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Relationships between Antarctic coastal and deep-sea particle fluxes: implications for the deep-sea benthos

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Abstract Downward particle fluxes measured by means of sediment traps to a shallow semi-closed bay (Johnson's Dock, Livingston Island) and to a deep basin in the western Bransfield Strait (Antarctic Peninsula) showed the important role of glaciers as sediment carriers and suppliers to the ocean in a continent without major rivers such as Antarctica. The trap moored in Johnson's Dock collected coarse sediment (>1 mm mesh) not observed in the offshore traps, which mainly received fine sediment and faecal pellets. The annual total mass flux (TMF) to the coastal zone (15 m) was 900- and three times that to mid-depth (500 m) and near-bottom (1,000 m) traps, respectively. The fine sediment flux was especially important due to its biogenic particle contents. Despite the differences in TMF to the coastal zone and near the bottom in the deep basin, the organic carbon (OC) flux was similar in both environments (16 and 18 g m^{-2}, respectively), whereas biogenic silica (BSi) flux increased three times with depth (75 and 201 g m^{-2}, respectively). These fluxes imply that an important part of the particulate organic matter deposited in the coastal zone is advected basinward within the fine-particle flux. Thus, benthos in deep areas depends largely on the lateral transport of biogenic material produced in shallow environments near the coast. It is also proposed that the disintegration of Antarctic ice shelves and the consequent increment of ice calving may produce local devastations of ecological importance not only on the shallow but also on the rich Antarctic deep-sea benthic communities due to an increment of iceberg scouring and reduction of the organic matter supply.

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Introduction

The sea floor is the final deposition site of particles exported from the euphotic zone and the material that enters into the marine environment. Rivers contribute approximately 70% (15×10^9 t $year^{-1}$) of the particulate matter that the world ocean receives (Milliman 1991). In Antarctica, the absence of large river systems due to extreme cold conditions restricts the transport of particulate material from the continent to the action of the ice. Thus, sediment releases from glacier ice and primary production are the main settling-particle sources in the Antarctic shallow marine environment. Both show evident seasonal variation with high fluxes (more than 90% of the annual flux) during the austral summer (Clarke 1988; Wefer and Fischer 1991; Dunbar et al. 1998; Palanques et al. 2002a), and negligible production in the winter (Cochlan et al. 1993).

The Antarctic continental shelf is unusually deep (500 m in average but down to 800 m in some places, whereas continental shelves elsewhere in the world are typically 100–200 m deep) and rugged due to the pressure of continental ice and glacial erosion (Anderson 1991). The physical conditions above the sea floor on this shelf are relatively constant throughout the year (e.g., temperature, salinity) (Arntz et al. 1994). They are only significantly disturbed by iceberg scouring, which mainly occurs between 150 and 300 m (Gutt et al. 1996; Peck et al. 1999). This unusual environment hosts benthic communities, which show physiological adaptations similar to those inhabiting the deep-sea at lower latitudes (Clarke and Johnston 2003).

Antarctic benthos is influenced by a unique combination and intensity of biotic (predation, competition, recruitment) and abiotic factors (substratum, depth, sedimentation, currents regime, food supply, ice scouring) (Dayton et al. 1974; Dayton 1989; Arntz et al. 1994; Slattery and Bockus 1997; Stanwell-Smith and Barnes 1997; Gutt 2000; Piepenburg et al. 2002). In addition, historical processes such as geologic and climatic events, dispersal and migration, extinction and speciation have particularly influenced the evolution of the present Antarctic fauna (Lipps and Hickman 1982; Dayton 1990; Clarke and Crame 1992; Clarke 1997).

