a.** KAST 1 from 27 December 1999–27 December 2000, and **b.** KAST 2 from 27 December 1999–24 December 2000.

efficiency (Gust *et al.* 1994).

Results and discussion

Temporal and spatial variability of particle fluxes in Bransfield Strait

Mass fluxes showed large seasonal variation in eastern Bransfield Strait (KAST 1), with summer fluxes two orders of magnitude higher than winter fluxes (Fig. 4a). They ranged from 6.3 mg m⁻² d⁻¹, recorded in June, to 902 mg m⁻² d⁻¹, recorded in February (Table I). The entire three-month summer to early autumn period was characterized by elevated mass fluxes over 370 mg m⁻² d⁻¹ (Fig. 4a). Mass fluxes decreased rapidly from 456 mg m⁻² d⁻¹ in March to 86 mg m⁻² d⁻¹ in April, and then a period of low particle fluxes, ranging from 5 to 50 mg m⁻² d⁻¹, persisted from May to early November (Table I). Following this period, mass fluxes increased slightly to 129 mg m⁻² d⁻¹ in late November and then decreased again to 62 mg m⁻² d⁻¹ in late December. In central Bransfield Strait (KAST 2), meanwhile, export flux was characterized by stronger seasonal, pulsed sedimentation with pronounced summer fluxes over 500 mg m⁻² d⁻¹ in January (Fig. 4b). Mass fluxes were at least 100 times lower, at less than 7.0 mg m⁻² d⁻¹, in the other months (Table I). These extremely small fluxes could constitute artificial anomalies with several potential causes. One possibility is a mechanical problem, as the sediment trap's rotor must be perfectly aligned with the hole of the funnel in order to collect sinking particles. We examined the rotor

alignment immediately after recovering the sediment trap array and found no sign of malfunction. A second potential problem is clogging the sediment trap's funnel by high sedimentation, but this did not occur in the traps that we deployed. When we recovered the sediment trap at KAST 2, the final sample bottle was located beneath the funnel but it contained no material. If the funnel end was clogged, some of the clogged material would be caught in the last bottle during recovery. A third possible reason for small fluxes is hydrodynamic bias, which can occur when the water current exceeds 15 cm s⁻¹. This causes particle fluxes to be significantly underestimated (Gust *et al.* 1994, Gardner 2000). However, the current speeds measured at KAST 2 during the five-month deployment were always less than 10 cm s⁻¹ (Fig. 3b), which is sufficiently low to expect maximal trapping efficiency. It is, therefore, unlikely that the sediment trap failed to record particle fluxes in central Bransfield Strait during the period of small flux.

This type of episodic summer sedimentation event in central Bransfield Strait was also observed in a previous study. Wefer *et al.* (1988, 1990) deployed time-series sediment traps at a mooring site in a similar location to ours in central Bransfield Strait, and measured particle fluxes from 1984–86. In each of these three years, they found an episodic summer sedimentation event, similar to our results, although the events in their study occurred mostly in December. In this region, therefore, almost all particle fluxes occurred during the short summer period. These sedimentation events differ from those in eastern Bransfield Strait where high mass fluxes were observed from January–March and intermediate fluxes from November–December (Fig. 4). Consequently, export flux showed a high regional variability in Bransfield Strait. This high regional variability is unlikely to be related to differences in primary production and biomass. Surface chlorophyll *a* concentrations estimated during the summer season by SeaWiFS algorithms did not exhibit high regional variability in Bransfield Strait (Lipsky 2001). Primary productivity levels, measured by the ¹⁴C incubation method for both regions during the summer, were not significantly different (Holm-Hansen & Mitchell 1991, Basterretxea & Aristegui 1999). The hydrography of Bransfield Strait is very complex as 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 current in Bransfield Strait is highly variable on a spatial scale; surface currents are faster than 15 cm s⁻¹ at the mooring site in central Bransfield Strait but less than 5 cm s⁻¹ at the mooring site in eastern Bransfield Strait (Lopez *et al.* 1999). A maximum current speed of *c.* 40 cm s⁻¹ was observed at the shelf break south of the South Shetland Islands (Zhou *et al.* 2002), which is close to our mooring site in central Bransfield Strait. Therefore, the high regional variability in export flux appears to be caused by central Bransfield Strait's strong

