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Annual evolution of downward particle fluxes in the Western Bransfield Strait (Antarctica) during the FRUELA project

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Abstract

Particle fluxes in the SW Bransfield Strait basin were determined by means of sediment traps deployed at intermediate and near-bottom water depths. Sampling was carried out during a complete year, from March 1995 to February 1996, during the FRUELA experiment. Total mass fluxes, major constituents, and ^{210}Pb were analyzed to study the temporal evolution of downward particle fluxes and to determine the origin of particles transferred to this basin. Mid-depth particle fluxes were much lower and showed a different temporal evolution than those near the bottom. Particle flux variability was mainly related to ice dynamics and biological productivity. The particulate matter transfer and export at mid-depth was very low and most of it took place between November and February during four 15-day sampling periods of the year. Downward carbon export at mid-depths was produced mainly by fecal pellets. The near-bottom fluxes were high (1.1–5.3 $g\,m^{-2}\,d^{-1}$) during the whole year, and the greatest carbon transfer took place by lateral transport of resuspended and winnowed particulate matter. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The southern ocean occupies a position of special interest because of its role in atmospheric pCO_2 control (Knox and McElroy, 1984). This interest has increased due to the urgent need to understand the biogeochemical cycle of carbon in relation to the recent anthropogenic increase of atmospheric CO_2 (Brewer et al., 1986). Despite this interest, few direct flux measurements have been made in Antarctic seas (Dunbar, 1984; Wefer et al., 1990). Polar Oceans are strongly influenced by the extent of ice coverage, particularly of dynamic marginal ice zones (Smith and Nelson, 1986). Seasonal variation in primary production in these regions is great because short-lived blooms of phytoplankton take place when ice cover opens, supplying a significant amount of the annual production of biogenic particles (Honjo, 1990).

Most experiments concerning annual particle fluxes in polar oceans have been done at least

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300 m below the surface to avoid collision with ice and 300 m above the sea floor to avoid collecting the near-bottom fluxes affected by lateral transport of particles. As annual downward particle flux data from the upper 300 m of the water column are not available, there are limitations to relating deep-ocean particulate carbon (POC) flux data to surface productivity. However, the processes and fate of oceanic particles in the polar oceans are closely controlled by the high seasonal variability of primary production, with the exception of lithogenic particles, although light clay and organic particles are also aggregated by biological mediators and are strongly coupled in polar oceans (Honjo, 1990).

In the Antarctic Ocean, particle fluxes and pelagic organic carbon and calcium carbonate fluxes are smaller than in other oceans. However, in some Antarctic nearshore environments such as the Ross Sea and the Antarctic Peninsula, fluxes of biogenic and lithogenic particles are orders of magnitude greater than in the pelagic areas of the Weddel Sea (Wefer et al., 1982; Dunbar et al., 1995; Honjo, 1990). One of these nearshore environments is the Bransfield Strait, a semienclosed sea bounded by the Antarctic Peninsula and the South Shetland Islands. There are three major basins in the western, central and eastern parts of the Bransfield Strait, separated by sills of about 500 m depth. The maximum depth of these basins increases from the western part (about 1000 m) to the eastern part (about 2500 m) (Huntley et al., 1991; Gràcia et al., 1997; Canals et al., 2000).

Previous experiments involving four-season time-series traps were conducted for several years at a 1900 m deep site in the central Bransfield basin south of King George Island (Dunbar, 1984; Dunbar et al., 1985; Gersonde and Wefer, 1987; Wefer et al., 1988; Wefer et al., 1990; Abelmann and Gersonde, 1991). These studies indicated that over 95% of the annual flux at mid-depths occurred during December and January and that the annual flux could range from 11.9 to 107.7 g m^{-2}. About 50% of the mid-depth flux consisted of biogenic constituents (Wefer et al., 1988, 1990), and all the particles were transported downward by *Euphausia superba* fecal pellets (Wefer et al., 1982, 1988; Dunbar, 1984). The flux of biologically produced particles can have an important lateral component, especially near the bottom in continental margins (Biscaye and Anderson, 1994; Monaco et al., 1990; Heussner et al., 1999; Puig and Palanques, 1998). In Antarctic sea, there are practically no measurements of near-bottom fluxes transported laterally, and their contribution to the carbon cycle is largely unknown.

During the "FRUELA" research project, downward particle fluxes were collected by sediment traps in the western Bransfield Strait south of Livingston Island during a year cycle at mid-depths and also near the seabed. The aim of this paper is to study the composition and annual variability of the downward fluxes of particulate matter in the western Bransfield Strait, and to analyze the contribution of the biogenic particles exported vertically out of the photic zone as well as the role of the lithogenic and biogenic particles transported laterally from shallower environments.

2. Methods

A mooring line equipped with two sequential sediment traps was deployed south of Livingston Island and west of Deception Island at 1000 m depth (Fig. 1). This area is located at the mouth of the Orleans canyon, which is incised along the northern Antarctic Peninsula slope. One sediment trap was placed 30 m above bottom (mab), and the other trap was installed at mid-depth, 500 mab. Unfortunately, other moorings deployed in the surrounding area and equipped with additional sediment traps and current meters could not be recovered.

The sediment traps used in this study were Technicap model PPS3. The upper part of the trap's internal sample-collecting hull is cylindrical, has an inner diameter of 40 cm (a collecting area of 0.125 m^2), and a height of 190 cm. The trap incorporates a carousel with 12 sampling bottles, which is controlled by a programmable motor to preset variable sampling intervals for each of the

