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Marine Geology 234 (2006) 63 – 92

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Spatial and temporal variability of downward particle fluxes on a continental slope: Lessons from an 8-yr experiment in the Gulf of Lions (NW Mediterranean)

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Accepted 5 September 2006

bstract

A long-term experiment of downward particle fluxes and currents has been initiated in 1993 on the continental slope of the Gulf f Lions (NW Mediterranean) and pursued within the frame of several French and European projects (PNEC, Euromarge-NB, MTP I-MATER, EUROSTRATAFORM). Sediment traps and current meters were deployed at several locations on this slope deeply ncised by numerous canyons, with an extensive spatial coverage for the first 2 years (canyons at the entrance, middle and exit of ne gulf with respect to the general along-slope circulation, head and mid-canyon depths, adjacent open slope). From late 1995 nwards, this design was reduced to the two mid-canyon moorings at the entrance and exit of the gulf. Monthly fluxes and hourly emperatures and currents were recorded at 500 m (30 m above bottom, mab) in the canyon heads, at 500 and 1000 m (respectively 30 and 30 mab) nominal depths at the mid-canyon sites, and at 750 m (30 mab) open slope.

This study aims at describing the spatial, seasonal and interannual variability of flux intensity and composition of settling articles, and at analyzing the role of diverse forcings in the control of particle exchange across the margin. Results from the first years (1993–2001) show that total mass fluxes – in the 10^1–10^4 mg m^{-2} d^{-1} range – increase along slope, particularly for the ear-bottom traps, between the NE (Planier Canyon) and the SW (Lacaze-Duthiers Canyon) limits of the Gulf of Lions, indicating n increased shelf export of particulate matter in the western part of the system. Bulk chemical composition (organic matter, arbonate, opal and lithogenic fraction) remained rather stable during the course of the experiment, tending towards values typical f superficial shelf sediments at higher mass fluxes. First-order calculations using a simple two-component mixing model suggest a ecreasing contribution of primary particles settling out of the overlying waters to the total flux from the entrance towards the exit f the system. Particulate material transferred to the deeper slope in the southwestern part of the Gulf of Lions appears therefore to redominantly originate in resuspended shelf and/or upper slope sediment. Downward particle fluxes and potential forcing arameters exhibit a high seasonal variability, with higher values from late autumn to early spring. Furthermore, unprecedented inter flux peaks observed in 1999 dominated the interannual differences, which otherwise were quite limited. Correlations etween sources of particulate material on the shelf (i.e., river and atmospheric inputs, phytoplankton biomass and sediment

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oi:10.1016/j.margeo.2006.09.003

resuspension), cross-slope exchange mechanisms (derived from in situ temperature and current records) and flux data indicate a predominant effect of dense cold water cascading on the exchange of particulate matter between the shelf and the slope.

Keywords: particle flux; continental margin; organic carbon; interannual variability; resuspension; NW Mediterranean

1. Introduction

Continental margins represent buffer zones between the continent, the open ocean and the atmosphere. They act both as a sink for particulate matter supplied by continental inputs (riverine and atmospheric) and biological production, and a source for the adjacent open ocean. From a biogeochemical viewpoint, assessing how shelves concentrate and export organic particulate matter to the open ocean is a necessary step to estimate their influence in the global carbon cycle (Liu et al., 2000). From a geological viewpoint, knowledge on the fate of particles is needed to investigate the present impact of coastal sediment dispersal in the formation of strata in deeper slope and basin environments (Nittrouer and Wright, 1994). It also helps to better understand how environmental conditions can be archived in the sediment record, an aspect of major importance in disentangling recent climatic and oceanographic evolution of the Earth.

Over the last two decades, knowledge on the present export of shelf particulate matter to the slope essentially derived from measurements of downward particle fluxes by sediment traps (e.g., Biscaye et al., 1988; Monaco et al., 1990; Biscaye and Anderson, 1994; Puig and Palanques, 1998; Antia et al., 1999; Heussner et al., 1999; McCave et al., 2001; Fabres et al., 2002; Iseki et al., 2003). All these experiments used basically the same strategy: weekly to monthly fluxes were measured at single locations or along transects and from short-term process studies to longer times scales, generally an annual cycle. Such observations allowed building a picture of horizontal and vertical gradients and seasonal variability of flux characteristics (intensity, composition). Monitoring of particle fluxes over several years has been largely restricted to the open ocean and was or is largely intended to evaluate variations in the export of carbon to the deep realm, a mechanism that contributes to the regulation of CO_2 exchange between the atmosphere and the sea (e.g., Deuser et al., 1995; Karl et al., 1996; Wong et al., 1999; Conte et al., 2001; Unger et al., 2003; Waniek et al., 2005). On continental margins however studies covering more than one annual cycle are more than scarce (e.g., Thunell, 1998), despite their fundamental importance in the characterization of shelf–slope exchange variability and the understanding of the factors controlling these fluctuations.

In the Gulf of Lions, a temperate continental margin of the northwestern Mediterranean Sea (Fig. 1a), several multidisciplinary studies such as the French ECOMARGE programme and its European extensions EUROMARGE-NB and MTP II-MATER unveiled a variety of factors that could potentially influence the pathways and observed spatial and temporal variabilities of particle export to the open ocean (Monaco et al., 1990, 1999; Durrieu de Madron et al., 1999; Flexas et al., 2002; Van Wambeke et al., 2002). These studies suggested that flux variations on the slope respond to the major particulate sources feeding the shelf and particularly to physical transport mechanisms. In order to improve the quantification of the particle flux towards the intermediate and deep layers of the adjacent basin, and also to validate and better understand the effective role and the recurrence of the exchange processes, two consecutive experiments have been carried out since 1993. A network of 3 sites distributed over the whole slope was first instrumented with an extended array of 7 moorings (Fig. 1b). This 2-year experiment was designed to describe horizontal and vertical variations of flux and particle composition at the local scale, within and outside canyons, and at a larger scale, by comparison of fluxes at several locations along the slope. The deeper moorings at both ends of the gulf were maintained to provide a long-term monitoring of downward fluxes (current duration: 13 years). This unique time series, part of three consecutive European projects (Euromarge-NB, MTP II-MATER and EUROSTRATAFORM) and the French PNEC (Programme National Environnement Côtier), was completed with contemporaneous information on the variability of major sources of particulate matter on the shelf, and physical exchange processes. The aim of the latter study was to describe the interannual variability of downward particle fluxes on the slope and that of potential forcing parameters (sources, physical exchange processes), and to possibly discriminate the forcings responsible for the major flux events

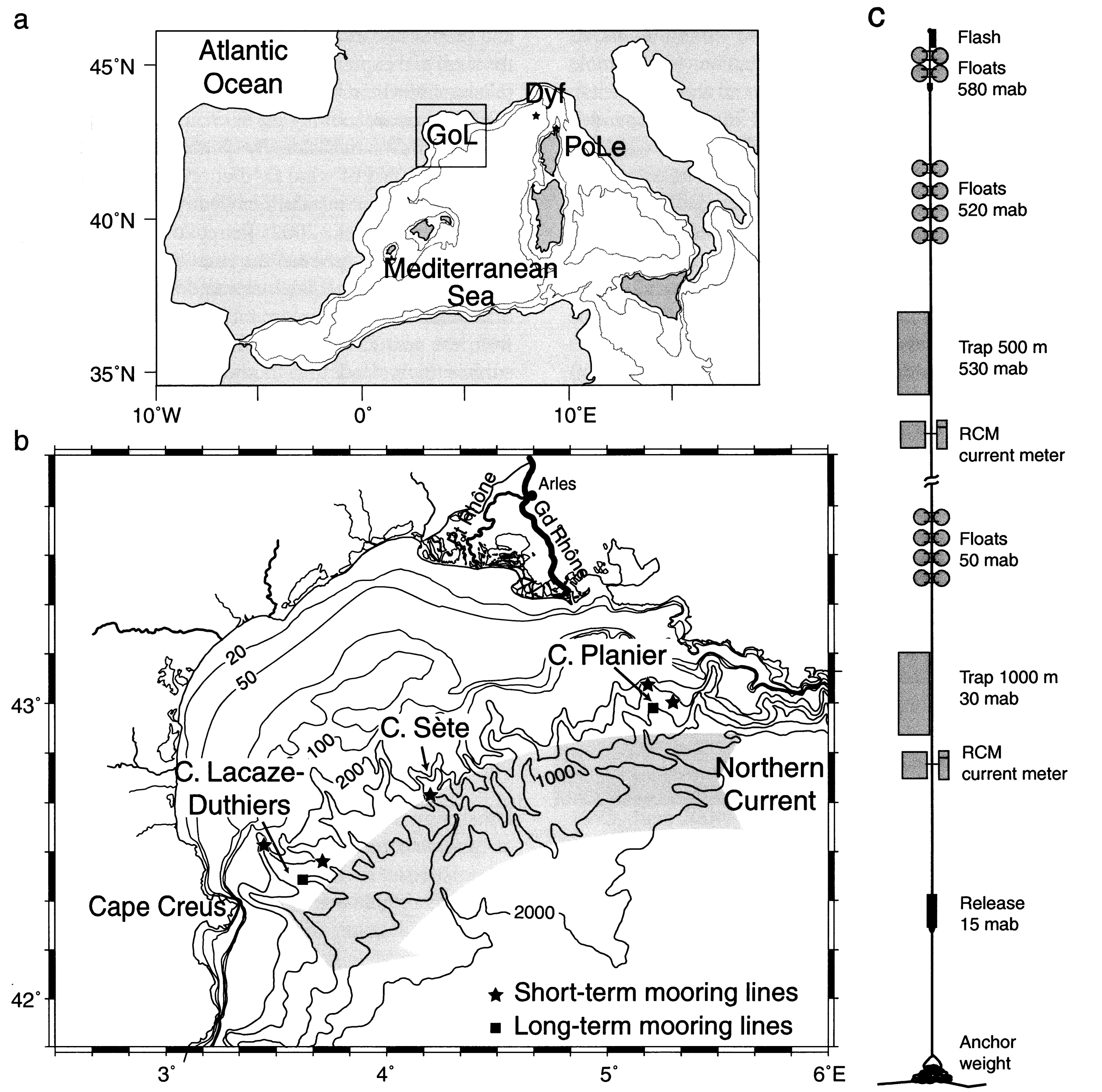


Fig. 1. (a) Location of the Gulf of Lions (GoL) in the Northwestern Mediterranean Sea. Stars indicate the DYFAMED site (Dyf) in the Ligurian Sea and the Ponte Leccia site (PoLe) in Corsica. (b) Location of the sediment trap/current meter moorings in the Planier Canyon, Sète Canyon and Lacaze-Duthiers Canyon on the continental slope of the Gulf of Lions (Northwestern Mediterranean Sea). Black stars represent the position of moorings during the short-term experiment (Oct. 1993–Nov. 1995) and black squares the long-term moorings (Oct 1993–June 2001). The large grey arrow underlines the mean path of the along-slope general circulation (Northern Current). (c) Sketch of the sediment trap/current meter mooring configuration used during the long-term experiment.

observed. The long-term monitoring was also intended to provide a temporal framework (i.e., "usual" versus "unusual" years) into which shorter, process-oriented experiments could be placed, as for example the High Frequency Flux Experiment, part of MTP II-MATER (e.g., Flexas et al., 2002; Van Wambeke et al., 2002).

2. Regional setting

The Gulf of Lions continental margin presents a crescent-shaped shelf and an upper slope indented by about ten submarine canyons (Fig. 1b). Several sources feed the shelf waters with particulate matter: riverine (primarily the Rhône River discharge) and atmospheric (primarily Saharan dust deposition) contributions of continental origin, biological production, and particle resuspension (freshly deposited material and sediments). Due to the predominance of river inputs, suspended particle concentrations present a strong, seaward-decreasing gradient all year round, nevertheless with a marked seasonal variation (Fig. 2). The distinct surface turbid layer, which extends over the shelf edge and slope, is largely composed of biological material. Conversely, the bottom turbid layer, which extends to the shelf edge, is mostly lithogenic (Aloïsi et al., 1982; Durrieu de Madron and Panouse, 1996).

A permanent along-slope current (Northern Current) and a mean shelf circulation appear to transport suspended matter in a general cyclonic (counter-clockwise) direction (Millot, 1990). During periods of high river discharge and major southeastern storms, river plumes and shelf water are primarily advected cyclonically along the shelf and exported at the southwestern end of the gulf (Ulses, 2004). In addition, other cross-shelf transport mechanisms are moving particles across the shelf break. Shallow flows occasionally penetrate over the shelf under the effect of wind (Millot, 1990; Estournel et al., 2003) and current instabilities (Durrieu de Madron et al., 1999; Flexas et al., 2002; Petrenko et al., 2005), and exchange matter between the shelf and the open sea. In winter, cold continental winds and air–sea temperature difference induce an important evaporation and heat loss from the sea. The sustained cooling and mixing of the surface layer lead to a homogenisation of the water column and the formation of dense, cold waters on the shelf that cascade down the slope (Durrieu de Madron and Panouse, 1996; Tusseau-Vuillemin et al., 1998;

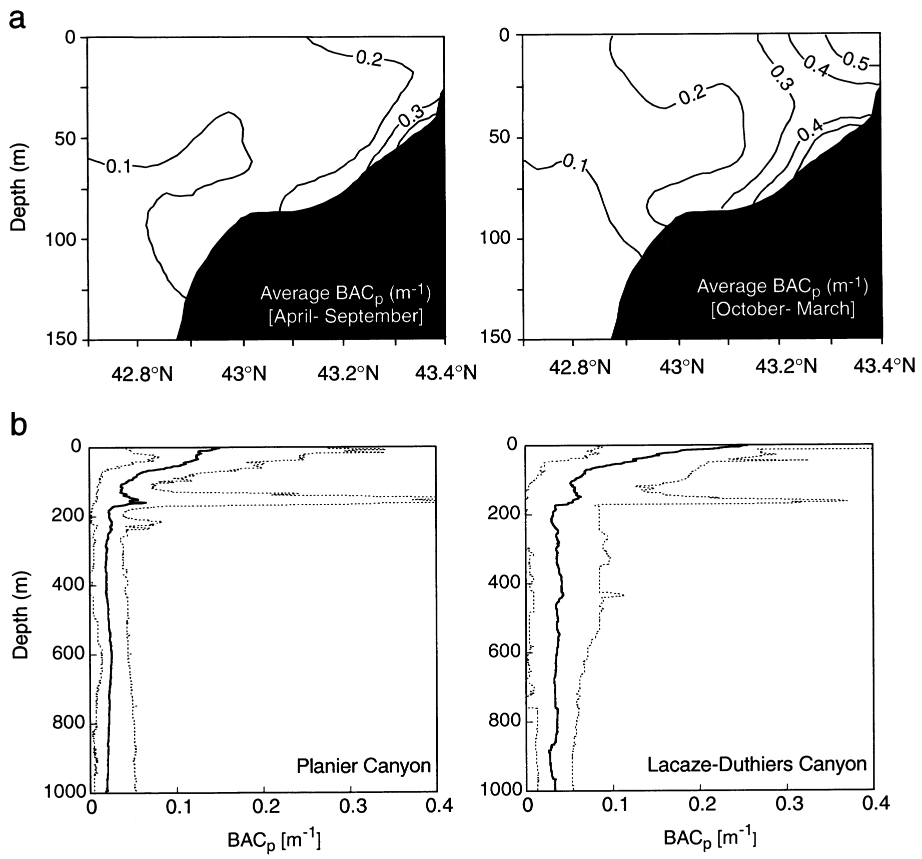


Fig. 2. (a) Seasonal distribution of suspended particulate matter concentration (particulate beam attenuation coefficient, BAC_p) across the shelf and slope of the Gulf of Lions. The "summer" (April–September) composite transect averages 644 stations and the "winter" (October–March) composite transect averages 609 stations collected between 1993 and 2004. (b) Average values (solid line) and range (dashed lines) of suspended particulate matter concentration (particulate beam attenuation coefficient, BAC_p) measured between 1993 and 1999 in the vicinity of the 1000 m moorings in the Planier and Lacaze-Duthiers canyons. The intermediate nepheloid layer around 150 m is the extension of the bottom nepheloid layer on the shelf. The suspended particulate matter concentration (SPM in mg l^{-1}) can be derived from the particulate beam attenuation coefficient (BAC_p in m^{-1}) using the relation $SPM = 1.17 \times BAC_p + 0.17$ of Lapouyade and Durrieu de Madron (2001).