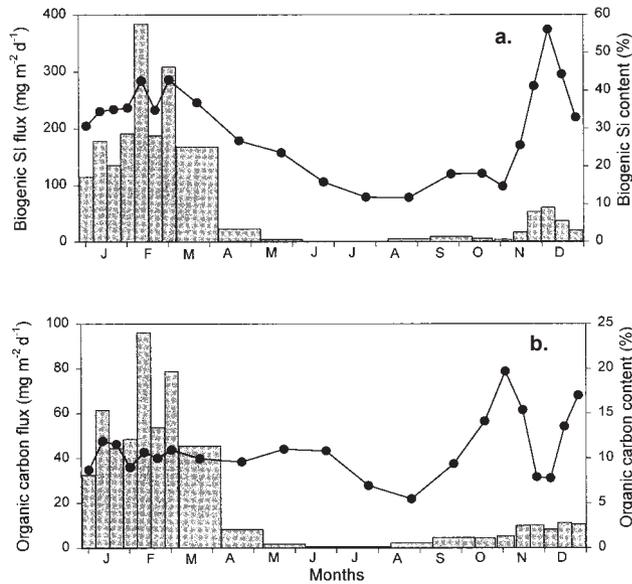


Fig. 5. Temporal evolution of **a.** biogenic Si fluxes and contents, and **b.** organic carbon fluxes and contents in eastern Bransfield Strait. Vertical bars indicate fluxes and closed circles contents.

surface current, which transports most settling particles produced in the surface waters away from the mooring site during the low summer flux period.

The seasonal variation of mass flux observed in eastern Bransfield Strait was similar to that in western Bransfield Strait (Palanques *et al.* 2002). At a mid-depth (500 m) in western Bransfield Strait, export flux was also characterized by elevated summer mass fluxes, like those in eastern Bransfield Strait. However, the magnitude and timing of high summer fluxes differed for western Bransfield Strait, with a range of 20 to 112 mg m⁻² d⁻¹ and occurrences from November–February. Thus, the mass fluxes in the eastern strait were about one order of magnitude higher than those in the western strait during the summer high-flux period. The summer high-flux period in the eastern strait also occurred one and a half months later than that in the western strait. The annual mass flux in eastern Bransfield Strait was 66 g m⁻², and in central Bransfield Strait it was 33 g m⁻² (Table I). In central Bransfield Strait, particle fluxes showed high interannual variability (Wefer *et al.* 1988, 1990), with an annual mass flux of 107 g m⁻² in 1984, 12 g m⁻² in 1985 and 37 g m⁻² in 1986. The annual mass flux measured in 2000 in this study was similar to that measured in 1986. The annual mass flux in western Bransfield Strait was 4.1 g m⁻² (Palanques *et al.* 2002), which was approximately one order of magnitude lower than the fluxes in the central and eastern straits. Palanques *et al.* (2002) suggested that the low downward particle flux at mid-depth in the western strait could be related to the strait's moderate primary productivity, and also to the morphology and hydrology of the study area.

Seasonality of biogenic fluxes in eastern Bransfield Strait

In eastern Bransfield Strait, biogenic silica exhibited a distinct seasonal variation, with high values in late spring and summer and low values in winter (Fig. 5a). Values ranged from 12–56%, with an average of 30% (Table I). In the high mass flux period from January to March, a high proportion of biogenic silica was also encountered. Biogenic silica decreased steadily from 43% in February to 12% in August, followed by a slight increase to 18% in October. After this period, the percentage increased rapidly to a maximum of 56% in late November and then decreased. This silica peak in late November probably reflects a diatom-dominated phytoplankton bloom. Due to the relatively limited range of variation in biogenic silica, as compared to the much higher variations of mass flux, the variations in biogenic silica flux matched those of the mass flux (Fig. 5a). Biogenic silica fluxes ranged from 1.0 to 384 mg m⁻² d⁻¹ (Table I). Unlike biogenic silica, organic carbon displayed no clear seasonal trends in eastern Bransfield Strait (Fig. 5b). Organic carbon was relatively constant at around 10% from January to June, with a decrease to 5.5% in late August and two peaks in early November and late December (Table I). The early November peak seemed to be related to the spring phytoplankton bloom. However, this peak did not coincide with the biogenic silica peak, which occurred one month later (Fig. 5). The peak of biogenic silica in late November coincided with the second peak of biogenic silica fluxes, reflecting that the spring phytoplankton bloom occurred at this time. However, organic carbon showed no correlation with organic carbon fluxes during the spring and early summer seasons, implying that the organic carbon peak in early November was not related to the phytoplankton bloom.