Antarctic benthic communities have been described as "multistoried assemblages", due to the epibiotic relationships between species (Knox and Lowry 1977; Gutt and Schickan 1998 and citations therein). These relationships create a complex three-dimensional community with a large biomass, intermediate to high diversity, and patchy distribution of organisms (Gutt and Starmans 1998; Gili et al. 2001; Teixidó et al. 2002; Gerdes et al. 2003). This ecosystem presents intermediate to high species richness (Starmans and Gutt 2002) and locally extreme high epifaunal biomass—up to 1.67 kg m^{-2} wet weight- (Gerdes et al. 1992). The fauna in this area is dominated by sessile suspension feeders e.g., sponges, gorgonians, bryozoans, and ascidians, which locally cover the sediment completely (Gutt and Starmans 1998; Starmans et al. 1999). Piepenburg et al. (2002) found that there are noe evident latitudinal gradients in benthic abundance and biomass in Antarctica and that the benthic fauna in the Antarctic Peninsula (0.95 kg m^{-2} wet weight) is comparable to that from the Weddell Sea. However, the distribution of macrobenthos may be determined by a depth-dependent factor related with food supply.

Particle fluxes offshore and beyond 250 m depth are usually very low (Dunbar et al. 1989; DeMaster et al. 1992; Nelson et al. 1996; Palanques et al. 2002a) and most of the near-shore total mass flux (TMF) settles in shallow environments and close to the coast (Ashley and Smith 2000; Isla et al. 2001), where the deposited matter is easily resuspended (Berkman et al. 1986; Ahn et al. 1997). These resuspension events and lateral transport generate the high TMF measured near the bottom in the deep sea (Dunbar et al. 1989; Palanques et al. 2002a) reducing the seasonal contrast of particle fluxes in the upper layers of the Antarctic Ocean. This fact provides conditions for a high deep-sea benthic biomass (Brey and Gerdes 1997) to feed on a year-round particle flux despite seasonal primary-production restrictions (Barnes and Clarke 1995). Therefore, this flux represents an important organic matter transfer from shallow to deep environments. The aim of this study is to analyze the relationships between biogenic and lithogenic fluxes to the coastal zone and to the deep ocean highlighting their implications for the deep-sea benthos and for the transport of organic carbon.

Methods

Particle fluxes were measured by means of sediment traps in a small semi-enclosed bay, the Johnson's Dock (JD) at Livingston Island (South Shetland Islands) and a deep basin in the western Bransfield Strait (BS) (Fig. 1). Due to its geographic setting, Johnson's Dock offers the opportunity to sample particle fluxes in a protected coastal environment where a sediment trap can be moored without being disturbed by ice or currents. Hence, it was possible to collect the local sediment input from the Johnson's glacier without interferences. The BS site is one of the deepest locations in western Bransfield Strait and the natural sink of material delivered by two glacial canyons, which are connected to shallower depositional areas of western Antarctic Peninsula. It is also close to the southeastern margin of Livingston and Deception Islands.

The sediment trap in Johnson's Dock was tethered at 4.5 m above bottom (mab) at a site 19.5 m deep. Due to logistic constraints, this trap operated from 10 December 1997 to 26 February 1998. Sediment traps in the deep basin were installed at 500 mab and 30 mab at a site of 1,000 m depth. The sampling period lasted from 1 March 1995 to 16 February 1996.

The present study was conducted with Technicap model PPS 3 and PPS 4 sediment traps (Heussner et al. 1990). These traps have a height to diameter aspect ratio of 2.5 and collecting area of 0.125 m^{-2} (40 cm inner diameter) and 0.05 m^{-2} (25 cm inner diameter), respectively. Both traps have a rotary carrousel with 12 polypropylene tubes operated by a preset electronic motor. Before deployments, each 250 ml capacity tube, was rinsed and filled with a 5% (~1.7 M) formalin solution prepared from Carlo Erba formaldehyde (analytical grade 40%), mixed with 0.4 μm-filtered seawater. The solution was buffered (ph 7.5–8) with Carlo Erba, analytical grade sodium borate. Sediment trap samples were sieved through a 1 mm mesh and particles >1 mm were removed by hand picking. The sum of the weights of each fraction yielded the total mass weight. The animals present in the >1 mm fraction presumably by swimming into the trap ("swimmers") were removed and not taken into account to calculate the total mass weight.