Dufau et al., 2004). This latter process appears to have a strong interannual variability (Béthoux et al., 2002).

Earlier ECOMARGE studies of particle fluxes conducted in 1985–86 within the Lacaze-Duthiers Canyon at the southwestern end of the gulf (Monaco et al., 1990), and in 1988–89 within the Grand-Rhône Canyon in its northeastern part (Monaco et al., 1999; Durrieu de Madron et al., 1999) showed that:

- The overall composition of settling particles collected above the shelf break depth (~ 150 m) was significantly different from material collected deeper. There was a clear biological contribution and flux peaks related to periods of surface biological production, especially in summer and autumn.
- Particulate matter trapped at deeper horizons was characterized by a more stable composition, with a major lithogenic contribution possibly related to resuspended sediments. Seasonal variability was apparent with larger fluxes in winter. It seemed to covary with that of major sources of particulate matter (river discharge) and physical forcing (winter convection, along-slope current intensity and mesoscale variability).
- Mean total mass fluxes on the slope increased with depth, indicating an increasing contribution of the lateral input of shelf and slope particles that accordingly dilute the material exported from shallower water layers.
- Fluxes inside the Grand-Rhône Canyon were larger than on the adjacent open slope, demonstrating, in the absence of enhanced local resuspension, a preferential transport of material within the canyon.
- Annual mass fluxes were 3–10 times higher at the southwestern end of the gulf than at its northeastern end. The limited variation in the chemical composition (major constituents) of the trapped material suggested that the particle reservoir feeding shelf–slope exchanges was homogeneous at the scale of the entire Gulf of Lions.

3. Material and methods

3.1. Field experiment

During the first phase of the experiment (1993–95) three sites were instrumented with 7 mooring lines within and outside the Planier and Lacaze-Duthiers canyons, respectively at the northeastern entrance and southwestern exit of the Gulf of Lions, and in the intermediate Sète Canyon (Fig. 1b). All moorings were equipped with one trap and current meter pair at roughly 30 m above bottom (mab hereafter). For the Planier and Lacaze-Duthiers sites, moorings were deployed at around 530 m water depth in the canyon head, 1000 m in the canyon axis at mid-slope, and 750 m on the open slope upstream of the canyons. The 1000 m canyon moorings were further equipped with one trap and current meter pair at 500 mab, to estimate vertical changes (Fig. 1). A single mooring was located at 1000 m depth in the Sète Canyon, roughly at mid-distance between the Planier and Lacaze-Duthiers canyons. All traps were PPS3 Technicap sediment traps: cylindro-conical in shape with a 0.4 m opening diameter (2.5 height/diameter aspect ratio for the cylindrical part) and equipped with 6 or 12 sampling cups (Heussner et al., 1990). They were coupled with Aanderaa rotor current meters (RCM 7 and 8) located 2 m below the traps (Fig. 1). Four 6-month deployments were realized between October 1993 and November 1995. Trap sampling interval was set at 14 d or 1 month (for the older trap version with only 6 sampling cups). Current meters recorded pressure, temperature, current speed and direction at 1-h intervals.

During the second phase of the experiment (1995–2001), only the mid-slope moorings within the axes of the Planier and Lacaze-Duthiers Canyons were maintained and serviced every 6 months. Trap sampling interval was set at 14 d until early 1997, and at 1 month from this time onwards. Current meters recorded pressure, temperature, current speed and direction at 1-h intervals.

Data are presented for the entire period October 1993–June 2001. The recovery percentage was satisfactory both for current meters (64 6-month time series out of a maximum of 71) and sediment traps (512 samples out of a maximum of 570). For the sake of convenience, the first phase will be thereafter referred as "short-term experiment" while the overall experiment will be referred as "long-term experiment".

3.2. Measurement of downward particle fluxes

3.2.1. Processing of sediment trap samples

A detailed description of the PPS3 sediment trap and the sample processing used during this experiment can be found in Heussner et al. (1990), and the main steps are therefore only summarized here. The trap sampling cups were filled before deployment with a buffered 5% (v/v) formaldehyde solution in 0.45 μm filtered seawater. This poisoning solution limits degradation of trapped particles, and prevents the mechanical disruption of swimming organisms ("swimmers") that occasionally enter the traps during sampling (e.g., Knap et al., 1996). After recovery, the cups were stored in the dark at 2–4 °C until they could be processed in the laboratory, within a maximum delay of a few months. After decantation of the supernatant, particles were wet-sieved through a 1 mm nylon mesh to retain the largest swimmers. Smaller ones were removed under a dissecting microscope using fine-tipped tweezers. Contrary to upper open-ocean trap samples (<500 m) that can be heavily contaminated by swimmers, it is worthy to note that biological contamination is a negligible problem in our slope traps. Most samples contained less than a few tens of individuals (predominantly copepods). Even though no check other than careful visual examination was performed, it can be considered that the bulk of swimmers was removed by this method, and that the "biological" contamination, if any, is negligible. The original samples were then precisely divided into subsamples for subsequent analyses using a rotary splitting method. Sample dry weights, from which total mass fluxes were calculated, were determined on four subsamples filtered onto 0.45 μm Millipore cellulose acetate filters, rinsed with distilled water to remove salts, and dried at 40 °C for 24 h. Overall precision for total mass flux, derived from a previous experiment under similar conditions, is around 7% (Heussner et al., 1999).

3.2.2. Quality check of downward particle fluxes

The use of sediment traps has contributed significantly to our understanding of particle transfer in natural environments, but questions remain about the potential bias in the measurement of downward particle fluxes. We therefore present here a brief quality assessment of our trap results by examining the hydrodynamic biases that could have been experienced by our instruments.

The mooring lines were maintained taut by the distribution of floats at the mooring head and along the line. Examination of the current meter pressure sensors showed that tilting and deepening of the canyon mooring line was insignificant even during strong current episodes (up to 80 cm s^{-1} on some very limited occasions). Mooring dynamics were computed for each line using actual current values. The results showed that tilting never exceeded a few degrees, i.e. with no detectable effect on the collection rate of cylindrical traps (Gardner, 1985).

Current statistics over the 8-yr period are given in Table 1. Mean speeds at the trap levels ranged from 1.3 to 3.4 cm s^{-1}. Maximum values were observed near-bottom in both canyons, but speeds were mostly lower than 10 cm s^{-1}, and rarely exceeded 15 cm s^{-1}. This latter value is generally considered as a threshold above which trapping efficiency of cylindrical traps strongly decreases (e.g., Baker et al., 1988). The cumulated time of current exceeding this threshold during the long-term

Table 1
Statistics on current speeds and frequency of observations (%) by velocity classes in the Lacaze-Duthiers and Planier Canyons over the 8-yr period (October 1993–June 2001)

	Planier 500 m	Planier 1000 m	Lacaze 500 m	Lacaze 1000 m
Number of observations	65795 (2825 d)	64560 (2690 d)	55226 (2301 d)	57790 (2408 d)
Minimum speed (cm s^{-1})	0.1	0.3	0.4	0.2
Maximum speed (cm s^{-1})	17.0	77.3	17.7	59.8
Mean speed (cm s^{-1})	1.3	2.5	1.9	3.4
Speed class :				
<5 cm s^{-1}	97.30%	88.29%	93.84%	76.63%
5–10 cm s^{-1}	2.53%	8.62%	5.76%	18.30%
10–15 cm s^{-1}	0.17%	2.24%	0.37%	4.16%
>15 cm s^{-1}	<0.01%	0.85%	0.03%	0.91%

experiment represented <1 d for the traps at 500 m and around 23 d for the 1000 m traps. These larger speeds occurred during bursts lasting several hours to a few days and affected only a few trap sampling periods. Local resuspension of sediments in the vicinity of the traps entrained by increased local current speed and followed by local deposition has been put forward as a mechanism susceptible to enhance "apparent" fluxes for traps located near to the seabed. Though such an artefact cannot be ruled out, it was certainly not an important bias during this experiment. Speeds high enough to entrain resuspension (>10 cm s^{-1}) represented only 3–5% of the total current record. Furthermore, such stronger currents, when they occur, affect larger parts of the slope for (e.g., Palanques et al., 2006-this issue). The sediment, once resuspended, is therefore advected laterally in the general direction of the currents, i.e. a situation that corresponds to a real transfer.

Three dimensionless parameters are important in the collection efficiency of cylindrical traps (Butman et al., 1986): (i) the trap Reynolds number, $R_t = uD/v$, where u is the flow velocity at the height of the trap mouth, D is the diameter of the trap mouth, and v is the kinematic viscosity (ratio of fluid viscosity to fluid density), (ii) the trap aspect ratio, and (iii) the ratio of flow speed to particle settling velocity. Only the effect of R_t can be checked since the trap aspect ratio is constant and particle settling velocities are variable and unknown. According to Butman et al. (1986) and US GOFS (1989), the collection efficiency of cylindrical traps (with aspect ratio >1) is expected to decrease over some range of increasing R_t for fixed values of the other two parameters. Trap Reynolds numbers were computed using averaged current intensity for each trap and each individual sampling period, and a constant temperature and salinity ($T = 13$ °C, $S = 38.5$, $v \approx 1.3 \times 10^{-6}$ m^{-2} s^{-1})

ıt each depth. The calculated mean R_t values varied between 3×10^3 and 40×10^3 (corresponding to current intensity of 1 and 13 cm s^{-1} respectively). Correlation coefficients between total mass flux and R_t were statistically not significant, except for the near-bottom Lacaze-Duthiers trap. The significant positive covariation calculated for the latter suggests that, at that depth, mass flux increased with R_t, that is the opposite from the expected effect due to a hydrodynamic bias. Since we were not able to detect unambiguously any of the supposed effect of R_t, we are inclined to consider that mass fluxes determined during the experiment were not significantly biased by the flow of water around the traps, and that the observed flux variability essentially reflected changes in downward particle transfer.

On two occasions at the Lacaze-Duthiers site, in February–March 1994 for the near-bottom trap in the canyon head and February–March 1999 for the near-bottom trap at 1000 m, the sampling cup overflowed due to very high fluxes and the excess material probably entered the following cup during the rotation of the carrousel. Thus, these consecutive flux values were respectively under- and overestimated, but with little effect on the overall statistics and results presented here.

3.2.3. Determination of major constituents

Replicate subsamples were filtered onto Whatman GF/F filters, rinsed with distilled water, and oven-dried at 40 °C. Total carbon was analyzed by combustion in a LECO CN 2000 analyzer. Organic carbon was analyzed in the same way after progressive, controlled acidification with 2 N HCl to remove carbonate. Organic carbon analysis can be problematic because of the difficulty in separating intimately associated organic and inorganic carbon phases, but it does not affect seasonal and interannual variations based on the consistent use of a given method (King et al., 1998). Organic matter content was estimated as twice the organic carbon content. Carbonate content was calculated assuming all inorganic carbon (total C − organic C) was $CaCO_3$ and using the molecular mass ratio 100/12. After filtration onto 0.45 μm Millipore filters, biogenic silica (opal) content was measured following the method of Mortlock and Froelich (1989). The siliciclastic residue was defined as the difference between total mass and the sum of biogenic components (i.e. organic matter, carbonate and opal). It includes quartz, feldspars, heavy minerals and aluminosilicate, and is generally referred to as the lithogenic fraction.

Changes in particle composition will be discussed hereafter based on average values. As the temporal variability of flux must be taken into account in the computation of the means, a flux-weighted mean content was computed for each constituent and each trap by weighting individual sample concentrations by their corresponding mass fluxes: $C_{fw}=\Sigma C_iF_i/\Sigma F_i$, where C_{fw} is the flux-weighted content for a given element, and C_i and F_i the measured content and mass flux for sample i. If the sampling interval is not constant, then it is also necessary to weight individual samples by the corresponding sampling duration to obtain a flux and time-weighted content: $C_{ftw}=\Sigma C_iF_iT_i/\Sigma F_iT_i$, where T_i is the sampling duration of sample i. This way of computing a mean yields a "true" average value equivalent to what would have been obtained if settling particles had been collected as a single sample during the averaged period.

3.3. Current meter derived variables

Variables, derived from current meter measurements, are used to characterize the major cross-slope transport processes. Monthly mean kinetic energy (MKE $=(\langle u\rangle^2+\langle v\rangle^2)/2$, where $\langle u\rangle$ and $\langle v\rangle$ are the average of the longitudinal and latitudinal components of the current), and eddy kinetic energy (EKE $=(s_u^2+s_v^2)/2$, where s_u^2 and s_v^2 are the variance of the longitudinal and latitudinal components of the current) were estimated from hourly current measurements. MKE is an indicator of the mean flow variability of the along-slope circulation, whereas EKE is an indicator of shorter current fluctuations, i.e. over periods of several days (e.g., meanders, current reversals, up/down oscillations along the canyon axis). In addition to the advection by the mean current, mixing induced by such shorter fluctuations represents a mechanism transporting particles across the slope (Durrieu de Madron et al., 1999). Temperature was used as an indicator of the magnitude of winter cooling and of dense, cold water cascading down the slope.

3.4. Complementary data sets

3.4.1. River inputs

More than ten rivers drain the area adjacent to the Gulf of Lions. The freshwater and particulate matter inputs are dominated by the Rhône River, in the northeastern part of the area, which delivers >80% of the total discharge (Aloïsi et al., 1977). Consequently, variations of the solid discharge provided by that river to the Gulf of Lions during the experimental period were used as a template. It was calculated using the daily water discharge measured at Arles (50 km upstream of the river mouth, Fig. 1b) by the Compagnie Nationale du Rhône and the suspended sediment concentration–water discharge regression derived by Sempéré et al. (2000).

3.4.2. Sediment resuspension

We consider here sediment resuspension associated to storms that generally act at the scale of the entire gulf and mobilize large amounts of sediment within short periods of time (Ferré, 2004; Ulses, 2004; Ferré et al., 2005). Wave-induced bottom shear stress was used to characterize the stormy periods and as an index of potential sediment resuspension. Bottom stress was calculated using the Swart (1974) equations for a water depth of 33 m, which is approximately the maximum influence depth of the average wave regime in the Gulf of Lions. The 6-hourly wave characteristics (significant wave height, wave period) were provided by the Météo-France VAGMED model and averaged over the Gulf of Lions shelf area. These data were available only from April 1996 onwards.

3.4.3. Atmospheric inputs

Saharan dust is the major source of atmospheric particulate inputs to the Mediterranean Sea (Löye-Pilot et al., 1986; Bergametti et al., 1989; Löye-Pilot and Martin, 1996). As atmospheric deposition was not documented for the Gulf of Lions during the 1993–2001 period, we approximated the dry and wet atmospheric deposition with measurements made in Ponte Leccia (Corsica, Fig. 1a) by M.D. Löye-Pilot (personal communication). It is worthy to note that during a survey performed in 2001–2002, time series of bulk atmospheric deposition in Ponte Leccia and near Cape Creus showed close seasonal patterns (Loÿe-Pilot, unpublished data). Absolute fluxes at the SW exit of the Gulf of Lions were however roughly 1/3 of that measured in Corsica, indicating that the Ponte Leccia values retained for the present study probably represent an upper limit.

3.4.4. Biomass

Spatial and temporal variabilities of primary production on the continental shelf of the Gulf of Lions are high (Lefevre et al., 1997; Diaz et al., 2000). In the absence of regular measurements during the 1993–2001 period, we used the depth-integrated chlorophyll-a time series available at the DYFAMED site in the Ligurian Sea (about 200 km upstream, east of the Gulf of Lions, Fig. 1a). Measurements made during 2 years (Oct 1997–Sep. 1999) at the shelf edge north of the Planier site provided similar results (P. Raimbault, unpublished data). Also, in their study derived from SeaWiFS observations, Bosc et al. (2004) showed very similar seasonal and interannual patterns of algal biomass and primary production between the Ligurian Sea and the Gulf of Lions between September 1997 and December 2001. Annual primary production during these 4 years was, on average, around 15–20% higher in the Gulf of Lions. Thus, despite the fact that the DYFAMED permanent station is an open-ocean site, it represents the best available reference point for the seasonal and interannual variability of phytoplankton biomass in the Northwestern Mediterranean.