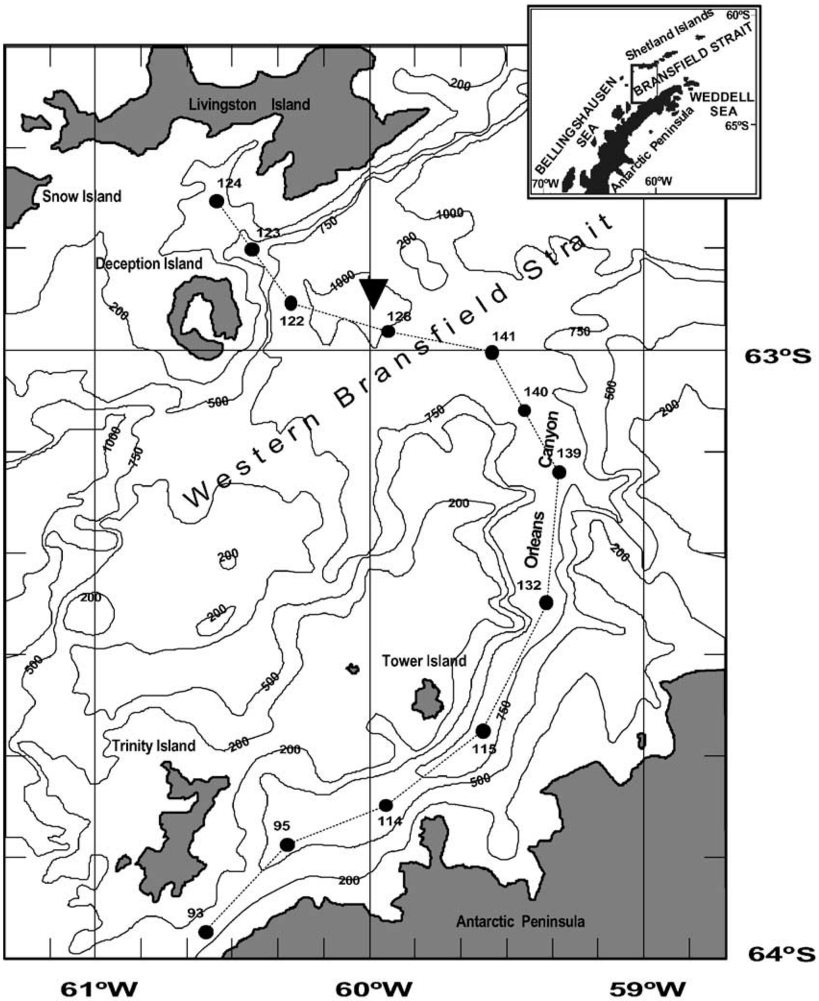

Fig. 1. Bathymetric map of the western Bransfield Strait showing the position of the sediment trap mooring (triangle) and the locations of hydrographic stations (dots) distributed in a hydrographic transect (Fig. 8) across the Bransfield Strait and along the Orleans Canyon.

bottles (Heussner et al., 1990). The sampling period comprised almost a complete year (345 days) from March 1 1995 to February 15 1996. In this experiment, the sample collecting interval was set to different time intervals: 60 days during late autumn–winter months (from April to September), 30 days in March and October and 15 days in spring and summer months (from November to February) in order to have a higher resolution during the high productivity.

Before the trap deployments, the sampling tubes were rinsed and filled with a 5% ($\sim 1.7\,M$) formalin solution prepared from Carlo Erba analytical-grade 40% formaldehyde mixed with 0.2-μm filtered seawater to avoid the degradation of organic matter in the trapped particles. The solution was buffered ($7.5 < pH < 8$) with Carlo Erba analytical-grade sodium borate. After the trap recovery, the pH indicated that the solutions had remained buffered.

The collected samples were processed in the laboratory according to the method described by Heussner et al. (1990). The total sample was divided into several aliquots to obtain different subsamples for analyzing total mass flux, major constituents (organic carbon, calcium carbonate, opal and lithogenic components) and ^{210}Pb. However, most of the mid-depth samples only had material for analyzing the total mass flux and the total carbon. The other analyses on the mid-depth samples could only be done in the three richest samples (late November, late December and early January). Zooplankton organisms, also called "swimmers", were removed by hand picking under a dissecting microscope using forceps and were stored for further analysis.

Sample dry weight was determined using three subsamples filtered onto 47-mm diameter, 0.45-μm preweighed Millipore filters rinsed with distilled water and dried at 40°C for 24 h. Total mass flux was calculated from the sample dry weight, the collecting trap area, and the sampling interval. Mean mass fluxes were weighted by time, and mean concentrations of constituents were weighted by time and flux.

For carbon and nitrogen analyses, four subsamples were filtered onto 47-mm diameter preweighed Whatman GF/F glass microfiber filters that previously had been combusted at 550°C for 24 h. Two subsamples were used to determine the total carbon (TC) and nitrogen percentages in a LECO CN 2000 analyzer. Another two subsamples were digested with HCl in a LECO CC 100 digestor, and the resulting CO_2 was analyzed in the same CN analyzer and assigned to inorganic carbon (IC) content, which was used to calculate the calcium carbonate ($CaCO_3$) percentage by multiplying the IC content by 8.33. The difference between the two values (TC−IC) is the percentage of organic carbon (OC).

Biogenic silica (opal) was analyzed using a wet-alkaline extraction with sodium carbonate using the method described by Mortlock and Froelich (1989). This analysis consists of a differential wet-chemical extraction into a 2 M Na_2CO_3 solution at 85°C for 5 h. The wet-chemical dissolution technique appears to be the most versatile in its application to marine samples of various types and compositions (DeMaster, 1991). The lithogenic component was computed as the difference between the total mass and the sum of the biogenic components (organic matter (twice the percentage of organic carbon), calcium carbonate and opal).

The ^{210}Pb content in the downward particulate matter can be related with its origin. Particles newly settling from the surface can have a higher ^{210}Pb content than those resuspended and transported laterally. ^{210}Pb analyses were performed following the methodology described in Sanchez-Cabeza et al. (1998), assuming that ^{210}Pb was in secular equilibrium with its daughter ^{210}Po. An aliquot of each sample was spiked with ^{209}Po and totally digested using a microwave oven. After digestion, samples were made 1 N HCl and ^{209}Po and ^{210}Po were deposited onto silver disks, previously coated on one side with a plastic lacquer, and left at 60–70°C for 8 h while stirring. Polonium isotopes were counted with α-spectrometers equipped with low-background SSB surface barrier detectors in vacuum conditions (EG&G Ortec). Chemical recoveries ranged from 93% to 100%, and several reagent blank analyses also were carried out and subtracted for activity determination.

3. Results

Time series of total mass fluxes are shown in Fig. 2, and time series of contents and fluxes of major constituents (organic carbon, calcium carbonate, biogenic silica and aluminosilicates) are shown in Figs. 3 and 4, respectively. Mean annual total mass fluxes and mean annual contents and fluxes of major constituents measured by the sediment traps during the experiment are listed in Table 1.

3.1. Total mass fluxes

Total mass fluxes in the study site ranged from a minimum of about 0.1 mg m^{-2} d^{-1} recorded at

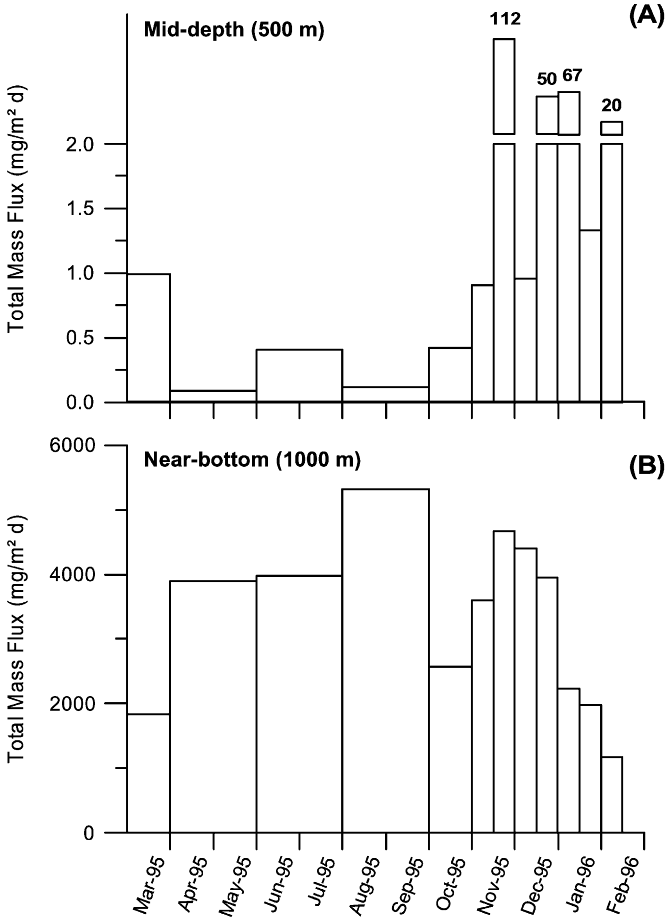

Fig. 2. Times series of total mass fluxes of settling particulate matter collected at (A) mid-depth (500 m water depth) and (B) near the bottom (1000 m water depth and 30 m above bottom) during the FRUELA project.

