



Stable Carbon and Nitrogen Isotopes of Sinking Particles in the Eastern Bransfield Strait (Antarctica)

Boo-Keun Khim^{1*}, Dongseon Kim², Hyoung Chul Shin³, and Dong Yup Kim⁴

¹Department of Marine Science, College of Natural Sciences, Pusan National University, Busan 609-735, Korea

²Marine Geoenvironment research Division, KORDI, Ansan P.O. Box 29, Seoul 425-600, Korea

³Polar Applied Science Division, KOPRI, KORDI, Ansan P.O. Box 29, Seoul 425-600, Korea

⁴Polar Environmental Research Division, KOPRI, KORDI, Ansan P.O. Box 29, Seoul 425-600, Korea

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Abstract – A time-series sediment trap was deployed at 1,034 m water depth in the eastern Bransfield Strait for a complete year from December 25, 1998 to December 24, 1999. About 99% of total mass flux was trapped during an austral summer, showing distinct seasonal variation. Biogenic particles (biogenic opal, particulate organic carbon, and calcium carbonate) account for about two thirds of annual total mass flux (49.2 g m^{-2}), among which biogenic opal flux is the most dominant (42% of the total flux). A positive relationship (except January) between biogenic opal and total organic carbon fluxes suggests that these two variables were coupled, due to the surface-water production (mainly diatoms). The relatively low $\delta^{13}\text{C}$ values of settling particles result from effects on C-fixation processes at low temperature and the high CO_2 availability to phytoplankton. The correspondingly low $\delta^{15}\text{N}$ values are due to intense and steady input of nitrates into surface waters, reflecting an unlikely nitrate isotope fractionation by degree of surface-water production. The $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values of sinking particles increased from the beginning to the end of a presumed phytoplankton bloom, except for anomalous $\delta^{15}\text{N}$ values. Krill and the zooplankton fecal pellets, the most important carriers of sinking particles, may have contributed gradually to the increasing $\delta^{13}\text{C}$ values towards the unproductive period through the biomodification of the $\delta^{13}\text{C}$ values in the food web, respiring preferentially and selectively ^{12}C atoms. Correspondingly, the increasing $\delta^{15}\text{N}$ values in the intermediate-water trap are likely associated with a switch in source from diatom aggregates to some remains of zooplankton, because organic matter dominated by diatom may be more liable and prone to remineralization, leading to greater isotopic alteration. In particular, the tendency for abnormally high $\delta^{15}\text{N}$ values in February seems to be enigmatic. A specific species dominance during the production may be suggested as a possible and speculative reason.

Key words – sinking particles, nitrogen isotope, carbon isotope, sediment trap, Bransfield Strait, Antarctica

1. Introduction

Concerning the global carbon cycle, the production of biogenic particles in the surface waters and subsequent sinking to deep waters is one of the important mechanisms transferring carbon derived from atmospheric CO_2 to the deep sea (Ittekkot *et al.* 1996). In particular, the Southern Ocean has been known as a significant region to regulate the atmospheric CO_2 cycle (Robertson and Watson 1995; Bakker *et al.* 1997), playing a dynamic role in the global opal cycle (Treguer and van Bennekom 1991; DeMaster *et al.* 1996; Rabouille *et al.* 1997). Time-series sediment traps have provided information on the biogeochemical cycles through the seasonal variation of particle flux in the Southern Ocean (Gersonde and Wefer 1987; Fisher *et al.* 1988; Wefer *et al.* 1988; Abelmann and Gersonde 1991; Wefer and Fisher 1991; Dunbar *et al.* 1998; Honjo *et al.* 2000; Palanques *et al.* 2002; Kim *et al.* 2004). In spite of large spatial and temporal variability in the magnitude and composition of biogenic fluxes in the Southern Ocean, the climate changes in the Southern Ocean can be elucidated by monitoring the long-term variation of these particle properties.