Seasonal variation in organic carbon fluxes closely matched the variation in mass fluxes (Fig. 5b). Organic carbon fluxes showed a range of 0.58–96 mg m⁻² d⁻¹, with a maximum flux in February and a minimum flux in July (Table I). 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 the autumn and winter, and increases in spring as solar radiation increases and the surface mixed layer becomes shallower (Smith *et al.* 1996, Arrigo *et al.* 1998). In Bransfield Strait, primary production increases rapidly in November and remains high throughout the summer (Holm-Hansen & Mitchell 1991). Primary production measured in Bransfield Strait is much greater in November and December than in February and March (Holm-Hansen & Mitchell 1991, Smith *et al.* 1996). The high primary production in November and December is supported by the large increases in organic carbon and biogenic silica in the trap materials during these months (Fig. 5). However, organic carbon fluxes measured in

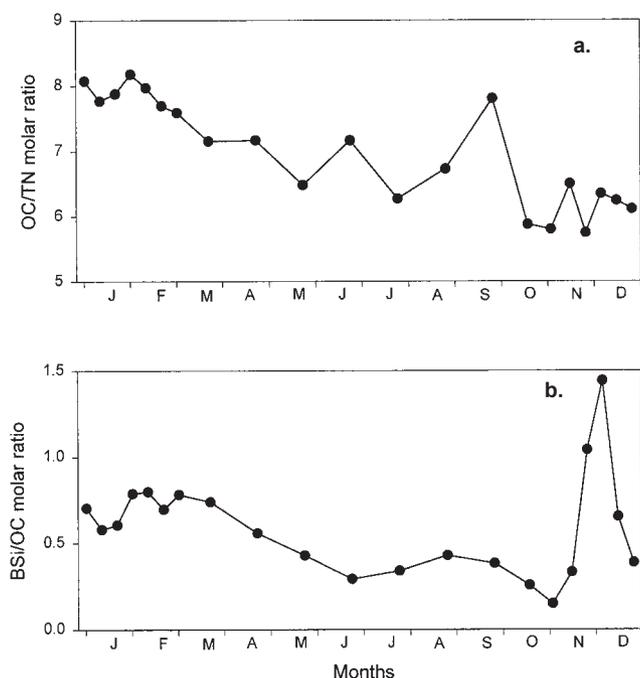


Fig. 6. Temporal evolution of **a.** OC/TN molar ratio, and **b.** BSi/OC molar ratio in eastern Bransfield Strait.

eastern Bransfield Strait in November and December were very small (range of 8.3–11 mg C m⁻² d⁻¹), as compared to fluxes from January–March (33–96 mg C m⁻² d⁻¹; Fig. 5b). Thus, the organic carbon flux did not follow the sudden increase in primary production that was found during November and December. Such an uncoupling of primary production and organic carbon flux may have two explanations. First, it may be that favourable environmental conditions in spring channel most primary production into phytoplankton growth, and only a few organic particles sink into the deep ocean. In the Ross Sea, the average phytoplankton growth rate in spring (0.60 d⁻¹) is much higher than the average mortality rate (0.14 d⁻¹), and therefore, most primary production is held in phytoplankton (Caron *et al.* 2000, Smith *et al.* 2000). A second explanation is that zooplankton only appear in eastern Bransfield Strait after December, and that their faecal pellets, the most important vehicle of sinking particles in Bransfield Strait (Bodungen *et al.* 1987), are too few in November and December to drive large organic carbon fluxes. During the initial peak in primary production in Bransfield Strait in December, few krill are caught, whereas many are caught later in the summer (February–March) (Brinton 1991). This explanation is supported by a seasonal variation of the organic carbon/total nitrogen (OC/TN) molar ratio in trap materials; the ratios measured from January–March were higher than those from October–December (Fig. 6a). The OC/TN ratio generally increases while passing through zooplankton guts, as the remineralization rate of nitrogen is faster than that of carbon (Wong *et al.* 1999). Thus, the

higher OC/TN ratios from January–March appear to result from the increased production of faecal pellets during these months. In reality, both of these explanations probably play a role in reducing organic carbon fluxes in November and December.