mid-depth to a maximum of about 5000 mg m^{-2} d^{-1} recorded near the bottom (Fig. 2). The maximum total mass flux at mid-depth was 112 mg m^{-2} d^{-1} and occurred in spring (late November sampling period), whereas near the bottom it was 5321 mg m^{-2} d^{-1} and occurred in winter (August–September sampling period). Minimum values were 0.08 mg m^{-2} d^{-1} in intermediate waters and 1178 mg m^{-2} d^{-1} near the bottom, and occurred in early winter (April–May sampling period) and in late summer (early February sampling period), respectively. Total mass fluxes near the bottom were 1–4 orders of magnitude higher than those at mid-depth during the same sampling periods.

The temporal evolution of the total mass fluxes at the two depths was also very different (Fig. 2). Whereas the near-bottom fluxes were always within the same order of magnitude, at mid-depth 95% of the annual mass flux occurred within four 15-day periods of the experiment year (late November, late December, early January and early February), when particle fluxes were 2–3 orders of magnitude higher than during the rest of the year. For this reason, we assume the mean

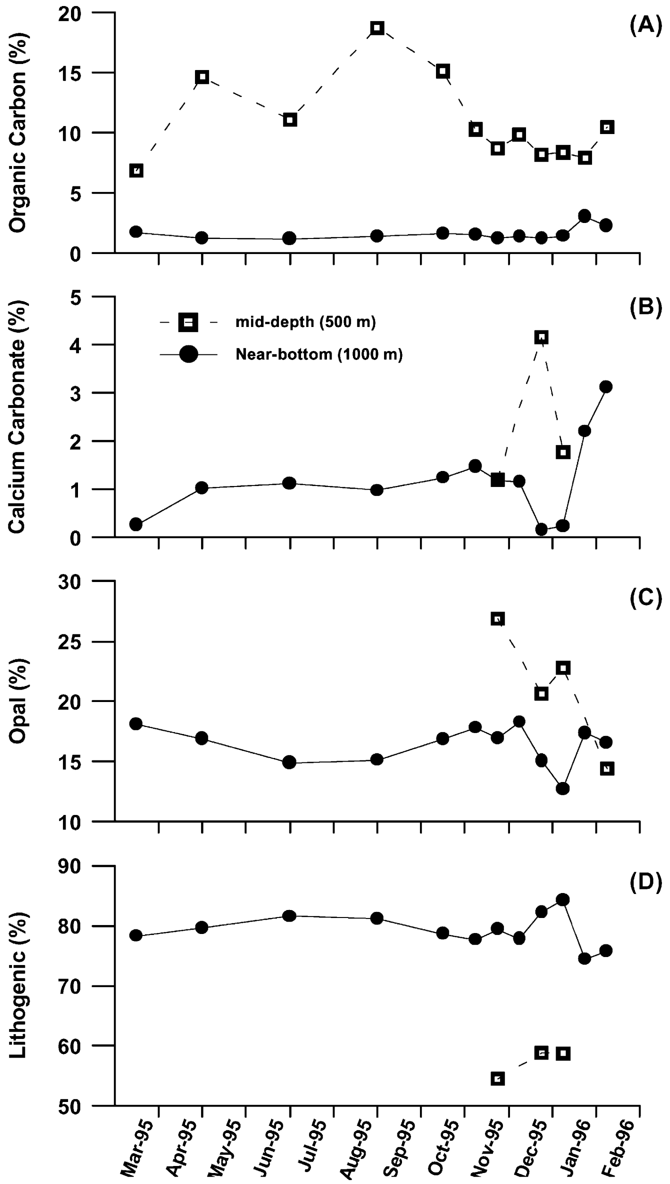

Fig. 3. Time series of major constituent's contents of settling particulate matter during the FRUELA project: organic carbon (A), calcium carbonate (B), opal (C), and lithogenic fraction (D) at mid-depth (open squares) and near the bottom (black dots).

contents and the mean fluxes of major constituents during these sampling periods to be the mean annual contents and the mean annual fluxes of these constituents at mid-depth.

3.2. Organic carbon

At the study site, the carbon content of the particulate matter was essentially organic (90–99%