The total carbon (TC) and nitrogen (N) were measured in a LECO CN-2000 auto-analyzer. Two sub samples were treated with 6N HCl in a LECO CC-100 digester and the resultant CO_2 was detected in the LECO CN-2000 analyzer yielding the inorganic carbon (IC) content. The organic carbon (OC) percentage is the difference between IC and TC values. The calcium carbonate content ($CaCO_3$) was calculated by multiplying IC % by 8.33 (Wefer and Fischer 1991) and the organic matter estimated as twice the OC percentage.

Biogenic silica (BSi) was measured following the Mortlock and Froelich (1989) alkaline extraction procedure. Lithogenics percentage was computed as the difference between the total mass and the sum of the major biogenic constituents (organic matter, calcium carbonate, and BSi).

Results and discussion

Total mass flux

The sediment released from Johnson's Glacier can generate an approximate annual TMF of 3,325 g m^{-2} in its adjacent coastal zone (Table 1). This flux is comparable

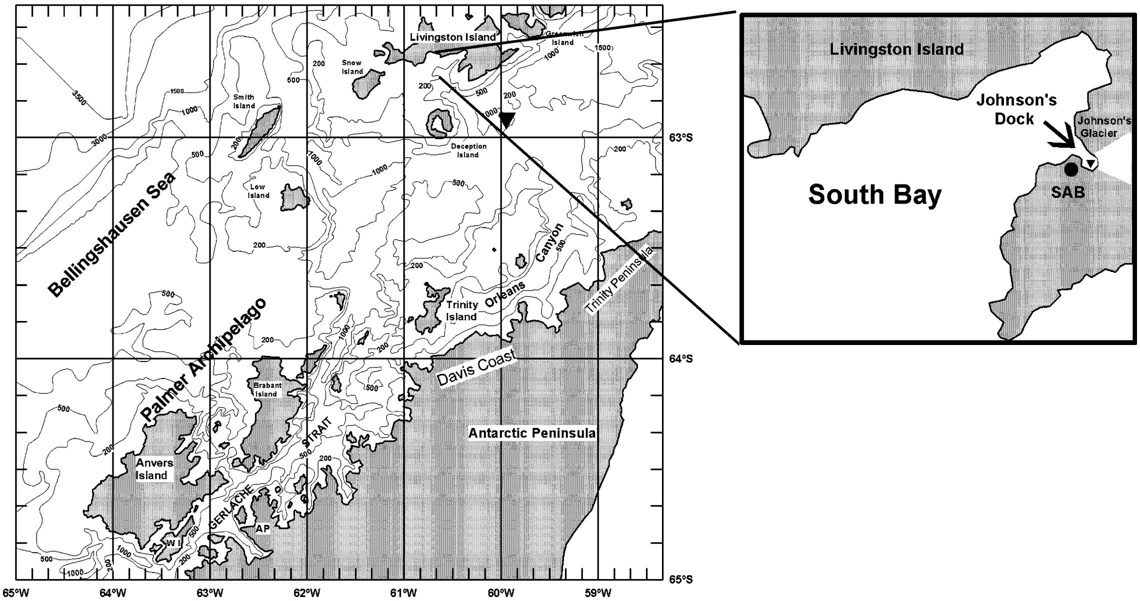


Fig. 1 Map of the study area. *Triangles* indicate sediment trap locations, SAB, WI, and AP stand for Spanish Antarctic Base (Juan Carlos I), Wiencke Island, and Arctowski Peninsula, respectively

to others in shallow environments at lower latitudes and those under the influence of rivers (Monaco et al. 1990; Biscaye and Anderson 1994). The sediment trap at Jonhson's Dock sampled a short period during the austral spring and summer (Fig. 2), which represents the season when most of the annual particle fluxes occur (Wefer et al. 1988; Dunbar et al. 1989; DeMaster et al. 1992; Nelson et al. 1996; Wefer and Fischer 1991). Therefore, the fluxes obtained at the Dock characterize a minimum annual flux, which in any case is still large enough to supply the material collected near the bottom of the basin (Table 1). Evident inter-annual particle flux variations below 600 m depth have been detected in Antarctica (Wefer et al. 1990) and this may also occur in shallower areas. However, the total mass flux at Johnson's Dock was similar to other fluxes measured in Antarctic shallow environments during different years and longer sampling periods (Cripps and Clarke 1998; Ashley and Smith 2000; Baldwin and Smith 2003).