The OC/TN molar ratios ranged from 5.8 to 8.2 in eastern Bransfield Strait (Fig. 6a, Table I). These values are similar to the Redfield ratio of 6.6 for phytoplankton, implying that the trapped organic materials are fresh. The OC/TN ratios were relatively high at around 8.0 in January and February, decreased to 6.3 in July, showed a small peak in September, and remained at relatively low values (5.8–6.5) from October–December. The biogenic silica/organic carbon (BSi/OC) molar ratios varied from 0.15 to 1.4 in eastern Bransfield Strait (Fig. 6b, Table I). The BSi/OC ratios were relatively constant at around 0.70 from January–March, decreased to 0.15 in early November and showed a large peak in early December. These BSi/OC ratios measured in eastern Bransfield Strait are higher than the ratio (0.13) measured in pure diatom cultures growing under nutrient-replete conditions (Brzerinski 1985). However, they are much lower than those measured in the Polar Frontal Zone and in the marginal winter sea ice zone (Honjo *et al.* 2000, Fisher *et al.* 2002), and are comparable to those in the Ross Sea (Collier *et al.* 2000). Fisher *et al.* (2002) explained that the high BSi/OC ratios of the trapped material in the eastern Atlantic sector of the Southern Ocean could be due to the limited availability of iron. Since the Si:C ratio of diatoms is 2–3 times higher under iron limitation (Hutchins & Bruland 1998, Takeda 1998), the relatively low BSi/OC ratios (an average of 0.59, Table I) measured in eastern Bransfield Strait may imply that the growth of phytoplankton is not limited by the micronutrient iron. This is supported by high lithogenic fluxes in this area, comprising about 41% of total mass fluxes (Table I). The low BSi/OC ratio could also be caused by high concentrations of *Phaeocystis*, a species that preferentially occurs in coastal and shelf waters, possibly because of high iron availability (Smith *et al.* 1999). *Phaeocystis antarctica* is the most abundant species and an important carbon contributor in the marginal ice zone of eastern Bransfield Strait and north-western Weddell Sea. It was found to account for 52% of total phytoplankton cell abundance and 27% of total phytoplankton carbon biomass (Kang *et al.* 2001). Therefore, the low BSi/OC ratios (0.15–0.8) measured from January to October probably resulted from the large population of *Phaeocystis antarctica* in eastern Bransfield Strait. The November peak in the BSi/OC ratio appears to be related to the spring bloom, dominated by larger diatoms.

Annual organic carbon flux and efficiency of the biological pump

By calculating the seasonal fluxes on a yearly basis, the integrated annual fluxes of organic carbon were estimated

Table II. Compilation of the annual organic carbon fluxes in the Southern Ocean.