3.5. Statistical analysis

3.5.1. Processing of time series

The raw time series, which had different regular or irregular time steps (from hourly to monthly periods) and occasionally presented gaps, were transformed into regular and continuous time series. This preliminary regularization was necessary to perform the subsequent time series analyses. A common time step of 1 month, corresponding to the largest sampling period of the sediment traps, was chosen for all time series. Data from each series were accordingly pooled and averaged

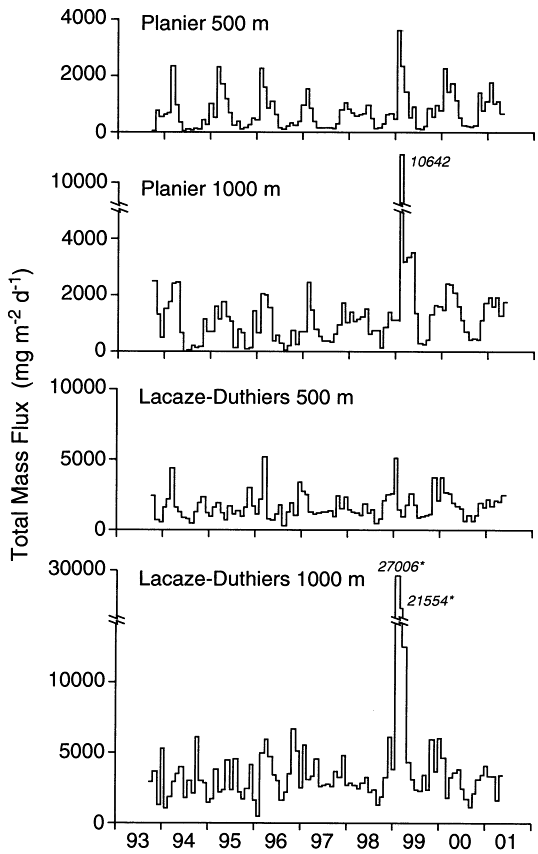


Fig. 3. Time series of total mass flux (mg m^{-2} d^{-1}) of downward settling particles collected by sediment traps during the course of the long-term experiment in the Planier and Lacaze-Duthiers Canyons, at depths of 500 m and 1000 m (30 mab). Note the changes in vertical scale. *Flux values respectively under- and overestimated, due to the overflowing of the first receiving cup into the second.

over successive monthly periods. Small gaps in total mass fluxes (e.g., the 15-d interval between two consecutive deployments) were linearly interpolated, while larger gaps (up to 7 months at the Planier site, i.e. a complete deployment period missing) were filled using flux values calculated from the overall linear relationship between total mass fluxes from the two traps at this site. Regarding the chemical composition of settling particles, no attempt was made to fill the existing gaps.

Although this averaging approach smoothes the high frequency signals (typically pulses), it generally appears adequate to describe and compare the seasonal and interannual variability of all signals, except temperature. A specific processing was used for the latter to keep track of the significant, but brief cooling events that otherwise would have disappeared during the regularization step. We therefore choose the minimum temperature recorded during each monthly period as an indicator of the magnitude of the downslope cascading of dense cold water.

3.5.2. Correlation analysis

The degree of dependence between time series was expressed by Pearson correlation coefficients. They were calculated on the one hand between total mass fluxes determined by each trap and the sources, common to all traps, and, on the other hand, between total mass fluxes and the physical exchanges processes, specific to each trap. It is assumed that monthly particle fluxes are in phase (i.e., no time lag) with forcing variables. This relies on the fact that shelf dynamics respond quickly to meteorological forcing (Estournel et al., 2003; Ulses, 2004) and that the residence time of shelf waters is <1 month (Durrieu de Madron et al., 2003). Correlation assumes a linear relationship between times series, and given the high scattering of data due in particular to a few peculiar events, data were Log-transformed to compress scale at both ends of the distributions and straighten the relationship. An effective 2-year sample size (window) was used to examine temporal variations in the strength of the linear correlations for the long-term time series. The statistical significance of the relationship for any of the 4 sub-periods was tested. Correlation significance was evaluated on the series (population) of time-windowed correlation coefficients, and adjusted using the "Bonferroni adjustment" to compensate for the increased likelihood of observing high correlations where no relation exists. When the population correlation was non-zero, we estimated for which sub-period the relationship was significant.

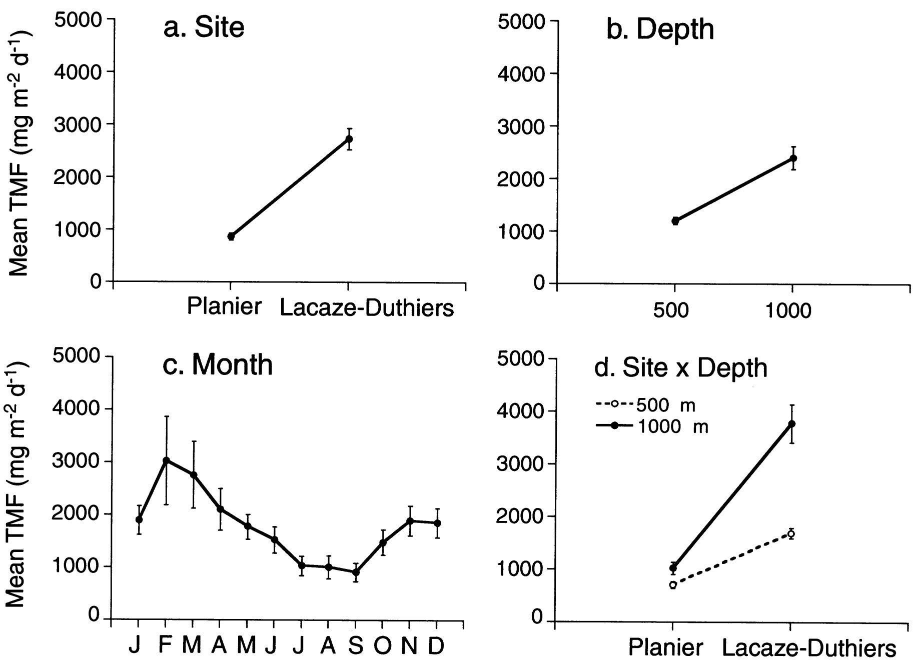


Fig. 4. Composite mean total mass fluxes (±1 SD) resulting from the multiway ANOVA performed on the entire 8-yr data set. Years were used as replicates. (a) site effect (Planier versus Lacaze-Duthiers), (b) trap depth effect (500 and 1000 m), (c) month effect, (d) site x depth interaction for the 500 m and 1000 m traps.

4. Results

4.1. Temporal and spatial variability of downward particle fluxes

The regularized monthly fluxes for the 4 traps deployed within the axes of the Planier and Lacaze-Duthiers Canyons are depicted in Fig. 3. Downward fluxes exhibited a strong variability, both temporal and spatial. The first point worthy to note is the temporal signal, demonstrated by the upper trap at the Planier site. Downward fluxes there, generally the lowest of all determined fluxes, clearly followed a similar annual pattern, in terms of timing and magnitude. For the other traps, and especially for the near-bottom trap in the Lacaze-Duthiers Canyon, short-term variability (i.e., from one sample to the next) confused this seasonal signal. Another important temporal feature concerns the major flux event that affected 3 of the 4 traps (except the Lacaze-Duthiers 500 m trap) during winter 1999. Relatively limited in the Planier upper trap, this event affected up to 3 collection periods (i.e., up to 3 months), and provided a quantity of matter comparable to that collected during one full, "normal" year. Finally, spatial variability was apparent across the region, with local flux increase from the upper to the lower trap and from the entrance (Planier site) to the exit (Lacaze-Duthiers) of the Gulf of Lions.

To examine closer the factors responsible for the observed flux variability, a multi-factorial ANOVA was conducted on monthly total mass fluxes. Three fixed factors – site, depth and month of collection – were considered, with the different years as replicates (Fig. 4 and Table 2). This statistical analysis confirms the visual examination of the data and further allows determining the respective contribution of the considered factors to the overall variability. On average, total mass flux increased from 869 mg m^{-2} d^{-1} in the Planier Canyon to 2736 mg m^{-2} d^{-1} in the Lacaze-Duthiers (Fig. 4a). With a ×3 increase and a 17% contribution to the overall variance, the site effect (i.e., entrance versus exit of the gulf) represents the main explained source of flux variation in the Gulf of Lions (Table 2). The depth effect was also highly significant, with an average mass flux increase from 1201 mg m^{-2} d^{-1} at 500 m to 2404 mg m^{-2} d^{-1} at 1000 m (Fig. 4b). This two-fold increase represented 7% of the overall variance. The third significant factor is the month of collection, which contributed 8%. Mean total

Table 2
Results of the multi-factorial ANOVA performed on total mass fluxes measured on the continental slope of the Gulf of Lions during the long-term experiment (upper box) and excluding the unusual year 1999 (lower box)

Overall long-term experiment (1993–2001)					
Factors	*DF*	SS	% total variability	*F*	p
Trap site	1	3.15E+08	17	86.3	<<0.001
Trap depth	1	1.30E+08	7	35.5	<<0.001
Month of collection	11	1.43E+08	8	3.6	<0.001
Site x depth	1	7.05E+07	4	19.3	<<0.001
Site x month	*11*	*8.43E+06*	*0*	*0.2*	*0.99*
Depth x month	*11*	*2.22E+07*	*<1*	*0.5*	*0.87*
Site x depth x month	*11*	*1.22E+07*	*<1*	*0.3*	*0.99*
Residual (unexplained)	320	1.17E+09	63		
Total	367	1.87E+09	100		

Long-term experiment without 1999					
Factors	*DF*	SS	% Total variability	*F*	p
Trap site	1	2.14E+08	44	332.1	<<0.001
Trap depth	1	6.04E+07	12	93.7	<<0.001
Month of collection	11	3.83E+05	<1	6.5	<<0.001
Site x depth	1	3.60E+07	7	55.9	<<0.001
Site x month	*11*	*9.90E+04*	*0*	*1.7*	*0.08*
Depth x month	*11*	*5.49E+04*	*0*	*0.9*	*0.51*
Site x depth x month	*11*	*4.63E+04*	*0*	*0.8*	*0.65*
Residual (unexplained)	272	1.75E+08	36		
Total	319	4.86E+08	100		

Three factors were considered: the trap site (Planier versus Lacaze-Duthiers), the trap depth (500 versus 1000 m), and the month of the year. Years were taken as replicates. The table presents the factors and the interactions among factors (plain numbers are significant, italics are not), the degree of freedom (*DF*), the sum of squares (SS), the contribution to the overall variability of fluxes, the *F* value and its probability *P*.

mass fluxes exhibited a clear seasonal signal, with a maximum flux in February and a minimum in September (Fig. 4c). A Tukey Post Hoc test was performed to specify internal differences between the 12 monthly means. It distinguished 3 groups of months: the first includes February and March that exhibit significantly higher mean fluxes; a second group comprises July, August and September with the lowest mean fluxes; and the third group contains all remaining months whose means could not be distinguished. Finally, among the different possible interactions between factors, only the Site x Depth interaction was significant (Fig. 4d). Mean total mass flux increase between the Planier and the Lacaze-Duthiers sites was significantly more important for the near-bottom traps at 1000 m (from 1037 to 3751 mg m^{-2} d^{-1}, i.e. a × 3.6 increase) than for the traps at 500 m (from 721 to 1701 mg m^{-2} d^{-1}, i.e. a ×2.4 increase). The Tukey test distinguished again 3 groups: Planier 500 m and 1000 m, Planier 1000 m and Lacaze 500 m (thus overlapping the first group), and, the isolated mean flux for the Lacaze 1000 m trap.

However, the overall explained source of variance described by this analysis reaches only 37% (including the non significant interactions), which means that over 60% of the total observed flux variance remains unexplained and has to be attributed to other factors than the three considered here. One obvious supplementary source of variability is the interannual one, which has not been taken into consideration since years were used as replicates. The above-mentioned strong flux event during winter 1999 largely contributed to increase the overall variability. Consequently, a second 3-way ANOVA was performed, excluding the 1999 data (Table 2). The significant factors remain unchanged but the model explained 64% of the variance, essentially with a strong increase of the site effect (from 17 to 44%).

Seasonal flux patterns for each trap were computed from the 8-yr time series (Fig. 5a). All 4 traps exhibited a similar pattern in total mass fluxes, showing an essentially unimodal distribution, with maximum fluxes in late winter (February to April), and minimum fluxes in summer (July to September). The Lacaze-Duthiers 500 m trap was somewhat different from the others in that it was the only one that did not peak in February. This situation largely resulted from the absence of flux peak in 1999. Differences between the seasonal patterns essentially concerned the relative span between winter maxima and summer minima, which was around an order of magnitude in the Planier Canyon traps (11.7 and 8.3 respectively at 500 m and 1000 m) but reduced to a factor of 3 in the Lacaze-Duthiers traps (respectively 1.8 and 2.7).

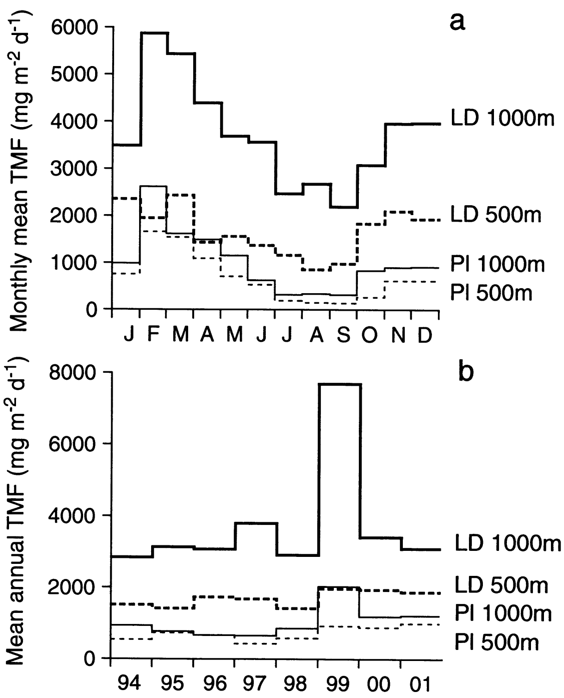


Fig. 5. Seasonal and interannual variability of total mass fluxes on the slope of the Gulf of Lions. (a) monthly means (in mg m^{-2} d^{-1}) for the four traps, (b) annual means; the integration period runs from October of the previous year to September. Pl: Planier Canyon (entrance of the gulf); LD: Lacaze-Duthiers Canyon (exit of the gulf).

Differences in annual mass flux means were, surprisingly, quite limited apart from the exceptional year 1999 (Fig. 5b). Interannual variability expressed as the ratio of the highest to the lowest annual mean was 2.3, 3.1, 1.4 and 2.7 for the Planier 500 m, Planier 1000 m, Lacaze-Duthiers 500 m and Lacaze-Duthiers 1000 m respectively. Again, the mid-water trap at the exit of the Gulf of Lions showed a slightly different pattern from the other 3. Fluctuations of the annual means around the overall mean of each time series were less than 40% for the Planier traps and 25% for the Lacaze-Duthiers traps. Downward particle fluxes over the considered 8-yr period are thus more constant at the exit of the Gulf of Lions than at the entrance. Another interesting point is that, for two consecutive years (1995–1996), mean annual fluxes were virtually equivalent between the two Planier traps, i.e. no flux increase with depth was observed. These statistics further give indication of some potential, longer-term trends in the annual means. Though the time series are obviously too short to draw any firm conclusions it is worth mentioning that, except for the near-bottom trap in the Lacaze-Duthiers, the last 3 years of each time series (1999–2001) represented the highest observed values.