The fine sediment fraction represented 80% of the lithogenic flux collected in Johnson's Dock, whereas the remaining 20% was constituted by coarse sediment (>1 mm mesh) not observed in the offshore traps (Fig. 2). The approximate annual TMF to these traps was 4 g m^{-2} to mid depth (500 m) and 1,254 g m^{-2} near the bottom (1,000 m depth) (Fig. 3). These fluxes were, respectively, 900 and three times smaller than that in the coastal zone and mainly consisted of fine sediment and faecal pellets (Palanques et al. 2002a). The TMF collected near the bottom was similar to other in continental margins (at similar depths and more septentrional latitudes) receiving sediment discharges from rivers (Puig and Palanques 1998). In addition, this near bottom flux was relatively high (>1,500 mg m^{-2} day^{-1}) throughout the year and did not show the seasonal variation of the TMF noted in the upper trap. Palanques et al. (2000b) found that the material accumulated in the deeper trap was resuspended and laterally transported; similar events are known to occur in the Ross Sea (Dunbar et al. 1989; DeMaster et al. 1991).

Considering that Johnson's Glacier is rather small, the TMF at Johnson's Dock strongly suggests that the icebergs-delivered material to the coastal zone, and its

Table 1 Concentration and fluxes of the total mass and major constituents of the settling particulate matter

		Total mass		Organic carbon		Biogenic silica		Lithogenics	
		MD	NB	MD	NB	MD	NB	MD	NB
Mean content (%)				8.7	1.4	16	22	57	80
Mean flux (mg m^{-2} day^{-1})	BS	11	3,634	1	51	3	583	6	2,912
Annual flux (g m^{-2})		4	1,326	0.3	19	0.9	213	2	1,075
Mean content (%)				0.5		2.4		95.8	
Mean flux (mg m^{-2} day^{-1})	JD	4,2857		206		962		41,225	
Annual flux (g m^{-2})		3,325		16		75		3,198	

BS, *JD*, *MD*, and *NB* stand for Bransfield Strait, Johnson's Dock, mid-depth, and near-bottom, respectively