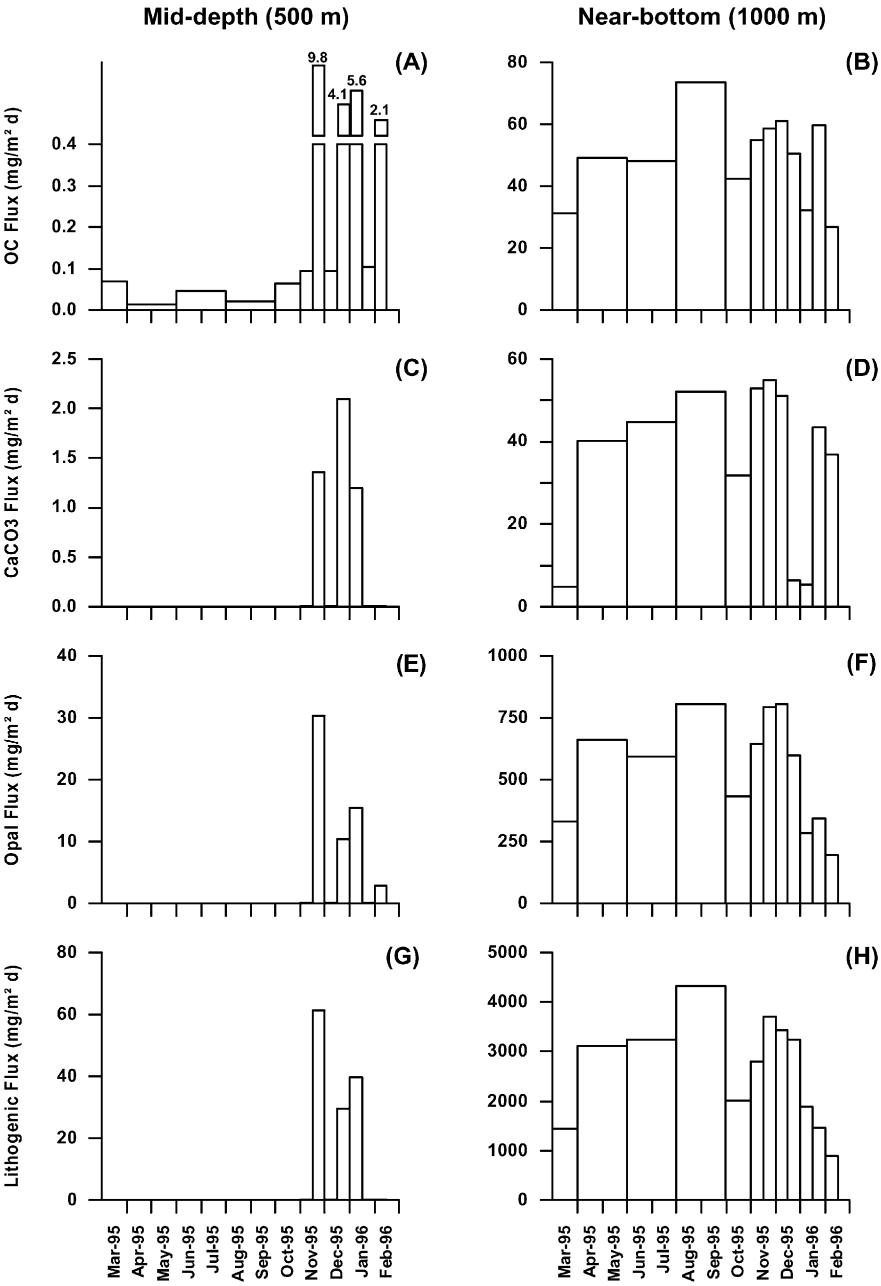

Fig. 4. Time series of the major constituent's fluxes of settling particulate matter at mid-depth and near the bottom during the FRUELA project. Near-bottom organic carbon (A), mid-depth calculated organic carbon (B), calcium carbonate (C, D), opal (E, F), and lithogenic fraction (G, H).

Table 1
Mean annual concentration and fluxes of the total mass and the major constituents of the settling particulate matter in the western Bransfield Strait.[a]

	Total mass		Organic carbon		Calcium carbonate		Biogenic silica		Lithogenic	
	MD	NB	MD	NB	MD	NB	MD	NB	MD	NB
Mean concentration (%)			8.70	1.4	1.78	1.04	16.03	22	57.0	80.0
Mean flux ($mg\,m^{-2}\,d^{-1}$)	11.27	3634	0.98	51.03	0.19	37.9	2.56	582.68	6.44	2912
Annual flux ($g\,m^{-2}$)	4.11	1326	0.35	18.62	0.73	13.84	0.922	212.6	2.3	1075

[a] Note: MD, Mid-depth; NB, near-bottom.

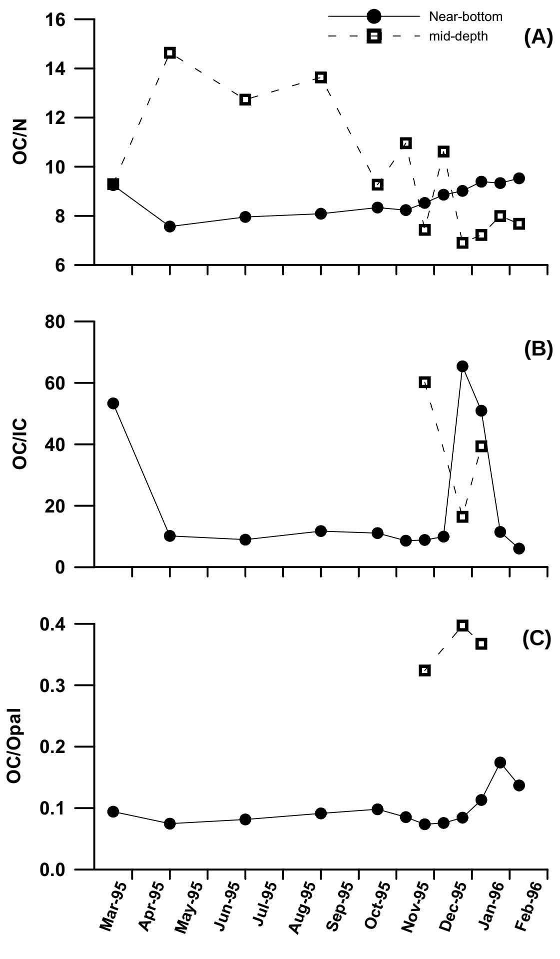

Fig. 5. Time series of ratios of biogenic components on the settling particulate matter during the FRUELA project. OC/N (Mol/Mol) (A), OC, IC (B), OC/Opal (C), at mid-depth (open squares) and near the bottom (black dots).

of the total carbon). In intermediate waters, the organic matter (OC) content during the three 15-day sampling periods with the highest total mass flux was quite constant (8.2–8.7%) and higher than that of near-bottom settling particles (Fig. 3A). During the rest of the year, only the TC content was available at mid-depth. However, considering the high OC/IC ratios (20–60) of the analyzed samples (Fig. 5B), we can assume the TC content as OC content for the periods of lowest total mass flux at mid-depth. Following this assumption, the estimated OC content at mid-depth could range from 6.8% to 18.7%. The highest OC content occurred during the August–September period, when the total mass flux was minimum ($0.1\,mg\,m^{-2}\,d^{-1}$). However, the lowest values of OC content (6–8%) were common to periods of different total mass flux. Thus, there was no clear relationship between the two parameters. The near-bottom OC content was relatively constant, ranging from 1.2% to 1.7% during most of the year, and only increasing to 3% in late summer (late January sampling period) (Fig. 3A).

Assuming the TC contents as OC contents during periods of low total mass, the OC fluxes at mid-depths ranged from $0.01\,mg\,m^{-2}\,d^{-1}$ in early winter (April–May), when the total mass flux was minimum, to $9.8\,mg\,m^{-2}\,d^{-1}$ in late spring (late November sampling period), when the total mass flux was maximum (Fig. 4B). In spite of this variability, the OC flux followed the same temporal pattern as the total mass flux (Fig. 2). This is because the variability of the total mass flux is much higher (within a factor of 100–1000) than that of the OC flux (within a factor of 2).

The OC flux near the bottom showed the same temporal pattern as the near-bottom total mass flux, because of the low variability of the OC content in the near-bottom settling particulate matter during the whole experiment. The near-bottom OC fluxes were 1–3 orders of magnitude higher than those measured at mid-depth during the same sampling periods. Near-bottom OC fluxes ranged from 26.7 $mg\,m^{-2}\,d^{-1}$ in late summer (early February sampling period) to 73.5 $mg\,m^{-2}\,d^{-1}$ in late winter (August–September sampling period) (Fig. 4A).

3.3. Organic carbon to nitrogen ratio (Mol/Mol)

The OC to nitrogen ratio (OC/N) of the settling material also showed a different pattern at the two depths (Fig. 5A). In intermediate waters this ratio reached the highest values (12.7–14.6) in winter, when total mass flux was minimum, and the lowest values (6.9–7.9) in the summer periods of highest total mass and OC fluxes (Fig. 5A). In October and November the OC/N increased to a value of about 10.