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of sedimentary organic matter in deep-sea sediments have recorded paleobiogeochemical

*Corresponding author. E-mail: bkkhim@pusan.ac.kr

changes in the surface ocean as a proxy of paleoproductivity and atmospheric $p\text{CO}_2$ levels (Fontugne and Calvert 1992; Holmes *et al.* 1997). The $\delta^{13}\text{C}$ values of organic particles depend mainly on changes in the ambient temperature, on the type of autotrophic species (marine or terrestrial), or on the number of degradation processes (Hinga *et al.* 1994; Law *et al.* 1995; Rau *et al.* 1997). Because the carbon isotopic fractionation during phytoplankton assimilation is influenced by the $\delta^{13}\text{C}$ of ambient concentration of carbon dioxide molecules, the $\delta^{13}\text{C}$ values of organic matter may reflect the $\delta^{13}\text{C}$ of $[\text{CO}_2]_{\text{aq}}$ concentration changes in surface water. The $\delta^{15}\text{N}$ values of organic matter are controlled mainly by the dynamics of inorganic nitrogen compounds in surface water (Altabet 1988; Altabet and Francois 1994), and to a lesser extent, on the trophic structure of the ecosystem (DeNiro and Epstein 1981). Thus, the $\delta^{15}\text{N}$ values in surface sediments have been used as a recorder of changes in the degree of nitrate utilization in surface water (Francois *et al.* 1992).

Wefer *et al.* (1988) measured particle fluxes using time-series sediment traps in the central Bransfield Strait from 1983 to 1986 for three years. They found huge seasonal

and inter-annual variability in particle fluxes. Karl *et al.* (1991) also measured organic carbon fluxes using the free-drifting sediment trap in the western Bransfield Strait from 1986 to 1987. Although Fischer (1991) and Rau *et al.* (1991) summarized the variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of particulate organic matter in the Weddell Sea, the seasonal variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values has not been provided yet in the Bransfield Strait. In this paper, we measured the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of settling particles collected over a 1-year period in the eastern Bransfield Strait to understand the seasonal variation of biogeochemical elements, although our data are incomplete because of an insufficient quantity of particles for measuring the isotopic compositions during the unproductive seasons.

2. Materials and Methods

The Bransfield Strait is bounded by the South Shetland Islands and the Antarctic Peninsula (Fig. 1). It is located in a relatively warm and humid regime with high precipitation (Reynolds 1981). Such climatic condition belongs to a sub-polar glacial setting which is sensitive to variation in environmental factors that control the waxing

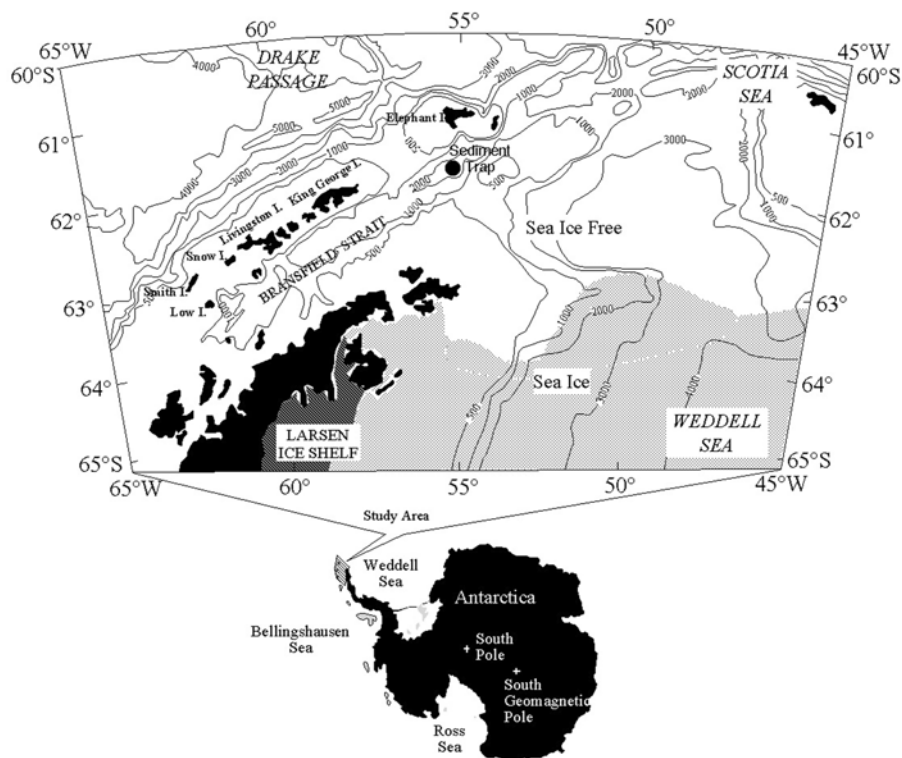


Fig. 1. Location of the sediment trap mooring site in the eastern Bransfield Strait. Mooring sites are represented by a closed circle (●).

and waning of ice sheets.