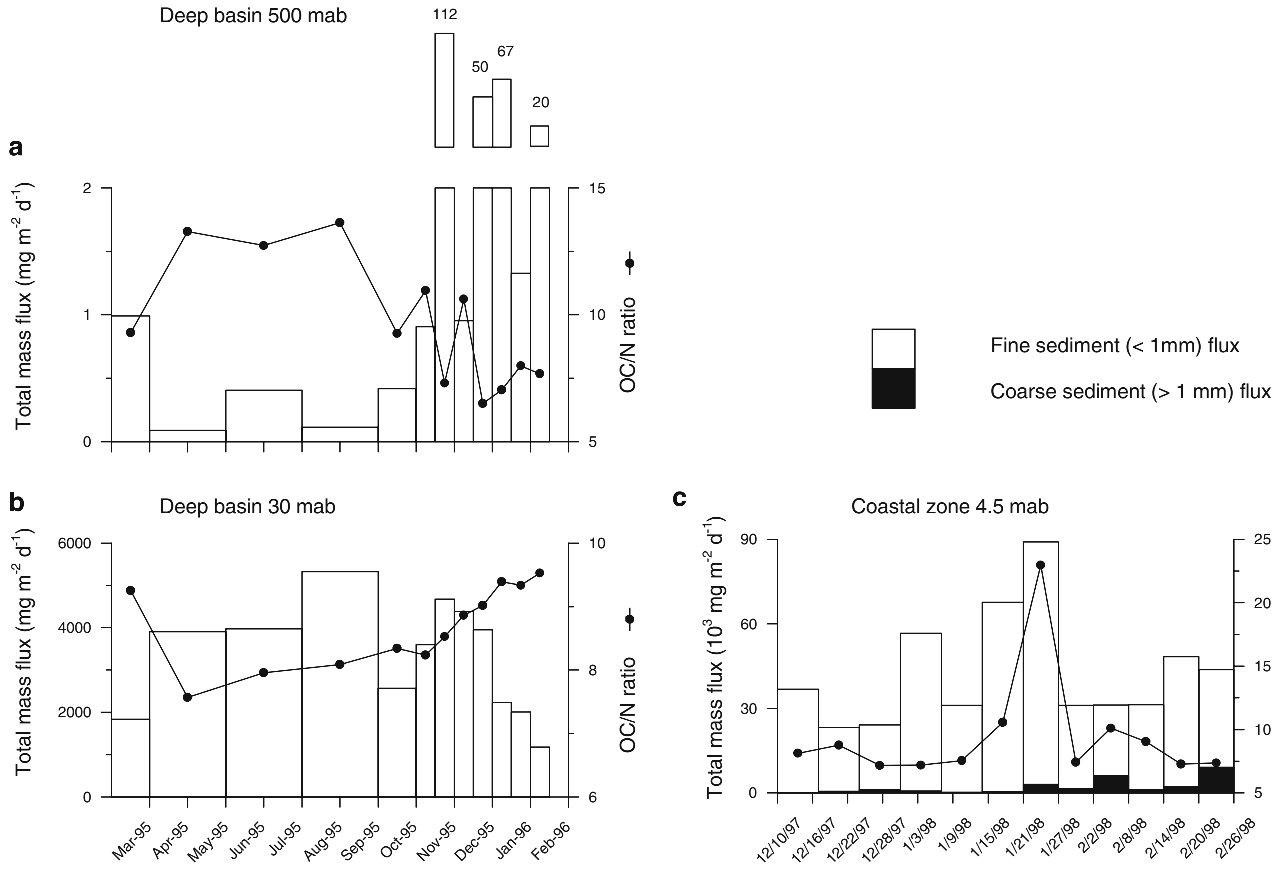


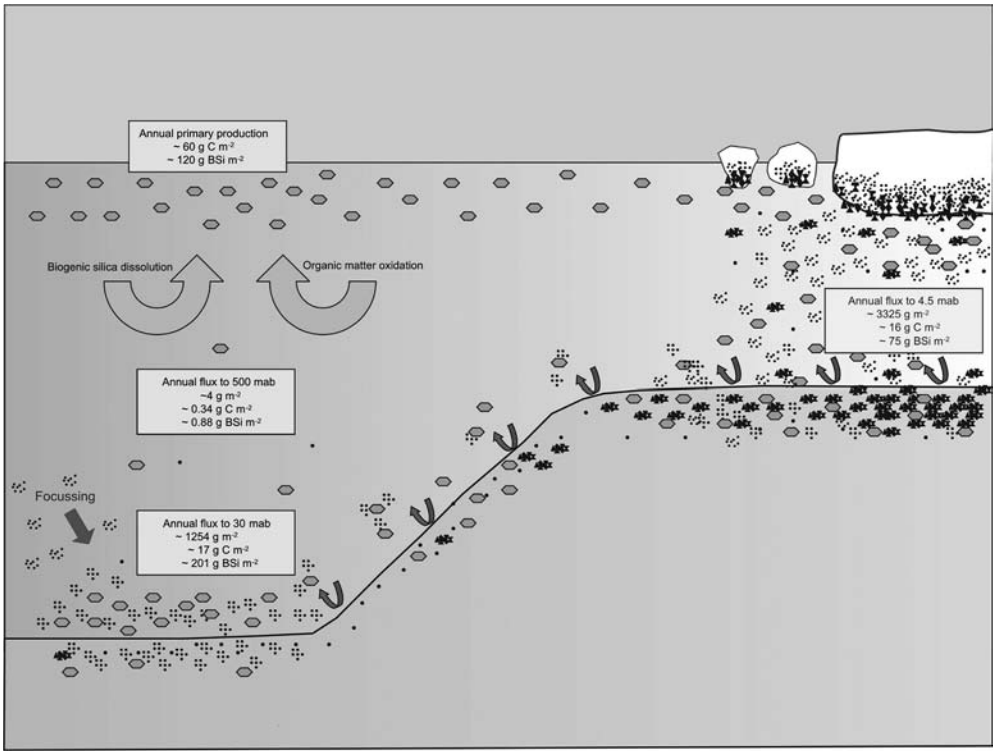
Fig. 2 Temporal variation of the total mass flux and the OC/N ratio (*lines and solid circles*) of the settling particles to (**a**, **b**) the deep basin and (**c**) the coastal zone. No coarse sediment (>1 mm diameter) was collected in the deep basin traps. Note different scales for the fluxes in the coastal zone. "mab" stands for meters above bottom