Finally, with its extended array of moorings, the short-term experiment (1993–1995) allowed us to get a closer view of the spatial variability of total mass fluxes at different scales (Fig. 6). At the local scale, i.e. inside each canyon, traps deployed at the same 500 m depth (canyon head versus mid-canyon) showed a similar seaward decrease of annual mass fluxes by a factor of ~6 in both sites. This seaward decrease was slightly less pronounced in near-bottom fluxes with a factor of 3–4. Such spatial trends were to some extent modulated at the seasonal scale. Indeed, the decrease in mean flux from the canyon head to the 1000 m trap in the canyon axis was highest during "summer" (i.e. April to September) in the Planier Canyon, but during "winter" (i.e. October to March) in the Lacaze-Duthiers. During these 2 years of extended survey, fluxes at mid-water depth (500 m) were on average about half the near-bottom ones. Near-bottom fluxes on the Planier open slope were slightly higher than their counterpart in the canyon axis at 1000 m, indicating no preferential transfer within the canyon at the entrance of the gulf. On the contrary, fluxes on the open slope upstream the Lacaze-Duthiers Canyon were about only half that within the canyon. At the scale of the entire gulf, fluxes significantly increased westward, a feature that remained permanent during the long-term experiment as already mentioned above. Annual mean fluxes for similar locations (canyon head, mid-canyon, mid-depth) generally increased by a factor of 2 to 4 from the Planier site towards the Lacaze-Duthiers, with some marked seasonal differences (e.g., more than a 10-fold increase in summer means, but only 2-fold in winter for the near-bottom trap at 1000 m in the axis). The near-bottom flux in the Sète Canyon was similar to that in the Lacaze-Duthiers during winter but only half during summer, indicating that the increasing trend from the eastern entrance towards the southwestern exit was not constant, but season-dependent. The increase was less (about 2) for open-slope fluxes.

4.2. Trends in the composition of settling particles

The particulate material collected by traps was composed of grey to yellow brown, fine-grained particles. In the mid-water traps at 500 m, and for samples with low mass fluxes the texture was generally coarser, fluffier and more aggregated. Grain size analysis performed on sonicated samples at mid-water (500 mab) and near-bottom levels (30 mab) within the canyon axis

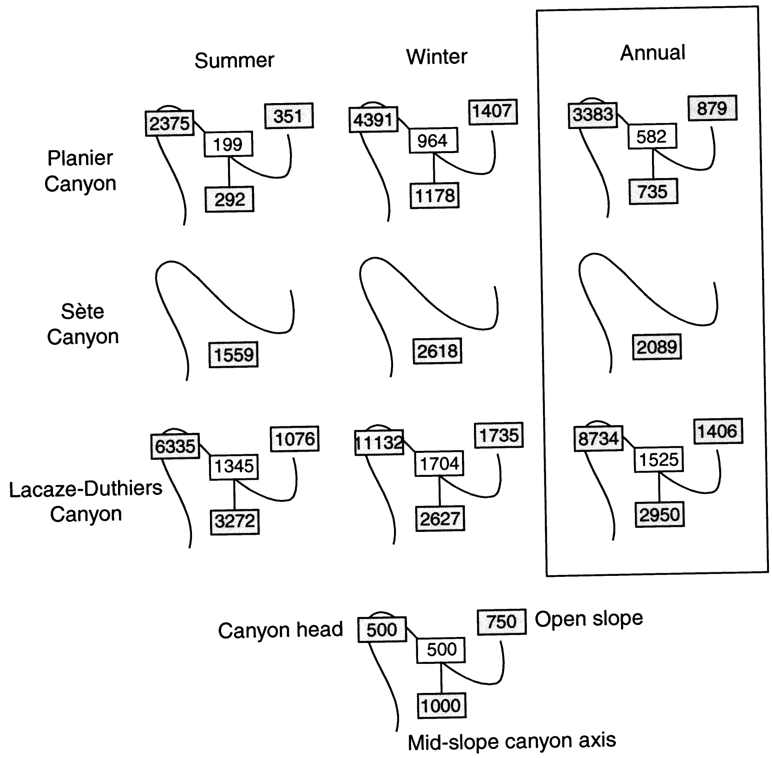


Fig. 6. Seasonal and annual mean mass fluxes (mg m^{-2} d^{-1}) for the different mooring sites during the short-term experiment (1993–1995) on the Gulf of Lions slope. The lower sketch represents the experimental design with trap locations and depths. The winter season runs from October to March, the summer season from April to September.

indicated that 10 to 30% of primary components of larger, aggregated particles were clays (<4 μm) and two major modes systematically appeared around 7 μm and 17 μm. D50 was around 8 μm at mid-water depth and 7 μm near the bottom.

Faecal pellets were present in all samples but presented generally only a small fraction (a few %) of total mass. The bulk of material was therefore essentially amorphous. Scanning Electron Microscope observations of selected samples showed the presence of typical components such as clay particles, and grains of quartz, feldspars and calcite embedded in an amorphous organic matrix. Biogenic components were essentially of planktonic origin, and were dominated by siliceous (diatoms) and calcareous (coccoliths) remains. Coccoliths always appeared more aggregated and less degraded than diatoms. Samples from periods of higher organic content were further characterized by the presence of large organic sheets, or films.

Time series of the bulk chemical composition of settling particles (major constituents) underline the predominant lithogenic content in all traps (Fig. 7). The range of individual values extended from 36 to 74%, and the overall (all traps) flux-weighted mean was 62.5%, with quite limited differences in annual means or among traps (Table 3). Statistics of the three major biogenic components were the following: individual organic matter contents ranged from 2 to 24% with an overall flux-weighted mean of 4.1%, carbonate between 13 and 53% with a mean of 29.2%, and opal ranged from 1 to 16% with a mean of 4.2%. Temporal variability was quite important, but fluctuations did not describe a clear seasonal signal, with the noticeable exception of organic matter in the two 500 m traps. Values generally evolved within a limited range for each trap, a feature that was best exemplified by the near-bottom trap in the Lacaze-Duthiers Canyon. Several unusual peaks or troughs in contents occasionally disrupted this evolution. This was the case for example for low lithogenic contents in the Planier traps in 1994 (for a period of several months), in the Planier near-bottom trap at the end of 1996 (2 months), or in the Lacaze-Duthiers 500 m trap in 1997 (2 months), which were to be related to higher than usual values in the contents of other constituents. Conversely, organic matter contents peaked on several occasions (end of spring 1994 in both Planier traps, summer 1994 and summer 2000 in the upper Lacaze-Duthiers trap).

Spatial variability in the content of major constituents of settling particles, as shown for example by the detailed flux-weighted means from the short-term experiment (Fig. 8), was less important than temporal variability. The main spatial changes can be summarized

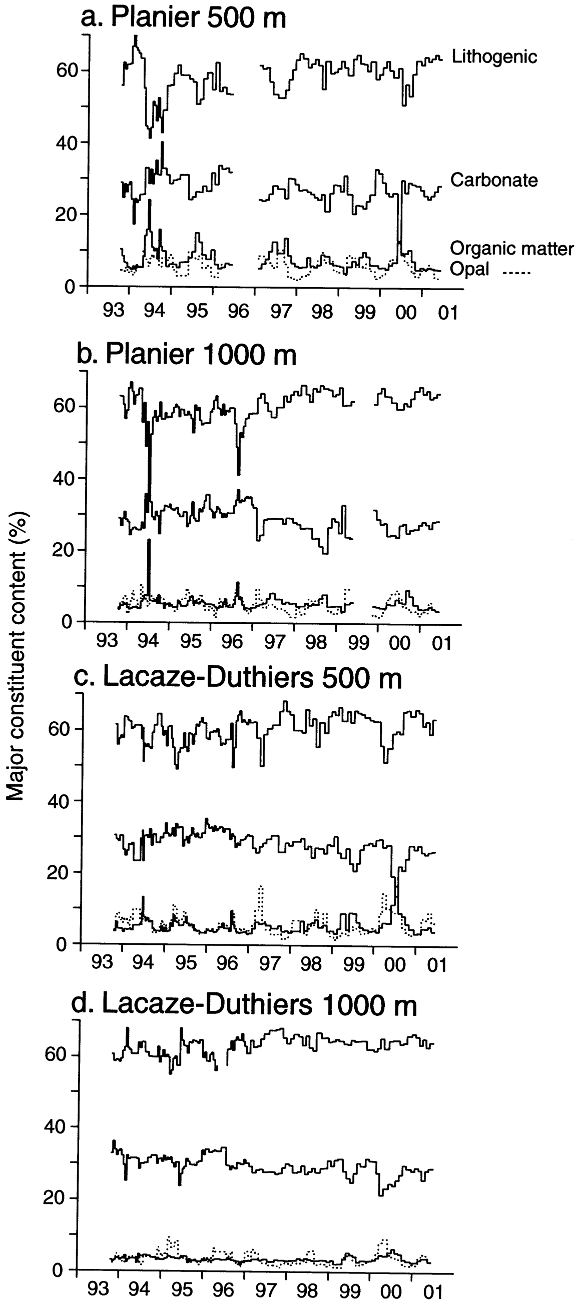


Fig. 7. Time series of the bulk chemical composition (%) of the trap-collected particles (major constituents: organic matter, carbonate, opal and lithogenic) during the course of the long-term experiment in the Planier and Lacaze-Duthiers Canyons on the slope of the Gulf of Lions.

in the following way: (i) a lithogenic content near the seabed slightly higher than at mid-water depth, and highest for the Lacaze canyon head trap, (ii) an organic matter content decreasing from the mid-water trap to the open slope trap, the 1000 m canyon trap and the canyon head trap, (iii) for a given trap position, an organic

Table 3
Annual mean total mass fluxes (in mg m^{-2} d^{-1}), flux-weighted mean biogenic (organic matter, carbonate, opal) and lithogenic contents (in %), and overall means of particles collected on the slope of the Gulf of Lions

		1994	1995	1996	1997	1998	1999	2000	2001	Overall
Planier 500 m	TMF	539	731	668	435	587	929	888	994	721±201
	O.M.	6.2	7.0	6.5	6.8	6.4	5.4	6.7	5.4	6.2
	Carb.	24.9	29.2	33.9	24.7	27.1	27.7	26.8	26.6	27.7
	Opal	5.2	6.9	6.2	8.2	4.0	5.0	5.8	4.5	5.6
	Lith.	63.7	56.9	53.4	60.3	62.5	61.9	60.7	63.5	60.5
Planier 1000 m	TMF	935	769	659	652	849	2035	1186	1211	1037±456
	O.M.	4.3	5.0	4.6	5.0	5.3	4.2	5.2	4.4	4.7
	Carb.	26.8	30.4	31.2	29.0	26.7	29.5	27.1	27.7	28.5
	Opal	6.0	5.6	4.5	5.8	4.0	4.7	5.1	3.7	4.8
	Lith.	62.9	59.0	60.2	60.2	64.0	61.6	62.6	64.2	62.0
Lacaze- Duthiers 500 mL	TMF	1519	1429	1743	1680	1428	1979	1951	1878	1701±225
	O.M.	5.1	5.2	3.9	4.0	4.7	5.1	5.9	4.6	4.8
	Carb.	28.0	30.5	32.0	30.3	27.4	27.1	27.3	26.3	28.5
	Opal	6.8	6.3	4.1	4.9	3.6	4.4	7.2	5.6	5.4
	Lith.	60.1	58.0	60	60.8	64.3	63.4	59.6	63.5	61.3
Lacaze-Duthiers 1000 m	TMF	2845	3137	3080	3809	2912	7707	3420	3099	3751±1627
	O.M.	3.6	3.4	3.2	2.8	3.3	2.8	4.2	3.2	3.2
	Carb.	32.3	30.0	32.2	29.4	28.7	30.5	28.1	28.5	30.0
	Opal	3.3	4.8	4.3	2.8	2.7	2.1	4.5	3.2	3.3
	Lith.	60.8	61.8	60.3	65.0	65.3	64.6	63.2	65.1	63.5

The annual integration period runs from October of the previous year to September.

matter content systematically higher in the Planier than in the Lacaze site (and lowest in the Sète Canyon axis), and (iv) for a given trap position, a lower carbonate content in the Planier (except for the canyon head) but a mixed pattern for opal. These main characteristics are also found in a quite similar way for annual means from the long-term experiment (Table 3).

Due to the relatively limited variation in the content of major constituents for each trap series (variation within a factor of 2 at the most, depending on constituent) in comparison with the much higher variations in individual total mass fluxes (from 1 to 2 orders of magnitude), time series of major constituent fluxes essentially mimicked fluxes of total mass and are therefore not shown. Some results concerning the interannual evolution of organic matter fluxes are, however, worthy to note. Overall mean fluxes for the entire experimental period, which can be derived from the data presented

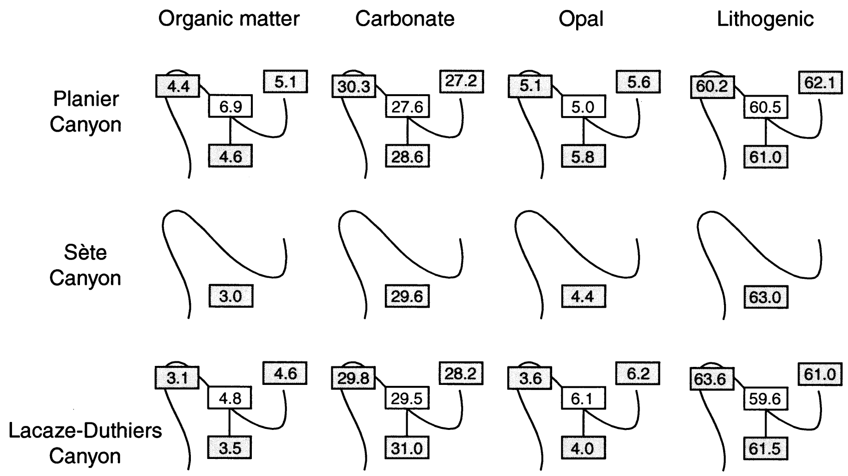


Fig. 8. Flux-weighted mean annual contents of the major constituents of particle fluxes for the Oct. 1993–Nov. 1995 period. Trap position and depth at each location is similar to Fig. 6.

in Table 3, were 45 and 49 mg m^{-2} d^{-1} for the upper and lower Planier traps respectively, and 82 and 120 mg m^{-2} d^{-1} for those in the Lacaze-Duthiers. Spatial trends at the scale of the entire gulf were similar to those found for total mass, but the increase factors were significantly less important (1.8 versus 2.4 for the 500 m traps, and 2.5 versus 3.6 for the near-bottom traps). This is even more noticeable at the local scale, with a moderate organic matter flux increase with depth in the Lacaze-Duthiers (×1.5 compared to ×2.2 for total mass), and virtually no increase between the 500 m and the 1000 m traps in the Planier Canyon. Strikingly, annual organic matter fluxes in the latter even decreased in 1995–1996, when mean annual fluxes were virtually equivalent between both traps. This specific depth behaviour of organic matter could relate to its degradation. Degradation with depth however can only be demonstrated when total mass flux increase is small enough or nonexistent so that lateral input of organic matter does not compensate for organic matter degradation.