Time-series sediment trap on seabed anchored mooring has been deployed from December 25, 1998 to December 24, 1999 in the eastern Bransfield Strait at 61°45.77'S, 54°59.10'W (2,134 m water depth; Fig. 1). A set of traps was deployed at 1,034 m water depth, which consisted of a McLane PARFLUX Mark 7G time-series sediment trap with 21 rotary sample cups. Sample collection intervals were 10 days in November, December, January, and February, 15 days in October, and 30/31 days in the rest of the months of the year (Table 1). Sediment trap samples were preserved by filling sample cups with a Na-borate buffered 5% formalin solution prior to deployment. Sample treatment prior to the laboratory experiments can be referred to Kim *et al.* (2004).

The lithogenic fraction was estimated by Al content (wt%) measured by ICP-MS at Korea Basic Science Institute (Honjo *et al.* 2000). Total carbon (TC) content was measured by Carlo Erba NA-1500 Elemental Analyzer at KOPRI. After removing CaCO₃ by 8% H₂SO₄, total organic carbon (TOC) content was obtained through the same procedure. Total inorganic carbon content is the difference between TC and TOC contents, from which CaCO₃ is calculated by multiplication of 8.333. Biogenic silica (Bsi) content was measured using a wet alkaline extraction method (DeMaster 1981). The precision of Bsi content measurements was better than 5%. Opal content is multiplied

by 2.4 to Bsi content. Stable carbon and nitrogen isotope analyses were measured at University of California, Davis, using a PDZEuropa ANCA sample combustion unit attached to the mass spectrometer. Carbon and nitrogen isotope ratios in carbonate-free sediment organic matter are expressed in conventional delta notation, which is the per mil deviation from the Vienna Pee Dee Belemnite (V-PDB) and atmospheric nitrogen. Precision for carbon and nitrogen isotopes is about ±0.1‰ and ±0.2‰ respectively.

3. Results

Total mass flux shows an extremely large seasonal variation (Fig. 2). Mostly it occurs only in three months (late December to early April), reaching values between 306 and 904 mg m⁻² d⁻¹ (Table 1). During all the other months, it is at least three orders of magnitude lower, ranging from 0.01 to 1.17 mg m⁻² d⁻¹ (Table 1). The annual total mass flux is 49.1 g m⁻², 99% of which occurs during the three most productive months. Biogenic flux comprises about two-thirds of total mass flux (Fig. 2) and its variation is similar to that of the total mass flux. Among the components consisting of biogenic flux, biogenic opal flux is the most dominant, and the next is total organic carbon (TOC) flux, which comprises about one-quarter of opal flux (Table 1). Calcium carbonate flux is minor. All these fluxes follow the variation pattern of total