Near bottom, the C/N of settling particulate matter ranged from 7.5–9.5 and was more constant than at mid-depths (Fig. 5A). The lowest ratios occurred in winter, coinciding with the highest ratios in intermediate waters. In summer, the near-bottom OC/N increased, reaching maximum values of about 9.5 in January and February, when the mid-depth ratios fell below near-bottom values (Fig. 5A).

3.4. Calcium carbonate

The calcium carbonate in the settling particulate matter of the study area varied from 0.2% to 4.1% (Fig. 3B). In intermediate waters, the calcium carbonate content could only be determined in the three 15-day sampling periods of highest total mass flux. The late November sample, which corresponded to the highest total mass flux in intermediate waters, showed the same content (1.2%) as the one recorded near the bottom in the same period. However, in the late December–early January samples at mid-depth the calcium carbonate content (4.1% and 1.8%, respectively) were one order of magnitude higher than those recorded near the bottom during the same sampling periods, which were the lowest calcium carbonate values recorded during this study (about 0.2%). Near the bottom, the calcium carbonate content was quite constant (1–1.5) during most of the year, except in summer when both the lowest (0.16%) and the highest (3.11%) values were recorded, the former between mid-November and mid-January and the latter in March (Fig. 3B).

The calcium carbonate fluxes at mid-depth ranged from non-detectable to a maximum of 2.09 $mg\,m^{-2}\,d^{-1}$ in mid-summer (late December sampling period). The maximum calcium carbonate fluxes did not correspond to maximum total mass fluxes (Fig. 4D). The calcium carbonate flux near the bottom had the same temporal trend as the total mass flux, except in summer (Fig. 4C). The calcium carbonate flux during the other seasons showed similar trends to the total mass flux because of its relatively constant content. The near-bottom calcium carbonate fluxes ranged from 4.8 $mg\,m^{-2}\,d^{-1}$ in early autumn (March sampling period) to 54.9 $mg\,m^{-2}\,d^{-1}$ in late spring (late November sampling period), coinciding with the maximum total mass flux (Fig. 4C).

3.5. Biogenic silica (opal)

Opal was the most abundant biogenic component in the particulate matter of the study area at both depths. At mid-depths, the opal content of the four sampling periods with highest total mass flux ranged from 12% to 26% (Fig. 3C). Near the bottom, the opal content ranged from about 14% in winter to about 17% in summer, except in late December and early January, when it fell to 12% (Fig. 3C).

At mid-depth, the opal fluxes during the four sampling periods of highest total mass flux ranged from 2.9 $mg\,m^{-2}\,d^{-1}$ in late January to 30.2 $mg\,m^{-2}\,d^{-1}$ in late November (Fig. 4F). The near-bottom opal fluxes were 1–2 orders of magnitude higher than those at mid-depth during the same sampling periods and ranged from 195 $mg\,m^{-2}\,d^{-1}$ in early February to about 800 $mg\,m^{-2}\,d^{-1}$ in late November and August–September (Fig. 4E). The opal flux had the same temporal pattern as the total mass flux because the variability of the total mass flux was much higher than that of the opal content.

3.6. Lithogenic components

The lithogenic components represent the major fraction of the settling particulate matter, both at mid-depth and near the bottom (Fig. 3D). At mid-depth, the lithogenic components during the three 15-day periods of highest total mass flux ranged from 54% to 58% (Fig 3D). Near-bottom lithogenic content ranged from a minimum of 75% to a maximum of 85% in early January.

The lithogenic flux had a relatively low variability and showed the same temporal pattern as the total mass flux. During the three periods of highest total mass flux at mid-depth, the lithogenic flux ranged from 29 to 61 $mg\,m^{-2}\,d^{-1}$ (Fig. 4H). Near-bottom lithogenic flux ranged from 893 $mg\,m^{-2}\,d^{-1}$ in the early February period to 4318 $mg\,m^{-2}\,d^{-1}$ in the August–September period (Fig. 4G), 1–2 orders of magnitude greater than the lithogenic flux at mid-depth during the same sampling periods.

3.7. Lead-210

The only three available ^{210}Pb measurements at mid-depth were obtained in summer. They ranged from 1200 to 1500 $Bq\,kg^{-1}$ (Fig 6A) and were 1.4–2.3 times higher than the near-bottom ones during the same sampling periods. Near the bottom there was a decreasing trend from 1300 to 870 $Bq\,kg^{-1}$ during autumn and winter (March–September), and a peak in October, followed by a sharper decrease during spring and summer (October–January), when the minimum value was recorded (650 $Bq\,kg^{-1}$). The maximum value (2000 $Bq\,kg^{-1}$) was recorded in February. This maximum peak also was observed for the calcium carbonate and the organic carbon contents. The mean near-bottom ^{210}Pb concentration was 987 $Bq\,kg^{-1}$.

^{210}Pb fluxes (Fig. 6) showed a temporal pattern similar to that of the total mass flux (Fig. 2), as all the fluxes of major constituents did. At mid-depth, the ^{210}Pb flux during the three available periods ranged from 0.07 to 0.13 $Bq\,m^{-2}\,d^{-1}$. From these fluxes, assuming a mean concentration of 1288 $Bq\,kg^{-1}$ for the particulate matter collected by the intermediate trap during the rest of the year, the annual ^{210}Pb flux at mid-depth was estimated at around 5.3 $Bq\,m^{-2}$. Near-bottom ^{210}Pb flux ranged from 1.5 $Bq\,m^{-2}\,d^{-1}$ in early January to 4.6 $Bq\,m^{-2}\,d^{-1}$ in the August–September and early December sampling periods (Fig. 6C). The mean near-bottom Pb flux was 3.5 $Bq\,m^{-2}\,d^{-1}$, and the annual ^{210}Pb flux near the bottom was 1310 $Bq\,m^{-2}$.

4. Discussion

Particles and particle fluxes at the studied depths are fundamentally different. Mid-depth fluxes are largely biological and controlled mainly by settling of fecal pellets, whereas near-bottom fluxes are more dynamic, being mainly controlled by lateral transport of material supplied from shallower environments. These fluxes and the processes generating them are discussed in this section.