4.3. Temporal variability of particulate matter sources on the shelf

River discharge, wave-induced bottom stress entraining sediment resuspension, bulk atmospheric deposition, and phytoplankton biomass provided proxies of particulate supply to the system. The fundamental characteristics of these variables at seasonal and interannual time scales are illustrated in Fig. 9. The first 3 sources were characterized by brief events (typically 1 d or less), which are respectively linked to floods of various intensities, southeastern storms and southern high altitude winds. Floods and southeastern storms were often concomitant. They

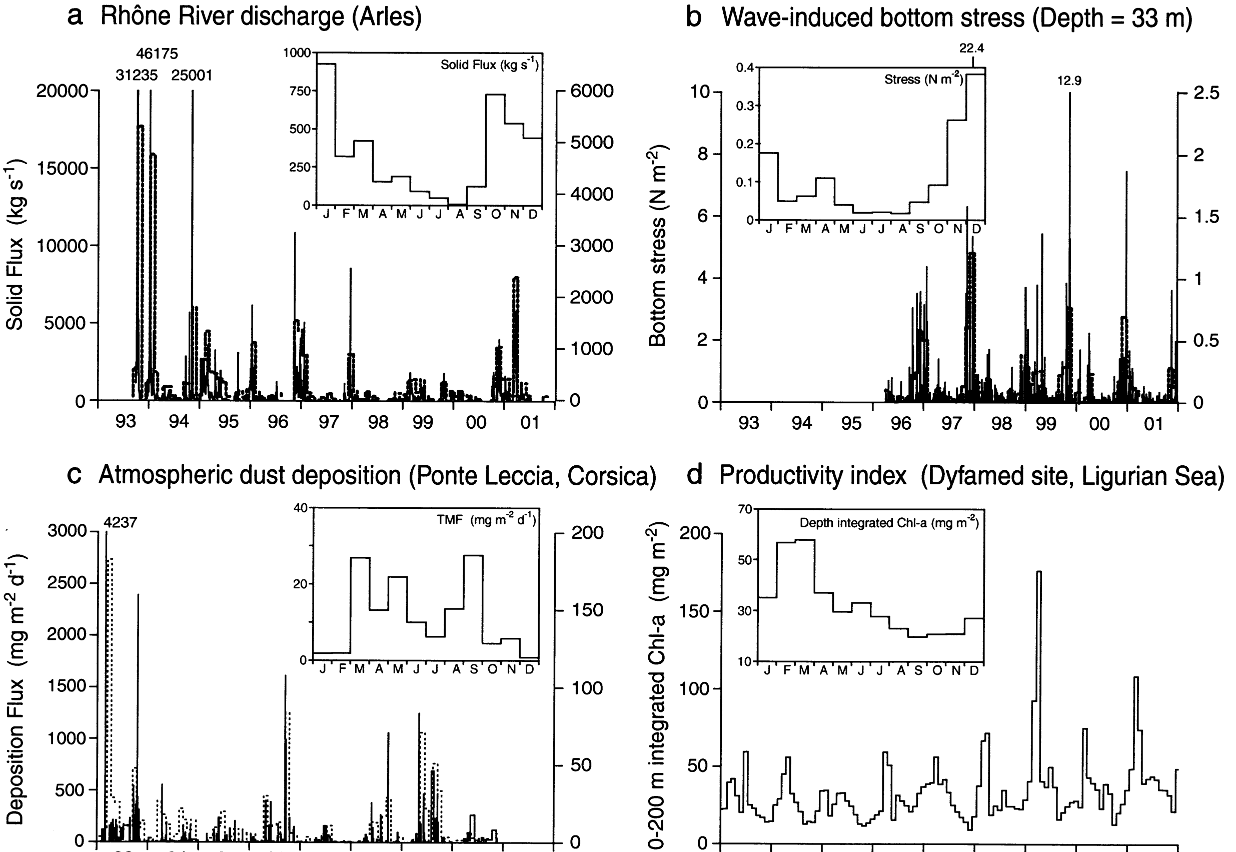


Fig. 9. Time series plots of particle sources (or proxies for sources) to the Gulf of Lions waters. (a) Rhône river solid discharge (kg s^{-1}) measured in Arles, (b) wave-induced bottom stress (N m^{-2}) for a depth of 33 m indicative of bottom sediment resuspension on the shelf, (c) atmospheric deposition (mg m^{-2} d^{-1}) of particulate matter collected in Ponte Leccia, Corsica (data from M.D. Loÿe-Pilot), and (d) integrated chlorophyll a content (0–200 m) at the DYFAMED site in the Ligurian Sea (data by courtesy of J.C. Marty) taken as a proxy of phytoplankton productivity in the NW Mediterranean. The dashed lines represent the regularized monthly data and are labelled according to the right axis. The inserts represent the monthly mean signals during a composite yearly period.

mostly arose during autumn and early winter, but their intensity strongly varied between years. The largest flood events were recorded in October 1993, and January and November 1994, while river discharge was lowest during 1998, 1999 and part of 2000 (Fig. 9a). High bottom stress related to storms occurred in December 1997 and November 1999 (Fig. 9b). Atmospheric input was more erratic with yet larger deposition during spring and autumn, and negligible deposition during winter (Fig. 9c). The largest atmospheric deposition events were recorded in March (i.e. before the start of the experiment) and October 1993. Phytoplankton biomass, sensed through Chlorophyll-a concentration (Fig. 9d), showed a distinctive seasonal signal with a late winter/early spring bloom and a secondary summer bloom. The interannual variability was dominated by the 1999 winter bloom, which exhibited a Chlorophyll-a concentration about 3 times larger than the other years.

4.4. Variability of cross-slope exchange mechanisms

Mid-water currents were generally low (a few cm s^{-1}) and isotropic, i.e. with no preferential direction (Fig. 10 and Table 1). Near-bottom currents were stronger and anisotropic due to bathymetric constraints. They were oriented along isobaths on the open slope (short-term experiment, data not shown), and cross-isobaths within the canyon axes due to their channelling effect.

The mesoscale variability of the flow (characterized by the eddy kinetic energy) dominated the mean flow (characterized by the mean kinetic energy), but their temporal variability broadly looked alike (Fig. 11). The Planier site displayed a seasonal signal with minimum current intensity at the end of summer (Fig. 11a, c). A period of maximal activity occurred in March–April 1996, due to bursts of mean current intensity and enhanced cross-slope fluctuations. Currents within the Lacaze-Duthiers Canyon were larger than in the Planier Canyon, but noisier (Fig. 11b, d). However, except for a few periods (summer 1998 at mid-depth, summer and autumn 2000 at 1000 m), mesoscale activity was larger in winter and minimum in summer. The near-bottom peak of February 1999 related to massive and continuous down canyon flows of cold water, with speed up to 60 cm s^{-1}.

The in situ temperature measured at the depth of each trap was used as an indicator of wintertime cascading of

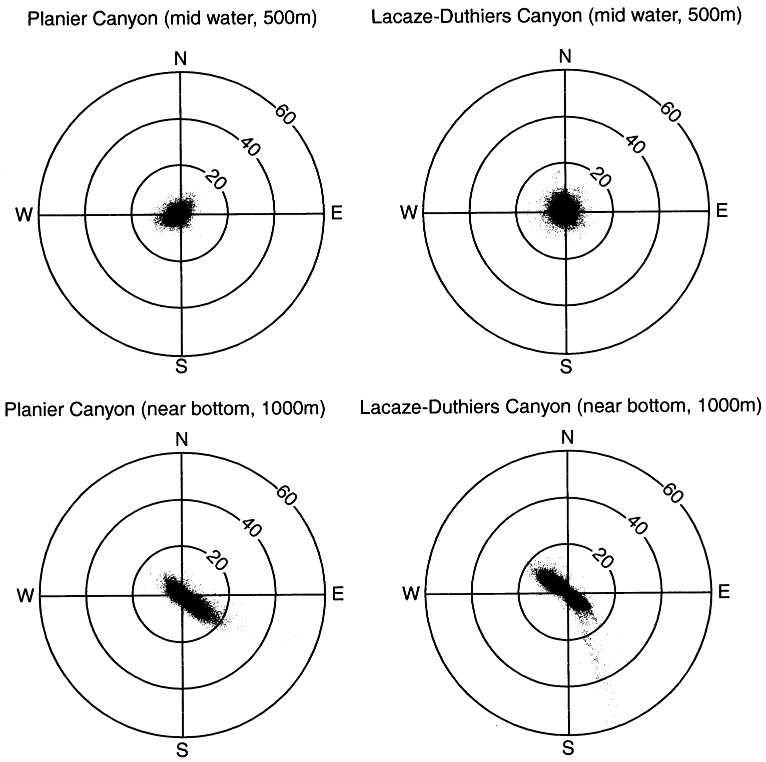


Fig. 10. Scatterplots of currents recorded between October 1993 and June 2001 at mid-water depth (500 m) and near the seabed (1000 m) in the Lacaze-Duthiers and Planier Canyons. Mid-depth currents are slow and isotropic (absence of prevailing flow direction), whereas near-bottom currents are stronger and anisotropic (prevailing flow direction along the axes of the canyons).

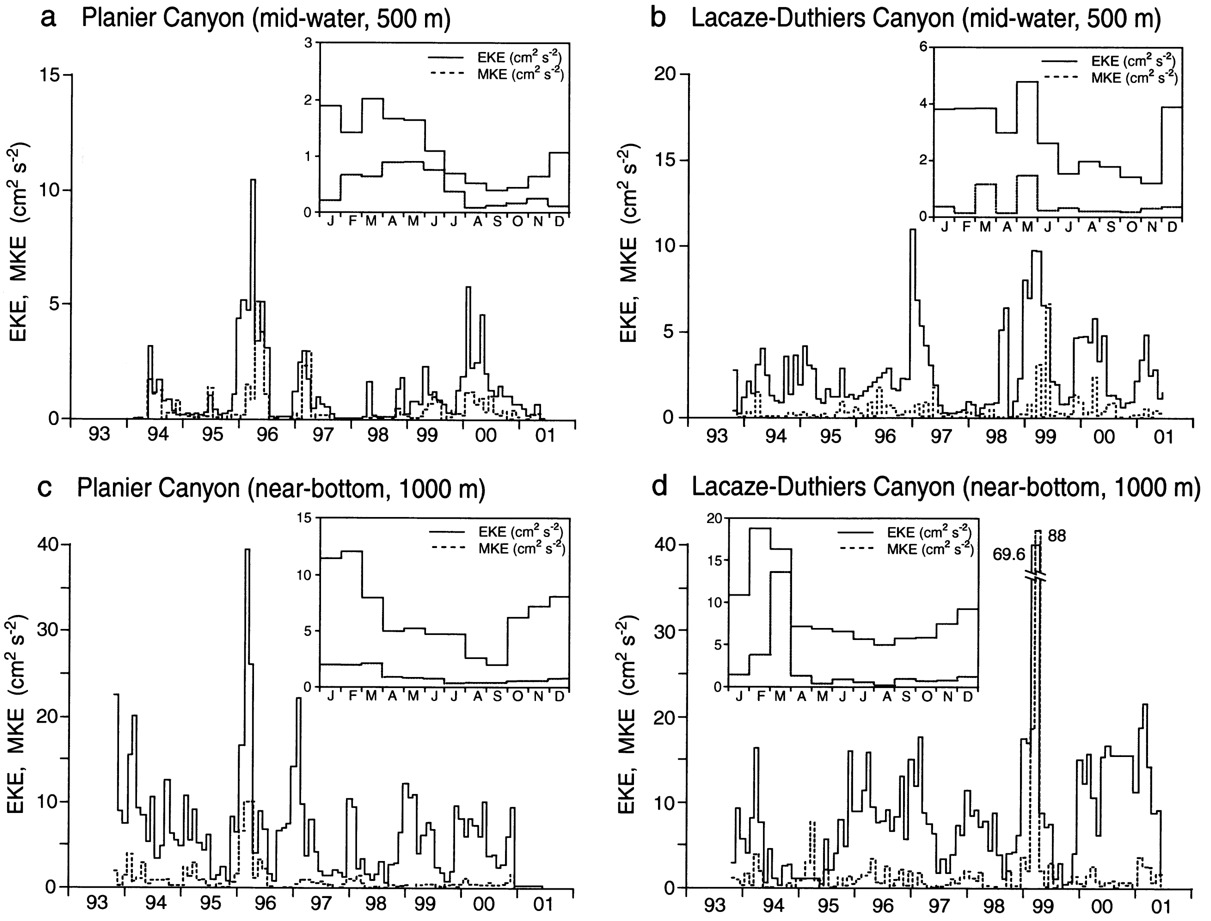


Fig. 11. Time series plots of Mean Kinetic Energy (MKE, dashed line) and Eddy Kinetic Energy (EKE, solid line) in the Planier and Lacaze-Duthiers Canyons on the Gulf of Lions slope, calculated from the current meter records provided by instruments located below each trap. Inserts represent the monthly mean mesoscale activity and mean current during a composite yearly period. Notice the differences in vertical scales.

cold and dense water formed on the shelf (Fig. 12). Winter cooling was more visible at mid-depth (500 m) than close to the bottom (1000 m). At mid-depth, temperature "normally" decreased by 0.2–0.5 °C, and exceptionally by 1.2 °C during the winters of 1999 and 2000, both events lasting several months (Fig. 12a, b). Near-bottom temperatures remained rather stable (13.2± 0.2 °C), except during the 1999 winter when a sudden decrease by 0.5 °C (1 day) and 1.4 °C (2 months) occurred for the Planier and Lacaze-Duthiers sites respectively (Fig. 12c, d).

5. Discussion

5.1. Spatial and temporal variability of downward particle fluxes on the Gulf of Lions slope

The range of settling particle fluxes measured in our different experimental sites was large, both in time and space (Fig. 3). Individual total mass fluxes covered a broad range of values – 3 orders of magnitude – from approximately 18 mg m^{-2} d^{-1} (June 94, 500 mab trap at the Planier site) to 27 g m^{-2} d^{-1} (February 99, near-bottom trap in the Lacaze-Duthiers Canyon, probably underestimated due to cup overflow). Regarding specifically the Northwestern Mediterranean, these values confirm previously established results. Indeed, total mass fluxes ranging from several tens of mg m^{-2} d^{-1} to several g are typical figures for margin environments in that area. They have been reported by Monaco et al. (1990) for the Lacaze-Duthiers Canyon, by Monaco et al. (1999) for the Grand-Rhône Canyon (nearby the Planier Canyon), and by Puig and Palanques (1998) for the Foix Canyon on the Catalan margin to the southwest of the Gulf of Lions. They are definitely one order of magnitude larger, on average, than open-ocean fluxes measured at the DYFAMED site in the Ligurian Sea (Miquel et al., 1994), offshore Almeria (Sanchez-Vidal

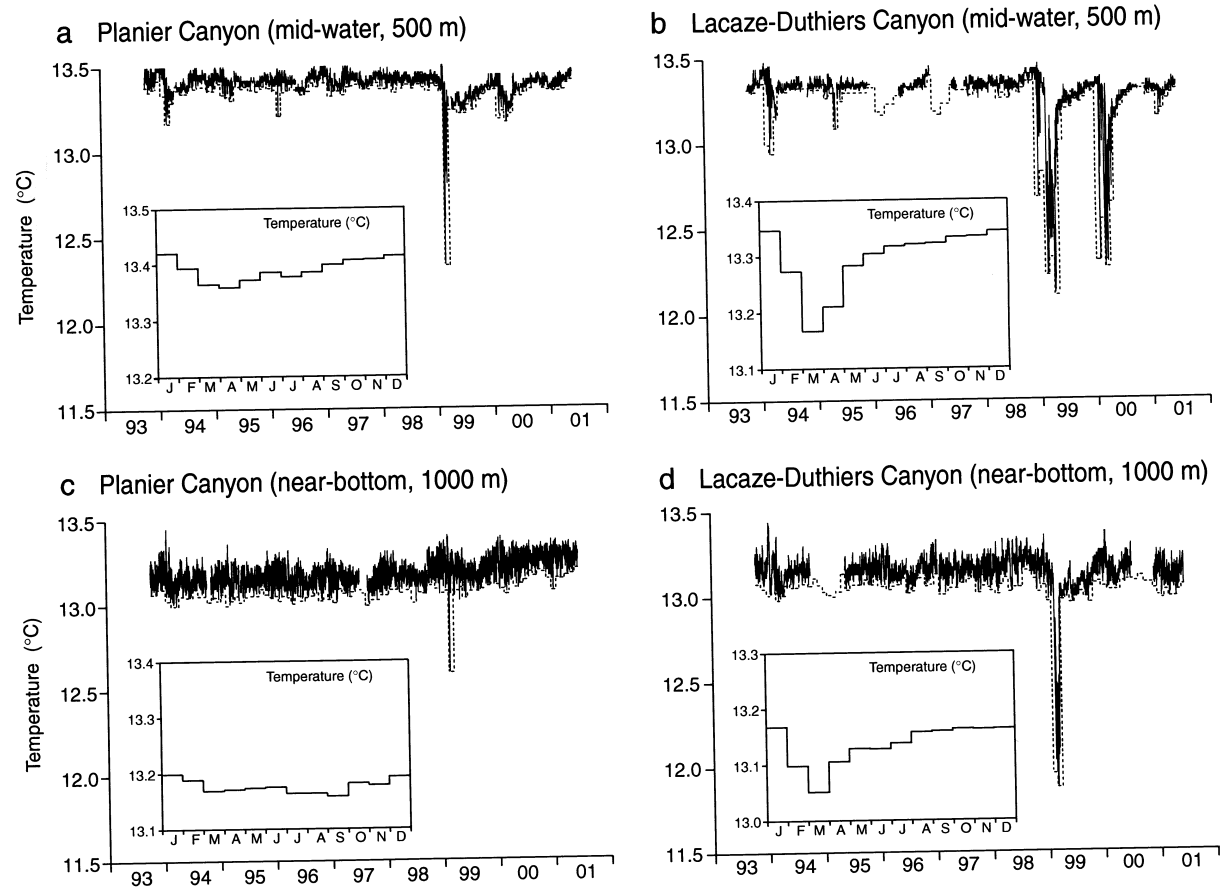


Fig. 12. Time series plots of in situ temperature in the Planier and Lacaze-Duthiers Canyons on the Gulf of Lions slope, recorded by current meters located below each trap. Inserts represent the monthly mean temperature during a composite yearly period.

et al., 2004) or in the central Western Mediterranean (Heussner et al., in preparation).