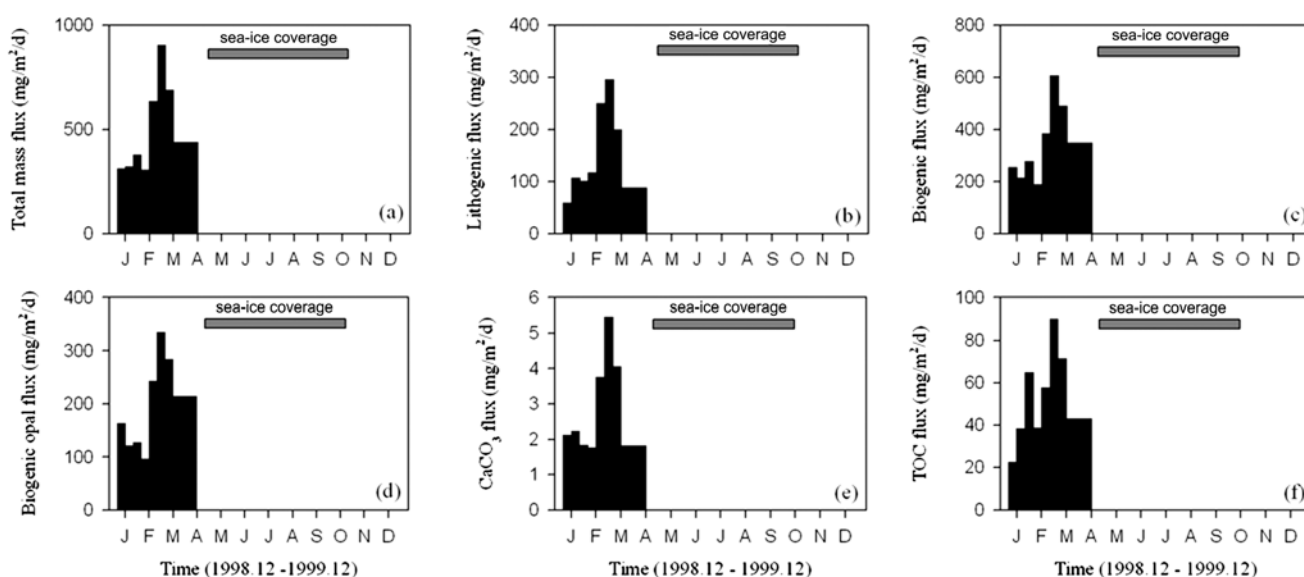


Fig. 2. Temporal variation of (a) total mass flux, (b) lithogenic flux, (c) biogenic flux, (d) biogenic opal flux, (e) CaCO₃ flux, and (f) total organic carbon (TOC) flux in the sediment trap deployed in the eastern Bransfield Strait.

Table 1. Fluxes of mass total, lithogenic, biogenic opal, calcium carbonate, organic carbon and stable C and N isotopes of organic matter observed at the sediment trap in the Bransfield Strait, Antarctica during the year 1999.

Cup	Date open	Days	Total mass fluxes (mg m ⁻² d ⁻¹)	Lithogenic fluxes (mg m ⁻² d ⁻¹)	Lithogenic contents (%)	Biogenic opal fluxes (mg m ⁻² d ⁻¹)	Biogenic opal contents (%)	CaCO ₃ fluxes (mg m ⁻² d ⁻¹)	CaCO ₃ contents (%)	Organic C fluxes (mg m ⁻² d ⁻¹)	Organic C contents (%)	TOC/TN mole ratio	Bsi/TOC mole ratio	δ ¹⁵ N (‰)	δ ¹³ C (‰)
1	12/25/98	10	314.0	59.1	18.8	163.3	52.0	2.12	0.68	22.64	7.21	7.87	1.29	1.01	-28.6
2	01/04/99	10	321.7	108.0	33.6	121.2	37.7	2.24	0.70	38.40	11.94	8.10	0.56	1.02	-29.2
3	01/14/99	10	379.0	101.3	26.7	127.5	33.6	1.83	0.48	64.81	17.10	6.97	0.35	1.23	-27.9
4	01/24/99	10	305.8	117.1	38.3	96.4	31.5	1.76	0.58	38.66	12.64	6.90	0.44	2.44	-27.2
5	02/03/99	10	635.4	251.2	39.5	243.3	38.3	3.75	0.59	57.69	9.08	7.48	0.75	2.22	-26.6
6	02/13/99	10	903.8	295.3	32.7	335.2	37.1	5.47	0.60	90.18	9.98	7.80	0.66	1.39	-25.4
7	02/23/99	10	690.0	200.2	29.0	284.1	41.2	4.07	0.59	71.55	10.37	7.29	0.71	1.64	-25.2
8	03/05/99	31	437.5	88.8	20.3	214.6	49.1	1.82	0.41	42.96	9.82	7.31	0.89	1.97	-24.4
9	04/05/99	30	1.17	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10	05/05/99	31	0.04	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
11	06/05/99	30	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12	07/05/99	31	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
13	08/05/99	31	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
14	09/07/00	30	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
15	10/05/99	15	0.03	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
16	10/20/99	15	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
17	11/04/99	10	0.23	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
18	11/14/99	10	0.06	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
19	11/24/99	10	0.12	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
20	12/04/99	10	0.04	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
21	12/14/99	10	0.04	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Annual flux(g m ⁻² yr ⁻¹)			49.10	14.1	-	20.4	-	0.27	-	5.17	-	-	-	-	-

mass flux, exhibiting the maximum flux in February (Fig. 2).

Unfortunately, because of very small amounts of materials collected during the unproductive period, the chemical and isotopic compositions could not be obtained in all samples. The δ¹³C and δ¹⁵N values of sinking organic matter increased monotonously from late December to late March, except for the anomalously high δ¹⁵N values in February (Fig. 3). The δ¹⁵N values are in the range of 1 and 2‰ with more than 2‰ in February, while the δ¹³C values vary from -29.2 to -24.4‰ (Table 1). These values are comparable to those measured from the particulate organic matters in the Weddell Sea (Rau *et al.* 1991).