4.1. Mid-depth downward particle fluxes

The mid-depth downward fluxes at the study site were about 2 orders of magnitude lower than those of continental margins from other latitudes at similar depths (e.g., Biscaye et al., 1988; Biscaye and Anderson, 1994; Heussner et al., 1996; Puig and Palanques, 1998). Even in the same Bransfield Strait, our annual total mass flux at mid-depth (4.11 $g\,m^{-2}$) was up to one order of magnitude lower than that collected south of King George Island in 1984 (107 $g\,m^{-2}$) (Wefer et al., 1988, 1990). However, the measured annual flux was similar to that collected in 1985 (11.9 $g\,m^{-2}$) and reported by Wefer et al. (1990), which is indicative of the high interannual variability of the mid-depth fluxes in the Bransfield Strait. The low downward particle fluxes at mid-depth could be related to the moderate primary production in this area (Varela et al., 2002), and probably also to the morphology and hydrology of the study area. Numerous studies have addressed the influence of hydrodynamic effects on trap collection biases (e.g. Butman et al., 1986, Gust et al., 1992, 1994), which

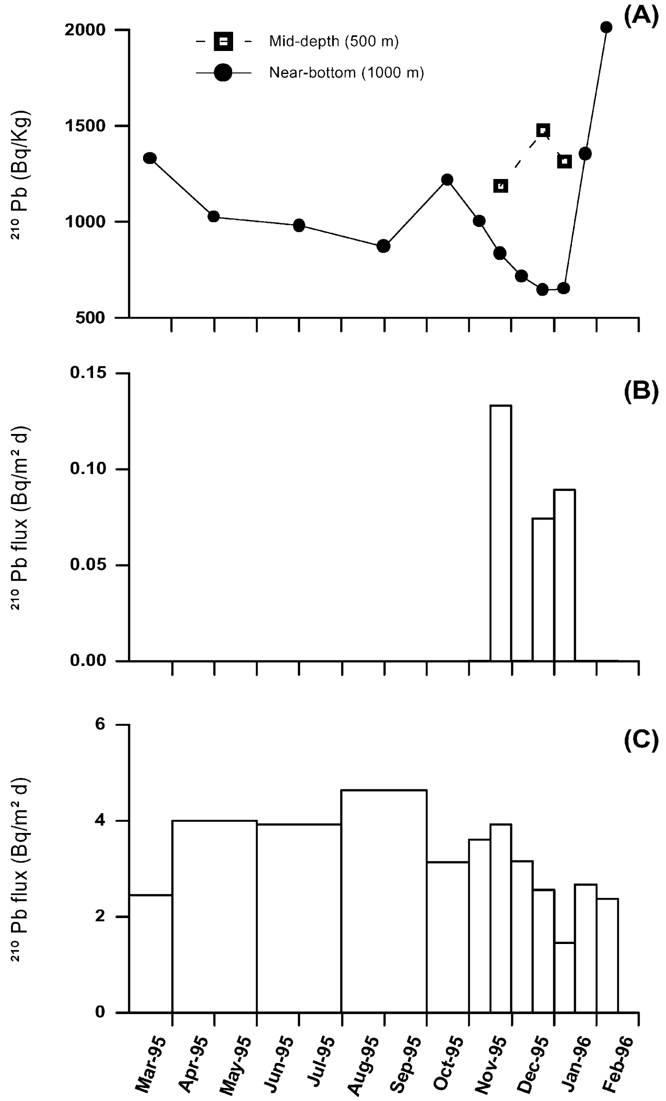

Fig. 6. Time series of ^{210}Pb concentration (A), at mid-depth (open squares) and near the bottom (black dots), and ^{210}Pb fluxes at mid-depth (B), and near the bottom (C) during the FRUELA project.

also would explain the low amount of particles collected in the mid-depth trap. However, a field experiment by Gardner et al. (1997) using sediment traps with a geometry similar to that of PPS3 showed no decrease in collection efficiency at mean velocities of 1–22 cm s^{-1}. In addition, another field experiment conducted by Heussner et al. (1999) with PPS3 sediment traps also demonstrated no relationship between total mass flux of particles and trap Reynolds number at mean speeds ranging from few to 12 cm s^{-1}. Unfortunately, no current measurements were available for this deployment, but previous current meter data obtained at 400 m depth in the Bransfield Strait (López et al., 1994) showed that currents at mid-depths in summer were tidally dominated, with some maximum values of about 25–30 $cm\,s^{-1}$ and typical residual currents of 15 $cm\,s^{-1}$. Based on the results obtained by Gardner et al. (1997) and Heussner et al. (1999), little effect on collection efficiencies can be expected for this study, although due to the slightly higher current regime, the mid-depth fluxes could be affected by hydrodynamic bias to some degree.

During the mooring deployment, drifting sediment traps were used south of Livingston Island in the FRUELA cruises. These traps collected fluxes of 115 and 175 $mg\,C\,m^{-2}\,d^{-1}$ at the end of December 1995 and in January 1996, respectively (Anadón et al., 2002). The carbon flux measured with the sequential trap at 500 m depth in late December and January represents about 3.3% of the surface fluxes measured by the drifting traps. However, we should consider that sequential traps cover 15-day sampling periods.

On the other hand, the mean primary production measured in the study area in spring was about 1 $g\,C\,m^{-2}\,d^{-1}$ (Varela et al., 2002). Thus, carbon fluxes at mid-depths in late December 1995 and January 1995 were less than 1% of the mean primary production. If we consider the annual productivity to be about 100 $g\,C\,m^2$ (Varela et al., 2002), however, the annual OC flux at mid depth represents only 0.35% of the annual productivity.

4.2. Near-bottom downward particle fluxes

In the Bransfield Strait, near-bottom fluxes had hardly been studied previously, and never during a complete annual cycle. The near-bottom fluxes found in this study were significantly high (from 1178 to 5321 $mg\,m^{-2}\,d^{-1}$) and similar to those measured near the bottom in the eastern Bransfield Strait during only a one-month deployment (Gersonde and Wefer, 1987; Liebezeit and von Bodungen, 1987). Compared to near-bottom fluxes in other areas at similar depths, our near-bottom sediment fluxes are similar only to those measured in the southern middle Atlantic Bight (Biscaye and Anderson, 1994) and within some submarine canyons, (e.g. Puig and Palanques, 1998; Heussner et al., 1996).

Although no near-bottom current data are available for this particular area of the Bransfield Strait, there is some evidence indicating that bottom currents were not strong enough to induce significant biases in the collection efficiency of the bottom trap. The OC/N ratio, the OC content and the mean ^{210}Pb activities of the settling particulate matter collected near the bottom are very similar to those of the surface sediment at the mooring site, which is mud (95% silt + clay) with a ^{210}Pb activity of 987 $Bq\,kg^{-1}$ (Masqué et al., 2002), a OC/N ratio of 6–7, and an OC content of 1.3%. This indicates that the material collected by the sediment trap is of the same nature as that which ultimately accumulates on the sea floor, and that the near-bottom trap measured particle fluxes that may be representative of present sediment accumulation. The mean sediment accumulation rate determined from ^{210}Pb was $351 \pm 14\,g\,m^{-2}\,y^{-1}$ (Masqué et al., 2002). Which is relatively high for these depths. This is one-fourth of the mean annual flux measured by the near-bottom trap (1326 $g\,m^{-2}$), but direct comparison between bottom sediment and trap data must be done with caution, as time scales differ by a factor of about 100 (from 1 to 100 years). Several factors, including interannual variability in downward particle fluxes, biological activity, and dynamics in the uppermost sediment column, might be a source of discrepancy between the two fluxes. The higher total mass flux of the near-bottom trap suggests that at least this trap did not underestimate downward particle fluxes. However, it is difficult to discern whether the near-bottom trap flux was inflated by hydrodynamic biases causing overtrapping. Based on the results obtained in field experiments by Gardner et al. (1997) and Heussner et al. (1999), few hydrodynamic effects on trap collection efficiency for the near bottom trap might be expected, unless high near-bottom currents operate in the deeper part of the basin at 1000 m depth. Taking into account the bottom morphology and the high accumulation rates of very fine sediment at the mooring site, bottom currents in the deep basin should not be high. All this suggests few hydrodynamic effects on trap collection efficiency for the near-bottom trap.