lateral transport could easily be the source of the high TMF collected near the bottom in the deep basins. Sediment releases from Johnson's Glacier represent a very little fraction of the annual glacial sediment input to Antarctic seas, approximately 0.5×10^9 t (Knox 1994), but provide a figure about the order of magnitude of the particulate matter supplied by single glaciers to the Antarctic coast. These fluxes also show that glacier sediment discharge can be comparable to that produced by rivers in continental shelves (Monaco et al. 1990; Biscaye and Anderson 1994). These results underscore the important role of glaciers in Antarctica as sediment carriers and suppliers to the ocean.

Resuspension at Johnson's dock

Resuspension events can mislead to an overestimation of the true total mass flux (TMF). In Antarctic semi-closed bays such as Johnson's Dock resuspension of sediment is mainly driven by wind storms (Berkman et al. 1986), which commonly occur. Thus, the results obtained with the sediment trap moored at this site may be overestimated to a certain degree. We cannot provide an accurate quantitative estimation of the total mass flux produced by resuspension; however, based on the organic carbon to nitrogen ratio (OC/N) (Fig. 2c) we calculated an approximate number. The OC/N values oscillated between 7.5 and 10 throughout the study period reflecting the presence of "fresh" phytoplanktonic matter, strongly supported by chlorophyll-*a* values reported previously (Isla et al. 2001). The evident increase at the seventh sampling interval (from February 21st to February 28th) indicates an input of degraded material, presumably resuspended matter. To estimate the size of this input we calculated an average of the total mass collected during each sampling period (12.7 g) without considering the value of the seventh sampling cup (26.7 g). The difference between the average and the total mass of the seventh cup was 14 g, which represents 8% of the total mass collected during the whole study period (167 g). Thus, considering the value of the 7th cup as the most exaggerated by resuspension we estimate that the true TMF collected by the coastal trap should be at least 8% smaller than the value reported in Table 1. Since the TMF measured at Johnson's Dock is 300% larger than that collected near the bottom at 1,000 m depth, the true TMF at the coastal zone is still large enough to feed the TMF near the bottom in the deeper basins. Accordingly, the amount of carbon introduced by resuspension (0.35% of 14 g divided by the collection area, 0.05 m^2) represents 5% of the flux listed in Table 1; though, it presented a different chemical quality.