Our longer-term measurements also confirm and expand some of the main conclusions derived from previous annual experiments. On a broad scale, they show in particular strong horizontal and vertical gradients of downward fluxes across the slope. Flux intensity rapidly decreases seaward and down canyon over the short distance of roughly 10–15 km separating the canyon head traps at 500 m and the near-bottom traps at 1000 m in the canyon axes (Fig. 6). This decrease is site-and season-dependent. Besides, at any given location, mean annual fluxes increase with depth (except for the Planier site in 1995–1996), indicating a lateral input of particulate material (Table 3). These spatial features have been largely described in the past, in most if not all experiments conducted on continental margins (e.g., Monaco et al., 1990; Biscaye and Anderson, 1994; Monaco et al., 1999; Antia et al., 1999; Heussner et al., 1999; Chung and Hung, 2000; Antia et al., 2001; Iseki et al., 2003).

As for the Grand-Rhône Canyon (Monaco et al., 1999) or the Foix Canyon (Puig and Palanques, 1998), fluxes measured within the Lacaze-Duthiers Canyon during the short-term experiment were larger than on the adjacent open slope, underlining the channelling effect of some canyons, which act as conduits for the transfer of particles to deeper parts of the slope (Fig. 6). However, the efficiency of canyons in doing so seems to be related to the intensity of the export from the shelf, as suggested by the opposite canyon/open slope gradient observed in the Planier Canyon, at the entrance of the Gulf of Lions.

The compilation of mean annual fluxes (Figs. 5 and 6) also reveals a permanent east-to-west flux increment for all trap positions, which represents the main source of the overall explained flux variability as shown by the ANOVA analysis. Over the 8-yr period, the average increase was 3-fold, but was significantly larger in the near-bottom traps (×3.6) than at mid-water (×2.4). This along-slope flux increase continues further to the south, since measurements performed in the Foix

Canyon on the Catalan margin are even higher than those in the Lacaze-Duthiers (Heussner et al., 1996; Puig and Palanques, 1998). In a modelling study of the shelf–slope exchanges of water during the winter seasons from 1996 to 2001, Guarracino et al. (2006) showed that shelf water was primarily exported in the western half of the gulf under the action of the mesoscale circulation and the cascading of dense shelf water generated by northern continental winds. Thus the canyons of the western part of the slope – a broad geographic subdivision that covers the area from the Sète Canyon towards the Lacaze-Duthiers – appear as major conduits of water and associated particulate matter exported from the shelf to the slope.

However, despite the differences in the intensity of transfer between the entrance and the exit of the Gulf of Lions, downward fluxes exhibited similar temporal patterns (Figs. 3 and 5). The mid-water Planier trap at 500 mab within the canyon provides the clearest seasonal signal, with a quite smooth transition from a marked winter high to a pronounced summer low. This temporal pattern is disrupted to various degrees for the other three traps. Centering, reducing and smoothing the raw time series presented in Fig. 3 make the comparison of the relative fluctuations within the series easier (Fig. 13). We limit our presentation here to the near-bottom Lacaze-Duthiers trap, which presents the most disturbed seasonal signal. Two main features characterize the "noise" around the original signal shown by the mid-water Planier trap. First, the Lacaze trap (and, to a lesser extent, the other two traps) shows a larger number of short-term oscillations around the zero mean of the transformed time series, indicating short flux pulses. Such pulses are frequently observed during the summer period or at the onset of the broad winter flux increase, which therefore appears earlier and more intensely in the near-bottom trap at the entrance and the two traps at the exit than in the mid-water Planier trap (also visible in Fig. 5a). Second, the amplitude of fluctuations is much more limited, a feature that contributes to lessen the winter–summer contrast. It can be safely assumed that the mid-water Planier trap is the one that experiences the minimum influence of particle inputs from the Gulf of Lions shelf. The "degradation" of the seasonal pattern shown by the other traps is therefore largely attributable to short export periods of particles from the shelf.

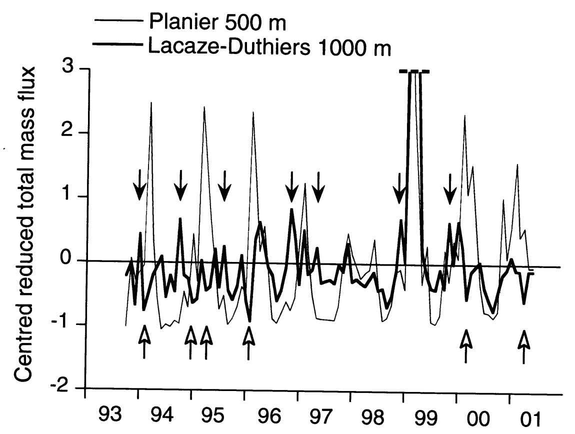


Fig. 13. Time series of transformed data (centred and reduced, $z=(x-\text{mean})/\text{standard deviation}$) of total mass fluxes measured by the mid-water trap (500 m) in the Planier Canyon, at the entrance of the Gulf of Lions, and by the near-bottom trap (1000 m) in the Lacaze-Duthiers Canyon, at the exit. The series were smoothed (3% moving average) to enhance the seasonal signal clearly visible in the 500 m trap. Black arrows indicate major additional flux peaks in the Lacaze trap, whereas open arrows indicate opposite trends.

Seasonal variability is a common feature of particle transfer in the world ocean. In the open environment it has been quite often attributed to seasonal changes in the productivity in the euphotic zone (e.g., Deuser and Ross, 1980; Lampitt, 1985; Jickells et al., 1996; Waniek et al., 2005). It was also suggested for the nearby open-ocean DYFAMED site that seasonal control of particle fluxes was largely due to pelagic production and increased during winter vertical mixing (Miquel et al., 1994). On continental margins, the seasonality of transfer is a more complex feature, since factors claimed to be responsible for the observed temporal variability are more diversified. In most cases seasonality relates to events that redistribute particles introduced into shelf waters by rivers or by resuspension events (e.g., Biscaye et al., 1988; Biscaye and Anderson, 1994; Puig and Palanques, 1998; Monaco et al., 1999; Iseki et al., 2003). But temporal variability of particle transfer to slope areas is not necessarily seasonal. On the continental margin of the Bay of Biscay for example transfer seems to be ultimately controlled by non-seasonal hydrodynamic processes that modulate and distribute the amount of material delivered from the shelf and upper slope particle reservoirs to the Cap-Ferret Canyon waters (Heussner et al., 1999). Our findings on the Gulf of Lions slope provide a mixed example in so far the seasonal signal clearly shown at the entrance of the system progressively fades out downstream under the influence of processes that control short pulses of settling material to the slope.

As mentioned in the introduction, trap experiments that cover periods long enough (>5 years) to address the interannual variability of particle transfer are, for obvious reasons, rare. The most recently published work (with earlier references therein) concern the HOT (Karl et al., 2001) and OSP (Wong et al., 1999) sites in the

Pacific, the OFP/BATS (Conte et al., 2001), ESTOC (Neuer et al., 1997) and JGOFS L1/K276 (Waniek et al., 2005) site in the Atlantic and three deep Bay of Bengal sites in the Indian Ocean (Unger et al., 2003). In the Mediterranean, downward fluxes are measured at the DYFAMED site in the Ligurian Sea since the late 80s (Miquel et al., 1994). All these experiments, some of which are still running, concern open environments and have been extensively documented. Interannual variability has been recognized and appears to be forced by variations in upper ocean physics and biology. Changes in the intensity of particle transfer to the deep ocean are relatively limited and interannual differences are more related to the phasing of the seasonal cycle than to the transferred amount itself. The 20-year record at the OFP-BATS site near Bermuda shows for example that annual means evolve within a factor of 2 (Conte et al., 2001). As for the seasonal signal when it exists, interannual variability at most of these sites is related to changes in surface water productivity, even if some decoupling exists between primary production and carbon export (Karl et al., 1996). For the Pacific sites a clear relation was further shown between increased biogenic transfer and warmer ENSO years (Karl et al., 1996; Wong et al., 1999; Marchant et al., 2004), whereas the Bay of Bengal time series revealed significant monsoon-induced interannual variations in total and component fluxes (Unger et al., 2003).

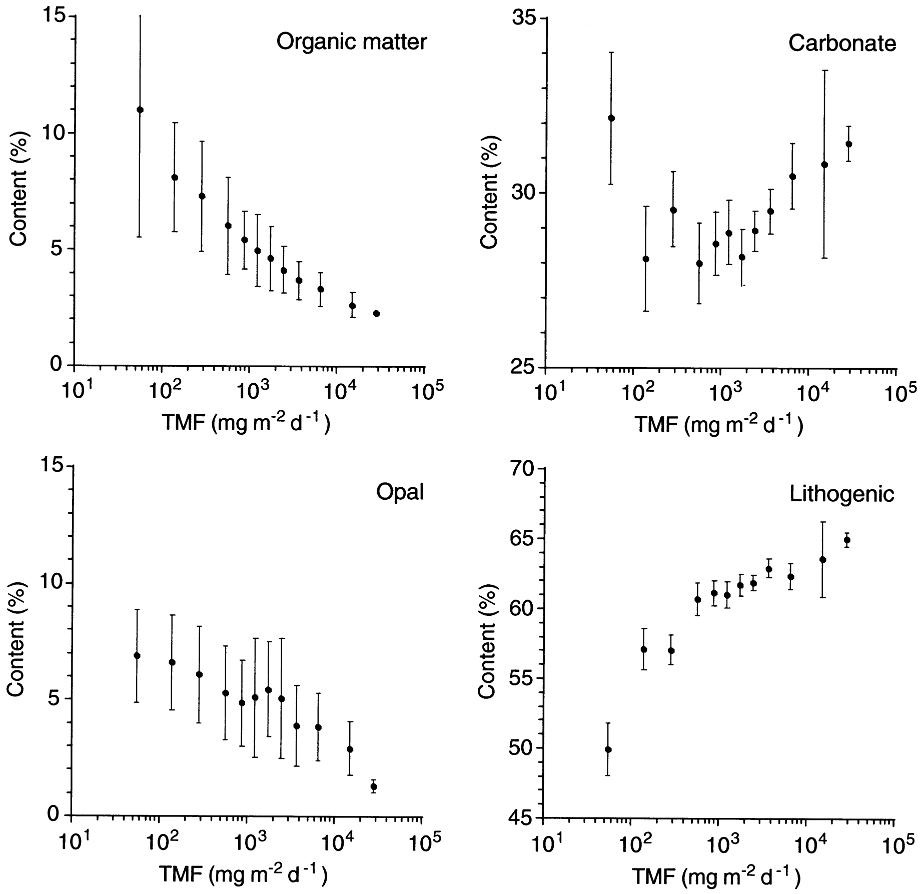
On continental margins, the existing database is extremely small. Several studies exceeded the classical 1-yr duration and provided data for longer periods (e.g., Goni et al., 2003), however not long enough to really address interannual trends. The longest experiment we were able to find, besides some grey literature references (e.g. Boynton et al., 1993), concerns a 6-yr time series obtained by a single trap deployed at 500 m depth (200 mab) in the Guyamas Basin, Gulf of California (Thunell, 1998). Interannual variability of total mass fluxes was quite limited (interannual ratio of 1.6) and more detectable in the changes of major constituents, which were attributed to ENSO versus non-ENSO conditions.

In the present study, the interannual evolution of mass fluxes was dominated by the year 1999 that affected the annual means of 3 of our 4 traps. Despite this unusual year characterized by a very strong flux event, the ratios of highest to lowest annual means varied from 1.3 to 2.7. Annual measurements were previously performed at a slightly shallower part (650 m) of the Lacaze-Duthiers Canyon in 1985–1986 (Monaco et al., 1990) and at similar depths in 1988–1989 within the Grand-Rhône Canyon and the adjacent open slope (Monaco et al., 1999), close to the Planier Canyon. Annual means reached 5600 mg m^{-2} d^{-1} at the 600 m trap (45 mab) in the Lacaze-Duthiers, i.e. in between the canyon head and the 1000 m depth means presented here. For the Grand-Rhône Canyon, the near-bottom annual means were slightly lower than the range of values reported for the Planier Canyon and open slope, reaching 450 and 250 mg m^{-2} d^{-1} respectively. These earlier values are nevertheless at the same level as those observed here, suggesting that the range of present values is representative of longer, decadal time scales.

5.2. Sources of the trapped material

The limited variation of the bulk composition of particles trapped at the different sites suggests that the reservoir(s) feeding shelf–slope exchanges is (are) relatively homogeneous at the scale of the entire Gulf of Lions. Atmospheric deposition (average: 50 mg m^{-2} d^{-1}, i.e. 0.22×10^6 T y^{-1} for the approximately 15 500 km^2 of the Gulf of Lions shelf and slope area down to 1000 m) represents only a negligible fraction (<2%) of the Rhône River inputs (average: 12×10^6 T y^{-1}). Newly introduced particulate matter is thus dominated by river discharge and surface biological production. An average estimate of the latter over the years 1997–2001, an upper limit when compared to previous estimates, is 530 mg C m^{-2} d^{-1} (Bosc et al., 2004), which leads to a total POC production of 3×10^6 T C y^{-1} for the area considered. Using the ×3 biomass to C ratio of Strickland (1960), this value represents an algal biomass production of 9×10^6 T y^{-1}, from which a large part (90%) is recycled within the photic layer (Durrieu de Madron et al., 2000). Sediment resuspension by storm-induced waves and bottom currents provides an additional input of material of mixed origin. This includes resuspension of superficial sediment and resuspension of freshly deposited material that has not become incorporated into the sediment. This latter category of particles or aggregates is often termed rebound particles or aggregates (Walsh et al., 1988; Gardner and Walsh, 1990; Monaco et al., 1990; Heussner et al., 1999; Lampitt et al., 2000). As mentioned by McCave et al. (2001), it is very difficult to distinguish between shelf export of modern supply and resuspension of past supply for lithogenic material, and between primary productivity within the statistical funnels of our traps (sensu Siegel and Deuser, 1997), shelf export, and resuspension for organic carbon and skeletal components. It has been suggested however that lateral advection of material from the sources on the adjacent shelf and slope is far more important than the settling flux of primary particles produced in surface waters (Biscaye and nderson, 1994; Van Weering et al., 2002; Inthorn et al., 006). In the Gulf of Lions, evidence of particle shelf xport has been provided by Lapouyade and Durrieu de Iadron (2001) and Palanques et al. (2006-this issue), or what concerns suspended sediments, and by Monaco : al. (1990, 1999) for settling particles. What is of ssential concern here is therefore the immediate source) of particles – on the shelf and upper (200–1000 m) ope – and the relative importance of primary versus esuspended material.

The bulk composition of the trapped particles varied ith total mass flux intensity. Biogenic content – in articular organic matter and opal – was maximum for e lowest fluxes and continuously decreased with creasing fluxes, tending towards values of respective- 2 and 1% (Fig. 14). Carbonate displayed a peculiar volution with a minimum content of about 28% for edium-range fluxes (around 1000 mg m^{-2} d^{-1}) and an crease for higher fluxes (towards 31–32%). Thus, ear-bottom total mass fluxes at 500 m in both canyon heads and at 1000 m in the Lacaze-Duthiers Canyon, which displayed the strongest flux values, had a rather stable composition with higher lithogenic content throughout the year. The other fluxes, particularly for the Planier site, generally showed periods with maximum biogenic content (between 45 and 65%) from late spring to early autumn, at a period of lowered total mass transfer. This evolution of composition linked to the flux intensity reflects the dual origin of particles on the slope, i.e. sediment resuspension and primary flux signal from superficial waters. Indeed, the asymptotic composition obtained for the largest fluxes approaches the composition of the superficial (upper 5 mm) sediments from the Gulf of Lions shelf and upper slope. The latter have an organic matter content ranging from ~1% on sandy substrate to ~4% on prodeltas (the primary depository for fluvial inputs), yielding an average content of 1.8% (Roussiez et al., 2006). Average carbonate content in the <63 µm fraction is 31% with some local differences, e.g. between prodelta deposits (higher for the Rhône



. 14. Variation of the mean content of major constituents (% dry weight) with increasing total mass flux (mg m^{-2} d^{-1}) of particulate matter lected by all sediment traps and arranged in size-classes. Error bars represent the 95% confidence interval of the means.

prodelta) or western versus eastern outer shelf sediments. Opal is nearly absent (~1%; Leblanc et al., 2005) or below the analytical detection limit.