Area	Position	Year	Water depth (m)	Trap depth (m)	Annual organic C flux ($\text{g m}^{-2} \text{yr}^{-1}$)	Sources
Eastern Bransfield Strait	61°46'S, 54°57'W	1999–2000	1778	678	6.8	Present study
Central Bransfield Strait	62°15'S, 57°38'W	1999–2000	1960	960	2.2	Present study
Central Bransfield Strait	62°15'S, 57°32'W	1983–84	1952	494	7.7	Wefer & Fisher (1991)
Central Bransfield Strait	62°20'S, 57°28'W	1984–85	1659	693	0.35	Wefer & Fisher (1991)
Central Bransfield Strait	62°22'S, 57°50'W	1985–86	1992	687	1.1	Wefer & Fisher (1991)
Western Bransfield Strait	62°52'S, 60°00'W	1995–96	1000	500	0.35	Palanques <i>et al.</i> (2002)
Northern Weddell Sea	62°27'S, 34°46'W	1985–86	3880	863	0.02	Wefer & Fisher (1991)
Maud Rise	64°55'S, 02°30'W	1987	5000	4456	0.17	Wefer & Fisher (1991)
Maud Rise	64°54'S, 02°34'W	1988–89	5053	360	2.3	Wefer & Fisher (1991)
Maud Rise	64°56'S, 02°36'W	1989–90	5044	352	0.16	Wefer & Fisher (1991)
Ross Sea	74°02'S, 175°06'E	1994–95	588	211	0.35	Langone <i>et al.</i> (2000)
Ross Sea	73°33'S, 176°53'E	1996–98	565	200	2.2	Collier <i>et al.</i> (2000)
Ross Sea	76°30'S, 178°10'E	1996–98	581	206	5.9	Collier <i>et al.</i> (2000)
Polar Front	50°09'S, 05°46'W	1987	3750	700	2.7	Fisher <i>et al.</i> (2002)
Polar Front	50°09'S, 05°46'W	1990	3785	614	3.2	Fisher <i>et al.</i> (2002)
Polar Front	50°11'S, 05°54'W	1995	3838	687	0.14	Fisher <i>et al.</i> (2002)
Bouvet Island	54°08'S, 03°23'W	1991	2734	450	2.7	Fisher <i>et al.</i> (2002)
Bouvet Island	54°21'S, 03°24'W	1992	2695	456	0.51	Fisher <i>et al.</i> (2002)
Bouvet Island	54°20'S, 03°18'W	1993	2734	507	0.15	Fisher <i>et al.</i> (2002)
Bouvet Island	54°20'S, 03°18'W	1994	2734	507	0.17	Fisher <i>et al.</i> (2002)
Bouvet Island	54°20'S, 03°18'W	1995	2744	515	0.51	Fisher <i>et al.</i> (2002)
Sub-Antarctic Front	51°00'S, 141°44'E	1997–98	3780	3080	0.80	Trull <i>et al.</i> (2001)
Polar Frontal zone	53°45'S, 141°45'E	1997–98	2280	830	0.80	Trull <i>et al.</i> (2001)
Polar Frontal zone	60°17'S, 170°03'W	1997	3957	1003	2.3	Honjo <i>et al.</i> (2000)
Polar Frontal zone	56°54'S, 170°10'W	1997	4924	982	1.7	Honjo <i>et al.</i> (2000)
Antarctic zone	63°09'S, 169°54'W	1997	2885	1031	2.2	Honjo <i>et al.</i> (2000)
Antarctic zone	66°10'S, 169°40'W	1997	3015	937	1.9	Honjo <i>et al.</i> (2000)

to be 6.8 and 2.2 $\text{g C m}^{-2} \text{yr}^{-1}$ in eastern and central Bransfield Strait, respectively. In the central Strait, the annual organic carbon flux was calculated by integrating 40-day organic carbon fluxes occurred in January since the 40-day mass fluxes account for about 99% of the total annual mass flux (Table I). These are high fluxes for the Southern Ocean (Table II). Measurements of organic carbon flux in the Southern Ocean vary over a wide range (Table II). In the central Bransfield Strait, they varied greatly between years ($0.35\text{--}7.7 \text{ g C m}^{-2} \text{yr}^{-1}$) from 1983–1986, as did organic carbon fluxes measured from 1987–1990 west of the Maud Rise ($0.16\text{--}2.3 \text{ g C m}^{-2} \text{yr}^{-1}$) and from 1991–1995 near Bouvet Island ($0.15\text{--}2.7 \text{ g C m}^{-2} \text{yr}^{-1}$; Table II). In the Ross Sea, annual organic carbon fluxes are measured at three different sites; these values vary considerably by site and range from $0.35\text{--}5.9 \text{ g C m}^{-2} \text{yr}^{-1}$ (Table II). However, annual organic carbon fluxes do not differ spatially in the Polar Frontal and Antarctic zones (Table II).

In the Southern Ocean, the relatively high organic carbon fluxes are observed in eastern Bransfield Strait (Table II). 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 colour scanner (CZCS). They divided the Southern Ocean into five geographical 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 Bransfield Strait does not differ significantly from that estimated for other Antarctic areas (the Polar Front, Antarctic zone, Maud Rise, and Ross Sea); the Ross Sea had the highest primary productivity in that study. Many investigators have measured primary productivity by using the ^{14}C incubation method in Bransfield Strait during the summer season (Holm-Hansen & Mitchell 1991, Helbling *et al.* 1995, Basterretxea & Aristegui 1999, Figueiras *et al.* 1999). The measured primary productivities usually range from $300\text{--}1000 \text{ mg C m}^{-2} \text{d}^{-1}$ with episodically high values (over $2000 \text{ mg C m}^{-2} \text{d}^{-1}$), which are not considerably different from those measured in other Antarctic areas (Smith *et al.* 2000, Strutton *et al.* 2000, Buesseler *et al.* 2003). Therefore, the high fluxes of organic carbon observed in eastern Bransfield Strait may not result from high primary productivity in the surface waters.