4. Discussion

Temporal variation of particle fluxes in the eastern Bransfield Strait

Particle fluxes exhibit prominent seasonal variation,

with main fluxes only in January, February, and March (Table 1). In terms of an annual average, the calculated particle flux of this intermediate-water sediment trap lies within the reported range. The annual particle flux of 49.1 g m⁻² is comparable with the previous results (11.9 to 120 g m⁻²) obtained by Wefer *et al.* (1988) in the central Bransfield Strait. Considering highly interannual variability of annual mass flux (Wefer *et al.* 1988), particle fluxes in this region are attributed to the moderate primary productivity (Varela *et al.* 2000), and the morphology and hydrography (Zhou *et al.* 2002). The Bransfield Strait is usually covered by sea-ice during austral summer in 1999 (<http://geochange.er.usgs.gov>). Thus, the minimal particle fluxes from April to October result from sea-ice cover at the sediment trap site during these months. In spite of the disappearance of sea ice, however, particle fluxes in November and December are still very low (less than 1.0 mg m⁻² d⁻¹). Therefore, the sediment trap experiment indicates

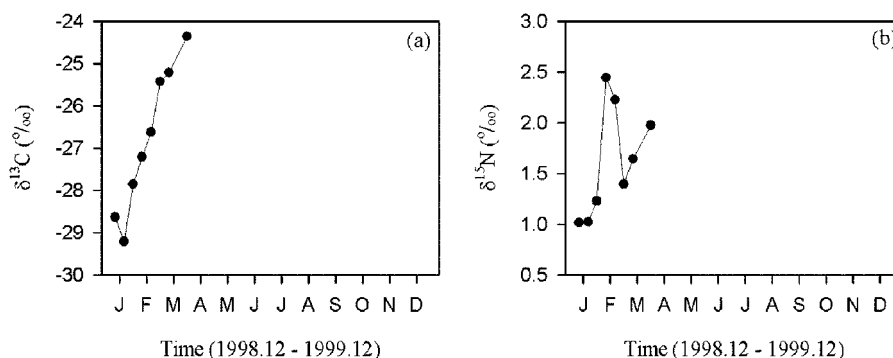


Fig. 3. Temporal variation of (a) $\delta^{13}\text{C}$ and (b) $\delta^{15}\text{N}$ values of particulate organic matter in the sediment trap deployed in the eastern Bransfield Strait.

that almost all the annual particle fluxes settled in a short interval. Previous time-series traps in the central Bransfield Strait also reported that episodic summer sedimentation during December and January occupied over 95% of the annual particle flux (Wefer and Fisher 1991).

Remains except for the lithogenic particles are biogenic materials (biogenic opal, calcium carbonate, particulate organic carbon), accounting for about 70% of the total mass flux (Table 1). This is consistent with the biogenic constituents measured in the previous sediment trap (Wefer *et al.* 1988). The variation pattern of biogenic flux is nearly identical to that of the total mass flux (Fig. 2), representing the fact that the maximum flux occurred at the same time. The most important biogenic phase is the biogenic opal flux, which is almost four times higher than the TOC flux (Fig. 2). According to previous studies (Gersonde and Wefer 1987; Abelman and Gersonde 1991), more than 90% of the biogenic silica consists of diatom frustules. The seasonal variation of biogenic opal flux is closely related to the insolation cycle and the oscillation and degree of sea-ice coverage in dynamic marginal ice zones (Smith and Nelson 1986; Fisher *et al.* 1988). However, sudden and complete termination of the biosiliceous particle flux in the central Bransfield Strait is unlikely to follow sea-ice melting processes in spring.

The unusual low flux during November and December in 1999 may be anticipated by the following two possibilities: One possibility is that most of the primary production occurring in November and December is built up in phytoplankton stock and thereby only few particles sink downward within the water column. Smith *et al.* (2000) also observed similar phytoplankton stock at primary production during early February in the Ross Sea. The

alternative explanation is that the activity of zooplankton in the study area increases after December. Thus, zooplankton fecal pellets, the most important carrier of sinking particles in the Bransfield Strait (Bodungen *et al.* 1987), are insufficient to record high particle fluxes during November and December. The number of krill in sample bottles of sediment traps increases from an initial (December to January) peak to the austral summer (February to March), as with the similar occurrence of *Euphausia superba* in the western Bransfield Strait (Brinton 1991). However, the true reason for the reduced flux during November and December should be investigated more thoroughly.