Besides the small hydrodynamic biases that may affect the collection efficiency of the two traps, the near-bottom fluxes at the study site were much higher than those at mid-depth. The annual total mass and OC fluxes increased from 500 to 1000 m water depth (30 m above bottom) by a factor of 324 and 53, respectively (Table 1). This great difference is not because the near-bottom fluxes of the Bransfield Strait are especially high but because mid-depth fluxes are extremely low.

During December 1995 and January 1996, the OC near-bottom flux was about 5% of the mean primary productivity during the same months estimated by Varela et al. (2002) (about $1\,g\,C\,m^{-2}\,d^{-1}$). If we consider a springe summer season of 100 days, the annual near-bottom OC flux represents 18% of the annual productivity of $100\,g\,C\,m^{-2}$ estimated from Varela et al., 2002 data. However, we should take into account that the Bransfield Strait can receive organic matter exported from the Gerlache Strait, where primary production is higher (Varela et al., 2002).

4.3. Sedimentary processes

Downward particulate matter has different characteristics throughout the year, which generally are not common to both sampling depths. The periods of highest fluxes at mid-depths were in spring when settling particulate matter had the highest opal content (>20%) and the lowest C/N ratio (6–7), suggesting that they were related to phytoplankton blooms.

Near the bottom, in contrast, between spring and summer there was an increase in terrigenous inputs, with lower organic matter content and ^{210}Pb activity and higher OC/N ratio, indicating more degraded organic matter. This was probably caused by the effects of thaw, and perhaps by wave storms (without ice cover) supplying sediment particles derived from nearshore areas. In summer, the lithogenic flux decreased, whereas the organic carbon, the OC/N ratio, the ^{210}Pb activity, and the calcium carbonate increased, probably due to the rapid sinking of new material incorporated in fecal pellets. The increase in the OC/N could be due to grazing and degradation of pellets by meso and macro zooplankton in subsurface levels (Gonzalez and Smetacek, 1994; Noji et al., 1991).

In winter, the simultaneous high near-bottom fluxes of low C/N and the decreasing trend of the Pb activity with extremely low mid-depth fluxes of high OC/N ratio (Figs. 2 and 5A) suggest a major and dominant lateral input of particles with fresh organic matter near the bottom. The maximum total mass flux in winter occurred in the August–September period, coinciding with a decrease in the ^{210}Pb activity. During these months, the near-bottom temperature in the central basin of the Bransfield Strait decreased dramatically, from –0.8°C to –1.55°C (Canals, 1996). This temperature decrease probably corresponded to the sinking of dense water formed on the shelf by winter cooling. The down-flow of dense bottom water could winnow the particles from shallow environments towards the deep basin. This mechanism also could flush out newly deposited unconsolidated sediment from the floor, causing a winter maximum of sediment transport, as suggested for the Barens Sea by Honjo et al. (1988).

The near-bottom Pb activity versus OC/N ratio shows an inverse covariation during the year except in summer (samples 11, 12, and 1). This suggests a dominant lateral input from shallower environments during most of the year and a higher influence of newly settled and transported laterally fecal pellets in summer.

Swimmers and diatoms in the samples of the near-bottom trap were studied (Palanques et al., in press), and also provided some indications for sedimentary processes. Among the amphipod fauna collected in this trap, there were some species seldom found (*Orchomenella pinguides*) or never found in the water column (*Hirondella Antarctica, Opisa* sp. *and Epimeriidae gen*. sp.). Similarly, there were benthic polychaete fauna, which in the case of the *Scalibregmatids* are infound. Among the collected diatoms, the most significant species and genus were *Amphora, Cocconeis* (*C. fasciolata*), and *Grammatophora (G. angulosa*), which also are benthic. Another group of common species frequently trapped during the year are *Actinocyclus actinochilus, Navicula directa, N. glaciei, Thalasiosira antarctica and Fragiliariopsis kergelensis*, which are littoral species.

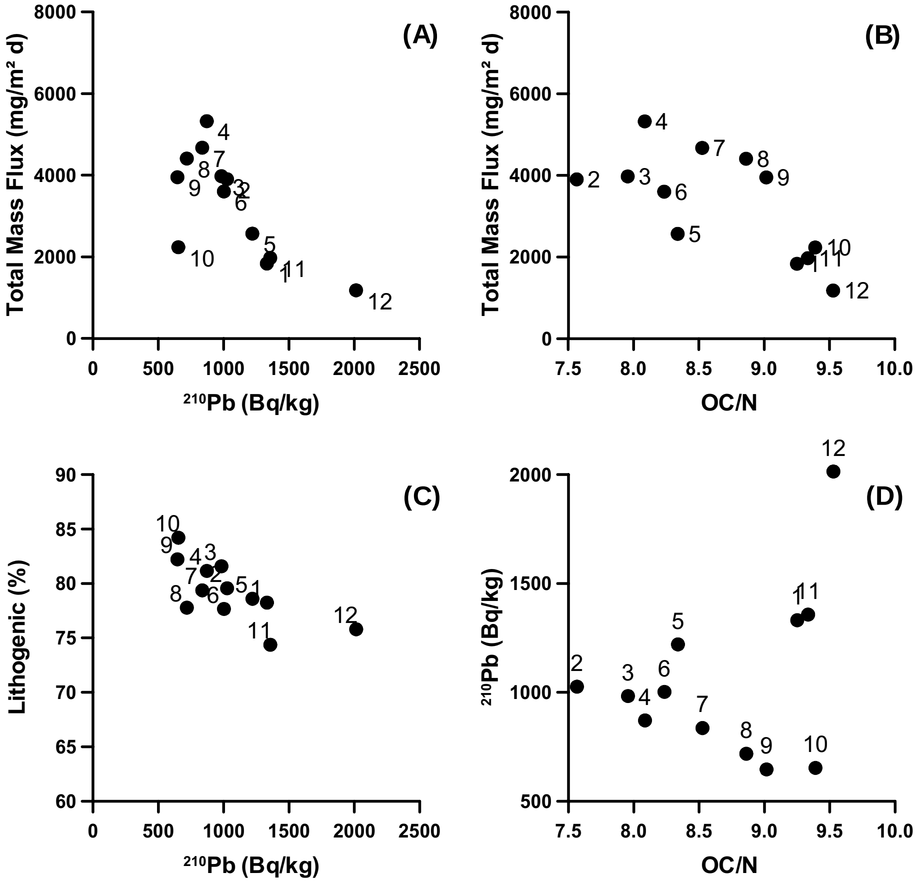

Fig. 7. Concentration of near-bottom ^{210}Pb plotted against near-bottom total mass flux (A), lithogenic content (C), and OC/N ratio (D). Near-bottom OC/N ratio plotted against total mass flux (B). Numbers indicate the sequential number of samples collected by the sediment trap. 1: March, 2: April and May, 3: June and July, 4: August and September, 5: October, 6: 1–15 November, 7: 16–30 November, 8: 1–15 December, 9: 16–31 December, 10: 1–15 January, 11: 16–31 January, 12: 1–15 February.