Concerning the immediate sources and the importance of shelf and upper slope resuspension in providing particles for slope export, these compositional trends justify the use of a simple mixing model with two end-members: on the one side superficial sediment resuspended from the shelf and upper slope areas with the above mentioned average characteristics, on the other primary flux particles that settle for the first time out of the upper water layers of the Gulf of Lions. Rebound flux is not explicitly taken into account here, since we have no compositional values for this category of particles, but its implication will be discussed below. The general mixing equation system for organic carbon at depth (z) is:

$$F_{\mathrm{Tcorg}}(z) = F_{\mathrm{T}}(z) \times C_{\mathrm{Tcorg}}(z) = (F_{\mathrm{P}}(z) \times C_{\mathrm{Pcorg}}(z)) + (F_{\mathrm{R}}(z) \times C_{\mathrm{Rcorg}}(z)) \text{ and,} \quad (1)$$
$$F_{\mathrm{T}}(z) = F_{\mathrm{P}}(z) + F_{\mathrm{R}}(z)$$

where F_{Tcorg} is the total flux of organic carbon, F_{T} is the total mass flux, F_{P} the mass flux of primary particles, F_{R} the mass flux of resuspended particles, and C_{Tcorg}, C_{Pcorg} and C_{Rcorg} the organic carbon content of total, primary and resuspended particles respectively. Eq. (1) can be rearranged into:

$$F_{\mathrm{P}}(z) = F_{\mathrm{T}}(z) \times (C_{\mathrm{Tcorg}}(z) - C_{\mathrm{Rcorg}}(z)) / (C_{\mathrm{Pcorg}}(z) - C_{\mathrm{Rcorg}}(z))$$
$$F_{\mathrm{R}}(z) = F_{\mathrm{T}}(z) \times (C_{\mathrm{Pcorg}}(z) - C_{\mathrm{Tcorg}}(z)) / (C_{\mathrm{Pcorg}}(z) - C_{\mathrm{Rcorg}}(z))$$

and the ratio of primary flux to resuspension flux reads:

$$F_{\mathrm{P}}/F_{\mathrm{R}} = (C_{\mathrm{Tcorg}}(z) - C_{\mathrm{Rcorg}}(z)) / (C_{\mathrm{Pcorg}}(z) - C_{(\mathrm{Tcorg})}(z)) \quad (2)$$

The total organic carbon content C_{Tcorg} and C_{Rcorg}, the organic carbon content of resuspended particles considered invariant with depth, are known.

The organic carbon content of primary particles, C_{Pcorg}, can be derived from complementary measurements from which depth change of carbon content due to degradation during settling from the production layers down to the trap depths can be estimated. Indeed, fresh organic matter leaving surface waters will be subject to mineralization, entraining a flux reduction with depth that can be generally fitted by a power function $F_{\mathrm{Pcorg}}(z) = a \times z^{-b}$, where F_{Pcorg} is the organic carbon flux at depth z and b the slope of the fit (e.g., Suess, 1980; Betzer et al., 1984; Pace et al., 1987; Berelson, 2001; Armstrong et al., 2002; Lutz et al., 2002; Muller-Karger et al., 2005). To characterize primary particles we use previous estimates of annual downward fluxes of organic carbon collected between 50 and 200 m depth in the area, and a weighted mean organic carbon content of 19% at 50 m (Monaco et al., 1990, 1999). Though "contamination" by resuspension cannot be entirely ruled out, these values represent the best available estimates of primary flux particles out of the 200 m surface layer (Fig. 15). The equation of the power fit to these annual mean fluxes is:

$$F_{\mathrm{Pcorg}}(z) = 602.1 \times z^{-0.687} \quad (3)$$

From this equation we extrapolate a residual primary flux of organic carbon of 8.4 mg m^{-2} d^{-1} at 500 m depth, and 5.2 mg m^{-2} d^{-1} at 1000 m. It is interesting to note that the latter flux at 1000 m, though severely extrapolated, is very close to the long-term mean organic carbon flux of 4.4 mg m^{-2} d^{-1} measured at the same depth in the nearby open-ocean DYFAMED site (calculated from the June 1988–March 2003 data available at http://www.obs-vlfr.fr/sodyf/home.htm), specially when one considers that primary production is 20% lower in the Ligurian Sea (Bosc et al., 2004). Compared to our long-term means, these extrapolated values of primary fluxes of organic carbon show that lateral advection of organic matter represents between ~60% (upper Planier trap) and ~90% (lower Lacaze-Duthiers trap) of the total flux of organic matter. This supplementary, laterally advected input includes primary and resuspended carbon.

Given that at any depth z, $F_{\mathrm{Pcorg}}(z) = F_{\mathrm{P}}(z) \times C_{\mathrm{Pcorg}}(z)$, the change of primary organic carbon content with depth between the surface layer (at $z = 50$ m) and the trap depth can be extrapolated using Eq. (3) as:

$$C_{\mathrm{Pcorg}}(z) = C_{\mathrm{Pcorg}}(50) \times (F_{\mathrm{P}}(50)/F_{\mathrm{P}}(z)) \times (z/50)^{-0.687} \quad (4)$$

The $F_{\mathrm{P}}(50)/F_{\mathrm{P}}(z)$ ratio allows to take into account the total primary flux decrease with depth, through partial dissolution of all biogenic flux components. Using the ratio observed between 200 and 1000 m depth at the DYFAMED site (1.175), we calculate a ratio of 2.2 10^{-4} m^{-1}. For our traps, this yields:

$$F_{\mathrm{P}}(50)/F_{\mathrm{P}}(z) = 1 + (2.2 \times 10^{-4} \times (z - 50))$$

Substituting this latter term into Eq. (4) yields:

$$C_{\mathrm{Pcorg}}(z) = C_{\mathrm{Pcorg}}(50) \times (1 + (2.2 \times 10^{-4} \times (z - 50))) \times (z/50)^{-0.687}$$

This correction for primary flux reduction leads to the upper limits for C_{Pcorg}, i.e. 4.61% at 500 m and

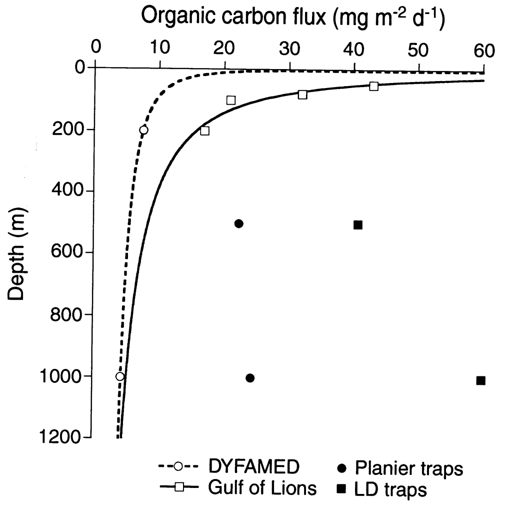


Fig. 15. Depth evolution of organic carbon flux in the Northwestern Mediterranean Sea. DYFAMED data represent the long-term, time-weighted fluxes at 200 and 1000 m depth in the Ligurian Sea averaged over the 1988–2003 period (calculated from the raw data available at http://www.obs-vlfr.fr/sodyf/home.htm), Gulf of Lions data are the annual means in surficial waters (50–200 m depth) calculated from previous slope experiments in that area (Monaco et al., 1990, 1999), and Planier and Lacaze traps are the 8-yr means from the present work. Solid and dashed lines represent power fits to the DYFAMED and Gulf of Lions means.

3.04% at 1000 m. Substituting the measured and calculated values to the terms of the general mixing Eq. (2) allows calculating the primary (F_P) and total resuspension (F_R) fluxes over the 8-yr period (Table 4). Primary flux contribution to total mass flux ranges from 33 to 68%. It is higher in the Planier Canyon (59–68%, with the highest value observed in the near-bottom trap), and decreases significantly in the Lacaze-Duthiers Canyon (33–40%). The lowest contribution, 1/3 of total transfer, is seen in the near-bottom trap there. Conversely, around 70% of the particles transferred to this location during the 8-yr period are of resuspended origin.

The absolute values of primary and resuspension fluxes in each trap provide some further insights into the transfer to the Gulf of Lions slope. Both fluxes increase between the mid-water and the near-bottom traps at both sites. This feature indicates that, in any case, lateral advection predominates and also militates in favour of a common reservoir that mixes primary and resuspended particles. Both fluxes further increase between the entrance and the exit of the gulf, and the highest transfer occurs in the near-bottom Lacaze-Duthiers trap. Depending on depth, the Lacaze-Duthiers Canyon transfers 1.6–1.8 times more primary particles and ~3.5–7.5 times more shelf and upper slope sediments than the Planier Canyon. However these diverse increases mark out the resuspension flux in the Lacaze-Duthiers where the depth increase factor between the 500 m trap and the near-bottom trap is 2.5 (from 1013 mg m^{-2} d^{-1} to 2517 mg m^{-2} d^{-1}), whereas it is 1.6–1.8 for primary fluxes in both canyons and only 1.1 for the resuspension flux in the Planier. Those processes responsible for the transfer of resuspended material must be particularly active in feeding the near-bottom region of the Lacaze-Duthiers Canyon. Very recent modelling of particle transport in the Gulf of Lions, using real meteorological conditions, suggested that superficial sediment was resuspended by storms and dense water cascading during winter and preferentially exported in the southwestern part of the gulf (Ferré, 2004). This resuspension entrained a substantial sediment erosion in specific areas of the shelf and upper slope (Ulses, 2004).

Though lateral advection predominates (Fig. 15), primary flux remains the predominant source of organic carbon in both canyons with a contribution of 62 to 88% to the total organic carbon transfer (Table 4). It is also interesting to note that the absolute flux in the near-bottom trap is 70% higher in the Lacaze (37.5 mg m^{-2} d^{-1}) than in the Planier Canyon (21.3 mg m^{-2} d^{-1}), a result that should be considered when addressing benthic–pelagic coupling, since less-degraded organic carbon of primary flux particles is more efficient in

Table 4
Primary and resuspension fluxes (in mg m^{-2} d^{-1}) and their respective contribution (%) to the total mass flux of donward settling particles on the continental slope of the Gulf of Lions

Trap depth	Total primary flux		Total resuspended flux		Organic C primary flux	
	(mg m^{-2} d^{-1})	(%)	(mg m^{-2} d^{-1})	(%)	(mg m^{-2} d^{-1})	(%)
Planier 500 m	428	59	293	41	19.7	88
Planier 1000 m	702	68	335	32	21.3	88
Lacaze 500 m	688	40	1013	60	31.7	78
Lacaze 1000 m	1234	33	2517	67	37.5	62

Primary flux of organic carbon and its contribution to the total flux of organic carbon.

sustaining benthic food webs than does carbon resuspended from shelf sediments.

As mentioned above, these first-order calculations did not take into account another source of particles, namely rebound aggregates. We have, indeed, no compositional values to apply to this category of particles and we do not exclude that they could represent a significant source of material transferred towards the deeper part of the Gulf of Lions slope. However the borderline case here is to consider that all particles that are not primary flux particles are rebound aggregates, and replace in the equations above C_{Rcorg}, the organic carbon content in superficial sediments, by C_{RAcorg} the content in rebound aggregates. To obtain realistic solutions, the unknown C_{RAcorg} values have to be bound on the one side by C_{Rcorg} (it is unlikely that the fresher aggregates lying on the superficial sediments show lover carbon contents than the underlying sediment) and on the other by C_{Tcorg}, the organic carbon content in the traps (higher values would entrain negative flux values). Within the realistic limits assigned to C_{RAcorg} for each trap, F_{P} will decrease for increasing C_{RAcorg} and will be lower than the values presented in Table 4. So, even if we did not considered rebound aggregates, our estimates of the contribution of primary flux in the diverse traps represent upper limits. We can therefore safely assume that resuspended sediment represents a significant (1/3 in the upper Planier trap) or even predominant (2/3 in the lower Lacaze trap) source for the particles transferred to the Gulf of Lions slope.

5.3. Factors controlling particle transfer to the slope

The shelf and upper slope water column reservoirs of particulate matter showed a seasonal variability with higher average turbidity during autumn and winter (Fig. 2) directly linked to the seasonality of the inputs. Before examining the relation between fluxes, particle sources and exchange processes it is important to notice that the interpretation of the available results is intrinsically limited by the experimental strategy used, in particular the sampling intervals and the location of our observation sites. The monthly time step used for all time series most probably smoothed out the effect of short export events associated to episodic fluvial discharge and storm events. More importantly, the dispersal of particulate matter during some intense transport events was dependent on the hydrological conditions. For example, export during stratified conditions is only perceptible on the upper slope. Thus the variability of our long-term flux observations is only representative of particulate transfer towards intermediate and deep waters, and not of the entire set of shelf–slope exchanges, since some of the latter are restricted to the shelf edge (see Palanques et al., 2006-this issue).

Correlations between the potential forcing – sources and exchange processes– are summarized in Table 5, together with their degree of statistical significance. It appears that the various coefficients computed are all except one lower than ±0.5 which means that the degree of flux variance explained by any given forcing does not exceed 25%, a result that is not very surprising considering the natural variability and the noise around the seasonal and interannual time series (Figs. 3, 9, 11, 12). For those correlations that were significant for most or all traps, the temporal evolution of the covariation strength was examined with a sliding, offset window of 2 years (Fig. 16). The 95% confidence intervals (CI) of the correlation coefficients adjusted for the Bonferroni correction (±0.58 for 22 *DF* and $K=4$ for the adjustment) or not (±0.44, 22 *DF*) are reported on the plots. The adjustment increases the threshold of significance and reduces the probability of a type-I error (i.e., rejecting the null hypothesis "none of the population correlations is different from zero" when it is true). Thus, despite the fact that some non-adjusted r-coefficients calculated for the 2 year periods are significant for a given window, only those adjusted *r*-coefficients that exceed the adjusted threshold significantly contribute to the rejection of the null hypothesis. The covariation of the two parameters during the corresponding period is non-zero.

Table 5
Overall correlation coefficients between total mass fluxes on the continental slope of the Gulf of Lions and forcing parameters (sources and shelf–slope exchange processes) for the entire 8-yr period

	Particle input or production processes				Exchange processes		
Trap position	Atmos. input	Rhône discharge	Bottom stress	Chlorophyll biomass	EKE	MKE	Min. temperature
Pl. 500 m	−0.09	0.32**	0.25*	0.57***	0.13	0.22*	−0.41***
Pl. 1000 m	−0.04	0.30**	0.28**	0.46***	0.10	0.19	−0.26*
LD 500 m	−0.27*	0.37***	0.24*	0.37***	0.25*	0.13	−0.33**
LD 1000 m	−0.01	0.04	0.22*	0.34**	0.32**	0.24*	−0.42***

*Significant correlation ($p<0.05$), **Highly significant ($p<0.01$), ***Very highly significant ($p<0.001$).