The high primary production in the Bransfield Strait results in large increases of organic carbon and biogenic silica content in the trap materials during the austral summer (Wefer *et al.* 1988; Wefer and Fischer 1991; Palanques *et al.* 2002; Kim *et al.* 2004). Highest diatom flux rates were also observed during the high production period in the Bransfield Strait (Gersonde and Wefer 1987; Abelman and Gersonde 1991). In the same manner, our results for intermediate-water trap exhibit a correspondence between biogenic opal and TOC fluxes, except for January (Fig. 4a). A positive correlation between these two fluxes indicates that these two parameters were coupled, although the biogenic opal and TOC contents were almost inversely related (Fig. 4b). The plausible cause for decoupling in January cannot be provided by the current data set.

Stable carbon and nitrogen isotope values of trapped particles in the eastern Bransfield Strait

The stable carbon isotopic compositions of photosynthetically-

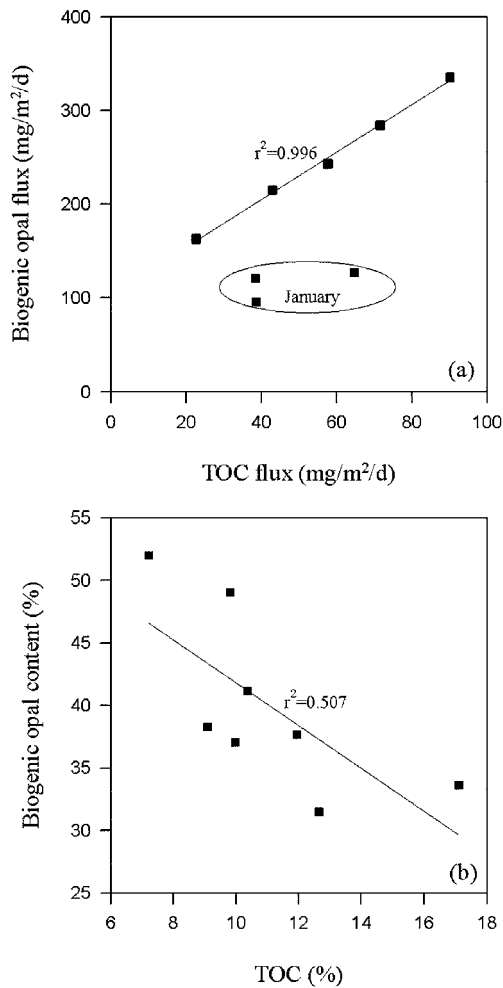


Fig. 4. Relationship (a) between biogenic opal and TOC fluxes and (b) biogenic opal and TOC content of the sediment trap deployed in the eastern Bransfield Strait.

produced organic particles are largely influenced by changes in the ambient temperature which affects the total $[\text{CO}_2]_{\text{aq}}$ concentration (Hinga *et al.* 1994; Law *et al.* 1995; Rau *et al.* 1997), according to type of autotrophic species (marine or terrestrial; O'Leary 1981) and/or by the number of degradation processes that particles undergo through the successive trophic levels (Rau *et al.* 1983). With regard to nitrogen, stable isotopic compositions in a marine system are mainly controlled by the dynamics of inorganic nitrogen compounds (NO_3^- , NH_4^+ , N_2) in surface waters (Altabet 1988) and to a lesser extent, by the trophic structure of the ecosystem (DeNiro and Epstein 1981). In general, most isotopic variations in organic marine matter first consist of a depletion of ^{13}C and ^{15}N , which is imparted during the initial formation of organic matter

from inorganic precursors (primary production). Then, a stepwise enrichment of ^{13}C and ^{15}N happens to the particles through the food chain (DeNiro and Epstein 1978, 1981).