Fig. 3 Main particle fluxes at the mooring sites. Approximate annual total mass, organic carbon, and biogenic silica fluxes in the coastal zone (Livingston Island) and offshore to mid-depth (500 m depth) and to 30 m above the bottom (mab) (ca.1,000 m depth) in one of the deepest sites in western Bransfield Strait (Antarctic Peninsula) show that most of the primary-produced particulate matter offshore (*grey polygons*) do not reach 500 m depth and that the material settling in shallower environments feeds the deep sea. Icebergs deliver coarse and fine sediment (*triangle aggregates and dots*, respectively) on shallow areas but only the latter reaches the deep sea. Lateral transport of fine sediment from the coastal zone enhances the biogenics flux to the deep basin. *Curved arrows* near the sea floor represent resuspension



Biogenic fluxes

The fine-sediment transfer to the deep-sea acquires special relevance when considering the biogenic fluxes. In spite of TMF differences between shallow and deep environments, the organic carbon (OC) fluxes to 1,000 m depth and in the coastal zone were similar, whereas biogenic silica (BSi) flux increased three times with depth (Fig. 3). This BSi flux increment reflects the preferential degradation of OC relative to BSi in the Antarctic marine environment and suggests focusing of fine sediment in deep basins (DeMaster 2003). Well-preserved benthic diatoms, amphipods, and polychaetes transported from shallow environments were collected throughout the study period in the deepest trap (1,000 m depth) (Palanques et al. 2002b). The presence of this biogenic material and the magnitude of the OC and BSi fluxes indicate that an important fraction of the organic matter which settles in the coastal zone is resuspended and transported basinward associated to the fine-particle flux, adding to the small vertical fluxes occurring farther offshore. Furthermore, the low OC/N ratio of particles collected near the bottom (30 mab) in the deep basin demonstrates the relatively ‘‘fresh’’ organic matter supply throughout the year (Fig. 2). The good preservation state of the shallow-water benthic organisms and the low OC/N ratio of the organic matter imply that this basinward transport is relatively fast and represents an efficient carbon transfer to the deep ocean. Here it is important to note that aggregation of particles enhances the association of the fine-particulate litho- and biogenic matter, which produces a rapid sinking flux that is a significant food source for the benthic communities (McCave 1984; Thomsen 1999). These aggregates were observed probably for the first time in Antarctica during the H.M.S. Challenger expedition (1873–1876) and they were defined as ‘‘fine washings’’ composed by a mixture of argillaceous matter, organic substances, siliceous organisms, and mineral particles (Murray and Renard 1891). Accordingly, the fine sediment delivered by the ice may facilitate the basinward transport of organic material via aggregation (Honjo 1990). In addition, the narrow continental shelf and the steep slopes in the Bransfield Strait may accelerate the fine-sediment transfer toward the basins (Gutt et al. 1998). Comparable results on particle fluxes have been reported for the Ross Sea (Dunbar et al. 1989).

Pelagic-benthic coupling

Mean primary production measured by Varela et al. (2002) in the western Bransfield Strait during part of the sediment-trap experiment (spring 1995) was about 1 g C m^{-2} day^{-1}. On the basis of 60 productive days per year—based on the annual temporal variation of the downward particle flux (Wefer and Fischer 1991; Dunbar et al. 1998; Palanques et al. 2002a)—and the approximate duration of some phytoplankton blooms (Smith and Nelson 1986), we estimated an annual production of about 60 g C m^{-2}. Then, the measured OC flux to mid-depth, 0.34 g m^{-2} (Fig. 3), would be approximately 0.6% of local annual primary production. Based on an Antarctic phytoplankton mean