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 faeces, thus playing an important role in transporting organic carbon from the euphotic zone to the deep ocean (Le Fevre *et al.* 1998, Perissinotto & Pakhomov 1998). In the Southern Ocean, the highest densities of krill and salp occur in the Antarctic Peninsula region, which includes Bransfield Strait (Ichii

et al. 1998, Pakhomov *et al.* 2002). Thus, most sediment trap samples collected in this and other studies in eastern Bransfield Strait are composed of krill faeces (Bodungen *et al.* 1987, Wefer *et al.* 1990). The sinking velocity of krill faeces is relatively high due to their large size; the sinking velocity of salp faecal pellets can reach 2700 m d⁻¹ (Bruland & Silver 1981). A high sinking velocity may mean that the faecal material is less digested by microbes in the water column. Therefore, the high organic carbon flux measured in eastern Bransfield Strait may be caused by the fast sinking of krill and salp faecal pellets, which leads to less decomposition of organic material in the water column.

Annual primary production in Bransfield Strait was calculated to be 94 g C m⁻² yr⁻¹, based on composite monthly mean CZCS chlorophyll images and a global equation estimating the water column integrated primary production (Fisher *et al.* 2000). This annual production is lower than the Southern Ocean average (Arrigo *et al.* 1998). In this study, the organic carbon flux at 678 m water depth in eastern Bransfield Strait was estimated to be 6.8 g C m⁻² yr⁻¹. Thus, about 7.2% of the surface water production of organic carbon is exported to a depth of 678 m in eastern Bransfield Strait. Fisher *et al.* (2000) calculated the export fractions of primary production to 1000 m to be 0.4 to 2.9% in the Atlantic Ocean and 0.01 to 3.9% in the Southern Ocean. The export fraction calculated for eastern Bransfield Strait exceeds these values. Therefore, eastern Bransfield Strait appears to be an important site in the Southern Ocean for the export of organic carbon to the deep sea. However, organic carbon flux shows large interannual variability in the Southern Ocean (Wefer & Fisher 1991, Fisher *et al.* 2002). Thus, more work is required to confirm that eastern Bransfield Strait is an important site for the export of organic carbon.

Summary

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

Particle fluxes showed large seasonal variation in Bransfield Strait; summer mass fluxes were two orders of magnitude higher than winter mass fluxes in the eastern strait, and mass fluxes in the central strait were characterized by a stronger pulsed sedimentation in January.

Export flux exhibited a high regional variability in Bransfield Strait. This regional variability is probably due to central Bransfield Strait's strong surface current, which carries most settling particles produced in the surface waters away from the mooring site during the low summer flux period.

Primary production and particle flux became uncoupled in November and December, probably due to a build-up

of phytoplankton and a dearth of faecal pellets.

The BSi/OC ratios measured in eastern Bransfield Strait were much lower than those in the Polar Frontal zone and in the marginal winter sea ice zone, implying that the growth of phytoplankton is not limited by the micronutrient iron in this area. The low BSi/OC ratio could also be caused by high concentrations of *Phaeocystis antarctica*, which is the most abundant species and important carbon contributor in the marginal ice zone of eastern Bransfield Strait and north-western Weddell Sea.

Annual organic carbon flux was 6.8 g C m⁻² at a depth of 678 m in eastern Bransfield Strait, three times higher than that (2.2 g C m⁻²) at a depth of 960 m in the central Strait. The high organic carbon flux estimated in eastern Bransfield Strait may not result from high primary productivity in this area, but may be due to fast-sinking faecal pellets that lead to less decomposition of organic material in the water column.

About 7.2% of calculated primary production in surface waters is exported down to 678 m in eastern Bransfield Strait, exceeding the maximum export of primary production to a depth of 1000 m in the Atlantic and Southern Oceans.

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