The $\delta^{13}\text{C}$ values of trapped particles show the increasing trend from -29 to -24‰ during the period from late December to March (Fig. 3a). Most of $\delta^{13}\text{C}$ values of organic particles depend mainly on the fractionation factor for carbon fixation, regardless of changes in the isotopic composition of nutrients (Descolas-Gros and Fontugne 1990). The ^{13}C in the sinking particles are relatively depleted, compared to those of more open oceans (Wada *et al.* 1987). Such low $\delta^{13}\text{C}$ values may be explained by the effects on C-fixation processes at low temperatures and the related high CO_2 availability to phytoplankton. Rau *et al.* (1989) suggested that the very low $\delta^{13}\text{C}$ values of Antarctic phytoplankton result from high $[\text{CO}_2]_{\text{aq}}$ concentrations related to low water temperatures. In addition, Wada *et al.* (1987) demonstrated that the low $\delta^{13}\text{C}$ values of Antarctic phytoplankton were probably caused by a high $p\text{CO}_2$ in the surface waters and slow growth rates under low light intensities. In general, high phytoplankton primary productivity is linked to ^{13}C enrichments in phytoplankton carbon because high internal carbon demands by rapid carbon fixation may cause isotopic disequilibria in and/or around the cells, reducing the magnitude of the isotopic fractionation (O'Leary 1981). In addition, ice algae can be an important source of ^{13}C -enriched sediment organic matter (Fischer 1991; Fischer and Wiencke 1992). It has been argued, however, that the ^{13}C enrichment of organic matter reflects diagenetic modification due to the consequence of a selective loss of ^{12}C during metabolism and degradation of organic matter with increasing depth during sinking (Wada *et al.* 1987).

The variation of $\delta^{15}\text{N}$ values of trapped particles follows the similar pattern to $\delta^{13}\text{C}$ values, exhibiting the increasing trend from 1 to 2‰ except for the anomalous high $\delta^{15}\text{N}$ values (more than 2‰) in early February (Fig. 3b). In the Antarctic, the low $\delta^{15}\text{N}$ values were attributed to the intense and steady input of upwelling nutrients, which cause a high content of nitrates in surface waters (Treguer and Jacques 1991). Theoretically, light isotopes are more easily assimilated by living organisms than heavy isotopes. Thus, the preferential incorporation of light ^{14}N - NO_3^- by phytoplankton entrains a depletion of ^{14}N - NO_3^- in seawater and causes an increase in $\delta^{15}\text{N}$ of the residual nitrate. The

consistent and sufficient supply of nutrients in Antarctic surface waters counteracts the $\delta^{15}\text{N}$ increase of the residual nitrate and thus generates the low values of $\delta^{15}\text{N}$ found in organic particles. Moreover, the isotope fractionation is highest for diatoms dominating the Antarctic ecosystem (Montoya and MacCarthy 1995). Therefore, the $\delta^{15}\text{N}$ values of Antarctic phytoplanktons during the production period are unlikely to reflect the nitrate isotope fractionation by degree of surface-water production because of excessively available macronutrients (Altabet and Francois 2001; Lourey *et al.* 2003). In contrast, Rau *et al.* (1991) observed the significant NH_4^+ utilization during biological production based on the non-linear relationship between NH_4^+ concentrations and $\delta^{15}\text{N}$ values of organic matter in the Weddell Sea. During the production, ammonium recycling alters the nitrogen isotope dynamics as a result of deamination fractionation. If ^{15}N -depleted ammonium released from zooplankton was re-uptaken by phytoplankton, a declined $\delta^{15}\text{N}$ value of surface suspended particulates can be generated during high production (Altabet 1988). Thus, such an effect due to ammonium-based phytoplankton production may alter the nitrogen isotope dynamics of surface particles in a decreasing way of $\delta^{15}\text{N}$ values (Altabet and Francois 2001).

The variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of trapped particles is discernibly and gradually increasing from the productive months towards the unproductive season, except for the anomalous occurrence of high $\delta^{15}\text{N}$ values in February (Fig. 3). Fischer and Wiencke (1992) hypothesized that the $\delta^{13}\text{C}$ values of macroalgae are related to the depth distribution: species inhabiting greater depth had much lower values (around -30‰), compared to species from shallow waters (around -17‰). However, because our sediment trap was deployed at the intermediate-water depth, the species change from deep-water algae to shallow-water algae seems to be unreasonable. The increasing seawater temperature and variation of $p\text{CO}_2$ in the surface waters may operate in the opposite direction of isotopic fractionation, which indicates that these factors are unlikely to operate. Because the level of productivity is closely related to ^{13}C enrichment in phytoplankton carbon, the increasing $\delta^{13}\text{C}$ of trapped particles contradicts the reducing magnitude of surface-water production. An alternative potential factor is the role of biomodification. Krill faeces are enriched by 3-4‰ with ^{13}C compared with phytoplankton. In addition, zooplankton reveals ^{13}C