BSi/OC weight ratio of 1.2 (DeMaster et al. 1992), we assumed an annual BSi production of 72 g m^{-2}. Subsequently, our measured BSi flux to mid depth, 0.88 g m^{-2}, would account for 1.2% of the annual production. Hence, in the western Bransfield Strait more than 98% of the offshore primary produced OC and BSi do not reach 500 m depth. If the most active primary production period were longer than 60 days the percentage of biogenic material collected below 500 m would be even smaller; therefore, the calculated numbers should be considered as maximum values. In the Ross Sea's euphotic layer, 65% of primary produced BSi was affected by dissolution, whereas more than 90% of the net carbon production was consumed by microbial degradation (DeMaster et al. 1992; Nelson et al. 1996). These results suggest that biogenics dissolution and degradation make the biogenic particle flux to mid depth extremely low; whereas, an important fraction of primary-produced organic matter settles in shallow, near-shore environments enhancing the organics preservation due to their short residence time in the water column (Cripps and Clarke 1998). Our results show that only the fine sediment reaches the deep sea, and associated with it, a significant part of the biogenic matter deposited in the coastal zone. Consequently, the benthos in deep areas depends largely on primary production over shallow areas and on the resuspension and basinward transport of fine particles. This underscores the importance of the fine sediment delivered by the ice as a carrier of primary produced material for the continuous supply of fresh organic matter to the deep benthic realm. Although near-shore primary production may account only for a small fraction of the total production in the Southern Ocean (Arrigo et al. 1998), it appears to be very important for the export of organic carbon to the deep sea. Accordingly, near-bottom lateral transport of organic material represents a net pump of carbon from the shallow sea to the deep ocean; moreover, Antarctic coastal areas may have a significant influence on the long-term removal of carbon dioxide from the atmosphere.

The deep Antarctic benthic ecosystem appears linked to the fine sediment dynamics and should be sensitive to its changes. The old and highly structured Antarctic benthic communities have evolved in an extreme physically constant environment (Arntz et al. 1994), which is now being significantly altered. Recent ice calving events such as in the Larsen and Ross Ice Shelves, presumably due to the warming of the Earth's atmosphere, may produce a double impact on the benthic community: (1) Reducing coastal primary production by occupying ice-free areas at the sea surface and preventing the sea ice to melt (Arrigo et al. 2002; Arrigo and van Dijken 2004) and (2) increasing the lithogenic supply to the coastal zone since more sediment-laden ice will thaw. If these phenomena increase the input of biogenics to the coastal zone will be substantially reduced, and therefore their supply to the deep ocean. As an example, a high sedimentation event over McMurdo Sound, shallow-sea benthos increased the mortality of one of the most common and fastest growing coral species (Slattery and Bockus 1997), and locally produced a significant ecological perturbation. Calving of icebergs will also increase the impact of iceberg scouring on the benthos, which is "among the five most significant disturbances that any large ecosystem on earth experiences" (Gutt and Starmans 2001). Antarctic benthos may not be as diverse as some coral reefs but between 100 and 800 m depth, benthic biomass in Antarctica is higher than in many temperate and subtropical environments (Brey and Gerdes 1997). Therefore, increment of ice calving should produce a dramatic effect not only on the shallow- but also on the, up to now, largely unknown (Clarke 1996) rich Antarctic deep-sea benthic communities. Here we point to a sensible link between deep-sea benthos and the frozen rivers of Antarctica.

Conclusions

Small Antarctic glaciers such as that in Johnson's Dock can release large amounts of lithogenic material comparable to that delivered by rivers at lower latitudes. The material released in the Antarctic coastal zone could easily maintain the high particle fluxes measured in a deep-sea basin, which is also similar to the fluxes measured at similar depths in more septentrional latitudes in river-influenced environments.

Fine particles (<1 mm) constitute more than 80% of the total mass flux to the coastal zone and represent the total of the flux collected near the bottom in the deep basin. The fine lithogenic material aggregates with organic matter in shallow environments and, due to resuspension and lateral transport, nourishes the deep sea throughout the year despite seasonal restrictions in primary production at the upper layers of the water column. Near-bottom lateral transport of resupended organic matter in the coastal zone represents a net pump of carbon to the deep ocean; moreover, Antarctic coastal areas may have a significant influence on the long-term removal of carbon dioxide from the atmosphere. Warming of the Earth's atmosphere is presumably linked to the augment of ice calving in Antarctica. This link may produce an increase in the sediment supply to the coastal zone and a reduction of the organic matter input to the deep sea, which in turn may cause an important ecological impact on the Antarctic deep-sea benthic communities. This relationship is not fully explored yet and offers interesting opportunities for future research.

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