Many of the species collected in the near-bottom trap are abundant in shallow bays of the South Shetland Islands (Ahn et al., 1997). Thus, the presence of these polychaetes, benthic amphipoda and diatoms at 1000 m depth indicate resuspension in shallow environments and lateral transport basinward along with the non-living particles. The low OC/N ratio of near-bottom settling particles in the study area throughout the year also could be related to resuspension and lateral transport of benthic or recently sedimented planktonic organic matter. The relatively high near-bottom fluxes of major organic constituents cannot be explained by vertical fluxes at the mooring site, and must be due to lateral transport from more productive zones. The highest primary productivity of the study area is found on the Antarctic shelf and slope around the Orleans Canyon (Holm-Hansen and Mitchell, 1991), which may also receive material exported from the high productive waters of the Gerlache Strait (Varela et al., 2002).

Near-bottom total mass flux and lithogenic content show an inverse relation ($r = -7$) with Pb activity and OC/N ratio (Fig. 7A–C), indicating that increases of lithogenic supplies are related to material transported laterally from shallow environments with fresher organic matter. This

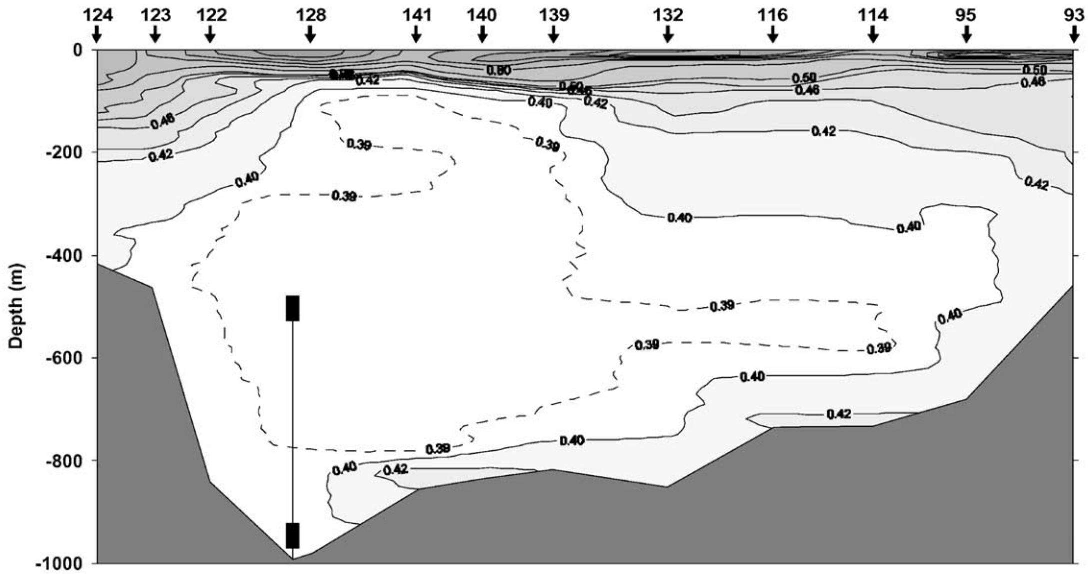

Fig. 8. Transect of beam attenuation coefficient across the western Bransfield Strait and along the Orleans Canyon (station positions are shown in Fig. 1). Note the presence of a wide bottom nepheloid layer developed along the Orleans Canyon towards the basin where the sediment traps (black rectangles) were deployed.

also suggests an input of resuspended material from shallower environments with either benthic organisms and/or recently sedimented planktonic organic matter.

Resuspension in shallow Antarctic environments can occur due to a number of processes, such as friction of icebergs against the seabed, formation of dense water and polynyas, wind-driven storms when there is no ice cover, and even internal waves. However, consistently high near-bottom fluxes throughout the year cannot be explained only by these processes, as they suggest a more or less continuous mechanism causing them. Time series of current data taken in the summer season by López et al. (1994) show that the local circulation in the Bransfield Strait was strongly influenced by tides and that surface (10–50 m water depth) maximum currents south of Deception Island were 30–40 cm s^{-1} towards the northeast. These maximum tidal currents are energetic enough to continuously resuspend fine sediment and benthic organisms on the continental shelves of the study area.

Bottom sediment on most of the continental shelves around the study site consists of sand and gravels (Yoon et al., 1992), which strongly suggests offshore winnowing. The narrow continental shelves and steep slopes of the study area also can favor shelf-slope sediment transfer towards the Bransfield Strait basins. The geostrophic current in the study area during summer is predominantly towards the northeast, and it has typical velocities of 15 cm s^{-1} and maximum velocities of around 20 cm s^{-1} (López et al., 1994; Gomis et al., 2002), This geostrophic current is energetic enough to winnow and transport fresh and resuspended particles advectively from the shelf towards the slope. In addition, the presence of a bottom nepheloid layer extending along the Orleans canyon axis towards the study site was observed in transmissometer profiles recorded during the December 95 FRUELA cruise (Fig. 8). These data indicate an active mechanism transporting suspended particulate matter near the bottom through this canyon. Thus, suspended particulate matter transferred from the Antarctic shelf and upper slope around this canyon is probably collected and reoriented basinward, helping to maintain the high and permanent downward particle fluxes observed near the bottom of the western Bransfield Strait basin.

5. Conclusions

In the Western subbasin of the Central Branfield Strait, the mid-depth annual total mass flux during the year of deployment was extremely low ($4.11\,g\,m^{-2}$). Most of this flux settled in summer during a time period no longer than 60 days. The maximum mid-depth fluxes of all the major constituents also occurred during these periods and were associated with planktonic blooms. Vertical carbon export was mainly by fecal pellets; mid-depth settling fluxes were very low in winter and contained degraded organic matter.

The annual near-bottom total mass fluxes were three orders of magnitude higher than those at mid-depth. Near-bottom fluxes were high during the whole year of experiment and in winter they were up to 4 orders of magnitude higher than those at mid-depth during the same sampling periods. The constantly high near-bottom fluxes of the study area indicate a permanent high transfer of sediment from shallow to deep environments. The most likely mechanism supplying this material is sediment resuspension by tidal currents over the shelf regions. Other mechanisms, such as ice friction with the seabed, ice melting or sinking of dense water, may contribute more sporadically to high near-bottom fluxes. The geostrophic current could winnow and transport particulate matter basinward, and the Orleans Canyon appears to funnel particles transferred from the continental shelf of the Antarctic Peninsula, reorienting them basinward.

The annual carbon flux at mid-depths and near the bottom represents 0.35% and 18% of the annual primary production, respectively. Near-bottom flux includes benthic organisms and lithogenic particles resuspended from shallow environments and transported laterally basinward. Thus, in Antarctic marginal seas and continental margins, lateral advection, resuspension and associated processes in the benthic boundary layer must be taken into account in the study of biogeochemical cycles.

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