enrichments of a few per mil relative to phytoplankton (Rau *et al.* 1983). The biomodification of the $\delta^{13}\text{C}$ values in the food web is apparently a result of selective respiration of ^{12}C by krill and zooplankton. Thus, the zooplankton fecal pellets, the most important carrier of sinking particles, may well contribute to the increasing $\delta^{13}\text{C}$ values towards the end of the bloom period.

The degree of nutrient utilization in the surface water and expansion of mixed-layer depth may not be linked to the increasing trend of $\delta^{15}\text{N}$ values from austral summer to fall (Altabet 1988; Altabet and Francois 2001). Heavier $\delta^{15}\text{N}$ values of sinking particles during the unproductive season and lighter $\delta^{15}\text{N}$ values during productive months have been observed, and these seasonal variations may be attributed to several possible causes such as a change in particle source region, a temporal bias of particle residence times in the water column, a contribution of sea-ice algae, changes in isotopic fractionation by the degree of production, or community-based differences in the isotope effect of nitrate assimilation (Lourey *et al.* 2002). Organic matter dominated by diatom may be more labile and prone to remineralization, leading to greater isotopic alteration. However, potential transfer of these vertical biosiliceous particles depends mainly on fecal pellets of grazers (krill) (Gersonde and Wefer 1987; Abelmann and Gersonde 1991). Thus, the greater the formation of fecal pellets toward the non-production time, the more the original signature is maintained without the slight isotopic alteration (Altabet and Small 1990). Therefore, the increasing $\delta^{15}\text{N}$ values in the intermediate-water trap are most likely associated with a switch in source from diatom aggregates to some remains of zooplankton (Wada *et al.* 1987).

Anomalously high $\delta^{15}\text{N}$ values measured in February seem to be enigmatic. The laterally transported and resuspended materials may not be the main contributor considering $\delta^{13}\text{C}$ values and water depth of trap deployment. The most plausible explanation is a different species dominancy with changes in isotopic fractionation. The succession of diatom species occurred with time during the production, verified from the almost sole dominancy of *Minidiscus chilensis* in February (Kang *et al.* 2000).

5. Conclusions

1. The results of one-year (December 25, 1998 to December 24, 1999) sediment trap deployment at the intermediate

water depth in the eastern Bransfield Strait shows a high degree of seasonal variation of particle fluxes, more than 99% of which concentrates on the limited time (January, February, and March). The annual total mass flux was estimated to be 49.2 g m⁻², which is comparable with the previous estimate in the central Bransfield Strait.

2. Biogenic particles (biogenic opal, particulate organic carbon, and calcium carbonate) occupy about two thirds of the total annual mass flux. About 42% of total mass flux is composed of biogenic opal flux. A positive relationship (except January) between biogenic opal and total organic carbon fluxes suggests that these two parameters were coupled, due to the surface-water primary production (mainly diatoms).

3. The low $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of trapped particles are characterized by the high latitude phytoplankton products. The low $\delta^{13}\text{C}$ values are attributed to effects on C-fixation processes at low temperature and the high CO₂ concentrations available for phytoplankton. The low $\delta^{15}\text{N}$ values result from the intense and steady input of upwelled nutrients, maintaining ¹⁵N-enriched nitrate contents in surface waters, recording an unlikely nitrate isotope fractionation by degree of surface-water production.

4. The seasonal variation of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values of trapped particles is obviously distinct, increasing gradually from the early summer to late summer, although the data is incomplete for covering a year cycle and the abnormally high $\delta^{15}\text{N}$ values observed in February. The most important carrier of sinking particles such as krill and zooplankton fecal pellets may be potential contributors to increase $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values towards the unproductive period through the biomodification in the food web, respiring preferentially and selectively light isotopes.

5. The tendency for high $\delta^{15}\text{N}$ values in February remains unexplained. Successive occurrence of different species blooming such as *Fragilariopsis cylindrus*, *Minidiscus chilensis*, and *Pseudo-nitzschia* sp. may be possible, although speculative, resulting in changes in isotopic fractionation, although the fractionation factors of individual species are not known.

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