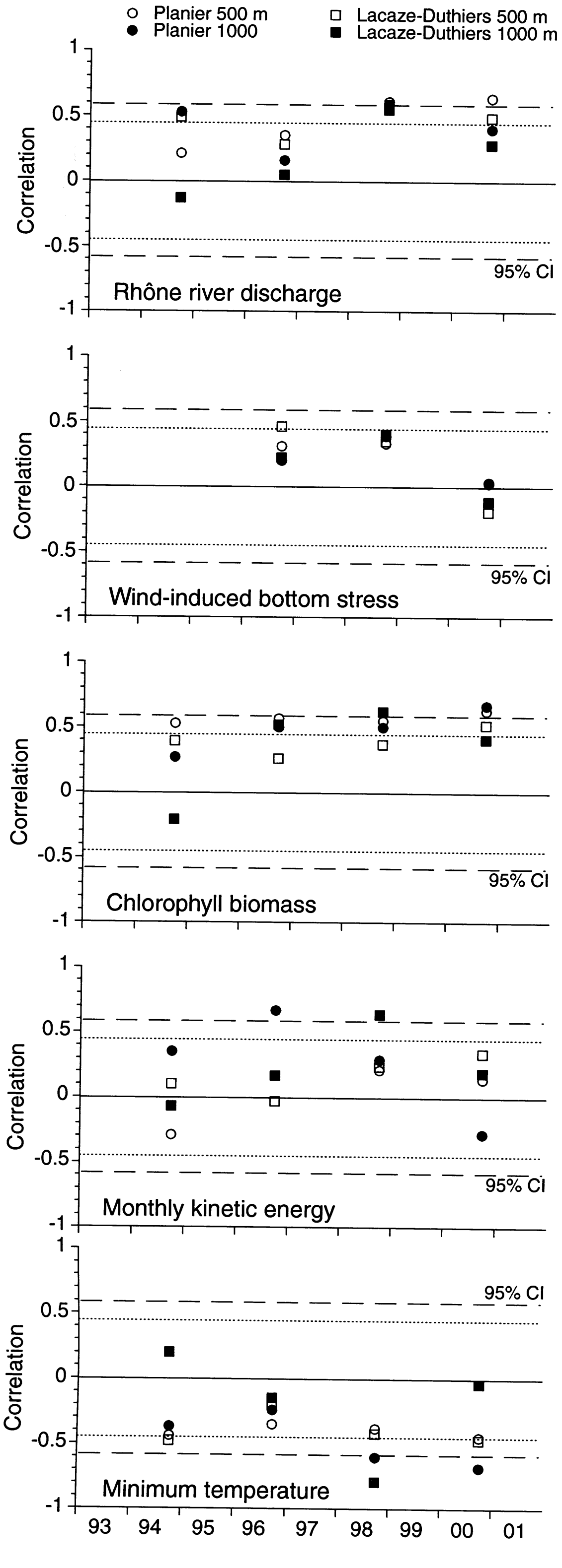


Fig. 16. Sliding correlation between particles fluxes and river discharge, wind-induced bottom stress, integrated chlorophyll-a, local mean kinetic energy and in situ minimum temperature for the 1993–2001 period. Correlations for each 2-year window are plotted in the middle of each period. Dotted line represents the 95% confidence interval for r (±0.44, 22 *DF*). Dashed line represents the 95% confidence interval for the population correlation coefficient adjusted for multiple (K=4) testing (95% CI=±0.58).

Concerning the sources of particles to the system, monthly fluxes on the slope were significantly correlated with the Rhône River discharge, the most important particle supplier to the Gulf of Lions. However, the noticeable exception is the lack of covariation for the near-bottom Lacaze-Duthiers trap, quite probably because the latter showed a very large number of short flux events induced by other mechanisms. Correlations for the shorter time windows were only significant for some traps during the second half of the experiment (98–01). This is the first example showing an overall statistically significant covariation but with a moderate strength in the relation between the two considered variables on shorter time scales. Wind-induced bottom stress, taken as an index of potential resuspension of sediments on the shelf, followed the same pattern and no short correlations were observed (data are only available from 1996 onwards). Phytoplankton biomass, approximated by integrated chlorophyll a, showed the highest correlations for all traps, and with the exception of the 94–95 window, most of the short correlation coefficients approached the upper CI limit. The best fit was observed for the mid-water Planier trap at the entrance of the gulf throughout the monitoring period, due to the remarkable coincidence of biomass and particle flux seasonal signals (compare Figs. 3 and 9d). The last considered source forcing, atmospheric deposition over the Gulf of Lions, was not significant, except for the mid-water trap at the exit. As mentioned above, this is not surprising if one considers the relative importance of atmospheric supply versus rivers.

Concerning the exchange processes induced by shelf–slope water motions, MKE and EKE were only weakly correlated with fluxes, though some overall coefficients were significant. For shorter periods, MKE, primarily due to the low frequency trend of the along-slope current, showed occasionally significant association with fluxes, as for the Planier traps in 96–97 or the Lacaze-Duthiers near-bottom trap in 98–99. Temperature drops, induced by cascading events, were inversely and significantly correlated in both canyons during the course of the entire experiment. However, at shorter time scales, the only significant covariations were found for the near-bottom traps in both canyons during the 98–99 period that included the very strong February–April

99 peak associated to an intense temperature drop (Fig. 12). The following 2-yr period (00–01) was also concerned for the Planier near-bottom trap, but not its equivalent in the Lacaze-Duthiers, where no temperature drop was observed in February–April 2000. Some forcing parameters were obviously inter connected. For example, the rapid down slope propagation of the dense water plume in the Lacaze Duthiers canyon during winter 1999 incidentally led to an increase of the mean intensity (MKE) and variability (EKE) of the near-bottom currents, concomitant to the temperature drop (Figs. 9d and 12d).

Regarding the practical significance and relative impact of the various controlling factors on the intermediate and deep fluxes, these results reveal the limitation of the correlation analysis performed on the existing data set. Furthermore, significant correlation does not mean causative relationship, but more often that the two variables considered vary according to a third one. This is particularly true for the Gulf of Lions, a temperate margin environment that experiences, during the autumn–winter season, increase of river discharge – hence of nutrients that promote phytoplankton productivity – and increase of storms events that contribute to resuspend deposited particles, making them available for export. But increasing sources of matter do not necessarily have a direct influence on slope fluxes since transfer towards intermediate and deep waters is primarily modulated by physical exchange processes, as shown for other margin environments (e.g., Biscaye and Anderson, 1994; Heussner et al., 1999; Antia et al., 2001; McCave et al., 2001; Iseki et al., 2003). E–SE storms cause a sudden, but brief, resuspension of sediment on the inner shelf (Ferré et al., 2005). The subsequent export of suspended particles from the shelf to the upper slope, in particular for the westernmost canyons, was clearly evidenced by Palanques et al. (2006-this issue). Ulses (2004) further showed that the large downwelling, promoted by the massive convergence of water to the southwestern end of the gulf, extended down to several hundreds of meters under stratified conditions (autumn), but could also enhance the export of dense shelf water to deeper levels during winter. Such processes could explain why the resuspension flux is so important in the near-bottom Lacaze-Duthiers trap. The absence of practical correlation of the long-term time series with large inputs of suspended particles during shelf storms events, which are often associated in the Gulf of Lions with river flood, is probably further related to the too large distance between the moorings and the shelf edge (~ 10 km) and also to the depth of the traps. Except for the peculiar 1999 dense water cascading event, fluctuations of the along-slope current are merely correlated to downward flux in the Planier Canyon. Here, the core of the current is close to the slope and its fluctuations generate significant cross-slope oscillations that, in turn, transport more turbid shelf waters down the slope (Durrieu de Madron et al., 1999). On the western part of the gulf, the core of current moves away from the slope and interacts less with topography. Cascading of dense shelf water, although of an annual recurrence, has variable density characteristics and equilibrium depths from one year to the next (Béthoux et al., 2002; Durrieu de Madron et al., 2005). Temperature records show that events that are perceptible down to 500 m, all the more so at 1000 m, are rare. But any of these events, regardless of their intensity, are likely to export material from the shelf (Lapouyade and Durrieu de Madron, 2001). Since the largest fluxes are clearly correlated with cascading, this process is believed to be a predominant factor to transfer particulate matter down to deep slope waters and to explain the observed interannual variability.

6. Conclusions

A number of conclusions may be drawn from this unique, long-term measurement of particle transfer to the deeper slope at the NE entrance and SW exit of the Gulf of Lions margin system:

(1) Settling particle fluxes present spatial and temporal variations in the 10^1–10^4 mg m^{-2} d^{-1} range. Total mass fluxes increase with depth at both sites, decrease seaward at equivalent depth, and exhibit an increasing gradient at equivalent position between the entrance and the exit of the gulf. The same spatial pattern is observed for all fluxes of major constituents (organic matter, carbonate, opal and lithogenic fraction). These features confirm similar trends previously reported in other margin environments and indicate lateral transport of particulate matter from the adjacent shelf and upper slope waters. However, higher fluxes within the canyon axis as compared to those on the adjacent open slope were only observed in the western part of the gulf, qualifying thus the generally accepted idea of the channelling effect of canyons.

(2) Settling particles are predominantly lithogenic (around 60%). Over the course of the experiment, the bulk chemical composition remained within a limited range of values for each major constituent, with a few exceptions of short duration. As a

consequence, fluxes of major constituents vary in a way similar to that of total mass. This homogeneity in composition associated with the increase of material delivered to depth leads us to consider that most settling particles originate from similar, quite homogeneous reservoirs that mix particles from various primary sources (riverine, atmospheric, biological production). Whereas the flux of organic matter remains constant (Planier Canyon) or even increases (Lacaze-Duthiers Canyon) its content in settling particles decreases at both sites, but also, for similar depths, between the entrance and the exit. This indicates a dilution of organic particles that relates to the lateral input of particles with lower organic content, modulated according to these two gradients.

(3) Downward fluxes exhibit a high temporal variability, with a clear signal of winter maxima and summer minima (sensu lato), perfectly evidenced in the mid-water trap at the entrance of the system. This seasonal signal progressively weakens for increased mass fluxes in the other traps, due to the occurrence of shorter events that disrupt the original pattern. Over the 8-yr course of the experiment, annual means did not vary by more than a factor of 2–3 between the lowest and highest values. Interannual variability was largely dominated by the unprecedented flux event that was observed in February–April 99, which consequently increased annual means of the two near-bottom traps.

(4) The content of major constituents of particles caught by the traps is directly related to the intensity of total mass fluxes and asymptotically tends towards values measured in superficial shelf and slope sediments. On the basis of a binary mixing model using bulk chemical composition of the latter on the one hand and of particles settling from the upper water layers (primary flux) on the other, we conclude that resuspended sediment represents a significant component of the particulate transfer towards the deeper area of the Gulf of Lions slope, between 1 / 3 and 2 / 3 of the total flux. The contribution of resuspended material is highest at the exit of the Gulf of Lions, especially in the near-bottom trap. However, the contribution of primary flux to the total export of organic matter remains high (from 60% to 90% depending on location) and, despite the overall predominance of resuspension there, "fresh" organic matter fluxes are highest in the Lacaze-Duthiers traps at the exit of the system.

(5) Forcing of the flux variability considered both the sources of particles feeding the Gulf of Lions (rivers, resuspension, atmospheric deposition and biological production) and the dynamical processes controlling shelf–slope exchange. The time series analyzed did not permit to clearly demonstrate causal relationships between the considered forcings and the variability of particulate transfer, partly because of the differences in the pertinent time scales of the selected parameters. This calls for dedicated experimental strategies – such as the experiment performed during EUROSTRATAFORM (Palanques et al., (2006-this issue)) specifically designed to decipher the complexity of the processes controlling the shelf to slope transfer. Nevertheless, the observed correlations between the various forcings and the slope fluxes reinforced the growing idea that input processes contribute to increase the load of the particulate reservoir(s) on the shelf from which physical exchange processes, and particularly winter cascading of dense shelf water, draw the particles responsible for increased transfer towards the deeper slope.

Acknowledgements

We acknowledge the support from the French "Programme National Environnement Côtier" and the European Commission under contracts MAS2-CT93-0053 (Euromarge-NB), MAS3-CT96-0051 (MTP II-MATER), and EVK3-CT-2002-0079 (EUROSTRATAFORM). We thank Claudie Marec and the CNRS-INSU team in Brest, for support with instrumentation, and the crews and captains from the various research vessels (*G. Petit, Tethys II, Europe*) for their invaluable assistance during the numerous mooring deployments and recoveries, sometimes under rough weather conditions. Special thanks also to Claude and Franck Ratti from Technicap for having constructed solid sediment traps that withstood, so far, 13 years of continuous deployment with (almost) no failure. We are grateful to Marie-Dominique Loÿe-Pilot for kindly providing the data on atmospheric deposition at the Ponte Leccia site in Corsica, to Jean-Claude Marty for the Chlorophyll-a data and the trap data from the DYFAMED site in the Ligurian Sea, and to Maud Guarracino for formatting the various times series of complementary and current meter derived data. Finally, we are deeply indebted to Béatrice Chatain for her efficient advice on the statistical analyses performed in this work, and to the two anonymous reviewers for their fruitful comments and pertinent corrections on the initial manuscript.

References

Aloïsi, J.C., Auffret, G.A., Auffret, J.P., Barusseau, J.P., Hommeril, P., Larsonneur, C., Monaco, A., 1977. Essai de modélisation de la sédimentation actuelle sur les plateaux continentaux français. Bull. Soc. Geol. Fr. 7, 183–195.

Aloïsi, J.C., Cambon, J.P., Carbonne, J., Cauwet, G., Millot, C., Monaco, A., Pauc, H., 1982. Origine et rôle du néphéloïde profond dans le transfert des particules au milieu marin. C. R. Acad. Sci. Paris 289, 879–882.

Antia, A.N., Von Bodungen, B., Peinert, R., 1999. Particle flux across the mid-European continental margin. Deep-Sea Res., Part I 46, 1999–2024.

Antia, A.N., Maassen, J., Herman, P., Voss, M., Scholten, J., Groom, S., Miller, P., 2001. Spatial and temporal variability of particle flux at the N.W. European continental margin. Deep-Sea Res., Part II 48, 3083–3106.

Armstrong, R.A., Lee, C., Hedges, J.I., Honjo, S., Wakeham, S.G., 2002. A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. Deep-Sea Res., Part II 49, 219–236.

Baker, E.T., Milburn, H.B., Tennant, D.A., 1988. Field assessment of sediment trap efficiency under varying flow conditions. J. Mar. Res. 46, 573–592.

Berelson, W.M., 2001. The flux of particulate organic carbon into the ocean interior: a comparison of four U.S. JGOFS regional studies. Oceanography 14 (4), 59–67.

Bergametti, G., Gomes, L., Remoudaki, E., Desbois, M., Martin, D., Buat-Menard, P., 1989. Present transport and deposition patterns of African dusts to the Northwestern Mediterranean. In: Leinen, M., Sarnthein, M. (Eds.), Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport, pp. 227–252.

Béthoux, J.P., Durrieu de Madron, X., Nyffeler, F., Taillez, D., 2002. Deep water in the western Mediterranean: peculiar 1999 and 2000 characteristics, shelf formation hypothesis, variability since 1970 and geochemical inferences. J. Mar. Syst. 33–34, 117–131.

Betzer, P.R., Showers, W.J., Laws, E.A., Winn, C.D., Di Tullio, G.R., Kroopnick, P.M., 1984. Primary production and particulate fluxes on a transect of the Equator at 153°W in the Pacific Ocean. Deep-Sea Res. 31, 1–11.

Biscaye, P.E., Anderson, R.F., 1994. Fluxes of particulate matter on the slope of the southern Middle Atlantic Bight: SEEP-II. Deep-Sea Res. 41 (2–3), 459–510.

Biscaye, P.E., Anderson, R.F., Deck, B.L., 1988. Fluxes of particles and constituents to the eastern United States continental slope and rise: SEEP-I. Cont. Shelf Res. 8, 855–904.

Bosc, E., Bricaud, A., Antoine, D., 2004. Seasonal and interannual variability in algal biomass and primary production in the Mediterranean Sea, as derived from 4 years of SeaWiFS observations. Glob. Biogeochem. Cycles 18, GB1005. doi:10.1029/2003GB002034.

Boynton, W.R., Kemp, W.M., Barnes, J.M., Matteson, L.L., Rohland, F.M., Jasinski, D.A., Kimble, H.L., 1993. Ecosystem Processes Component Level 1 Interpretive Report, vol. 10. Chesapeake Biological Laboratory, University of Maryland System, Solomons, MD. 20688-0038. Ref. No.[UMCEES]CBL 93-030a.

Butman, C.A., Grant, W.D., Stolzenbach, K.D., 1986. Predictions of sediment trap biases in turbulent flows: a theoretical analysis based on observations from the literature. J. Mar. Res. 44, 601–644.

Chung, Y., Hung, G.W., 2000. Particulate fluxes and transports on the slope between the southern East China Sea and South Okinawa Trough. Cont. Shelf Res. 20, 571–597.

Conte, M.H., Ralph, N., Ross, E.H., 2001. Seasonal and interannual variability in deep ocean particle fluxes at the Oceanic Flux Program (OFP)/Bermuda Atlantic Time Series (BATS) site in the Sargasso Sea near Bermuda. Deep-Sea Res., Part II 48, 1471–1505.

Deuser, W.G., Ross, E.H., 1980. Seasonal changes in the flux of organic carbon to the deep Sargasso Sea. Nature 283, 364–365.

Deuser, W.G., Jickells, T.D., King, P., Commeau, J.A., 1995. Decadal and annual changes in biogenic opal and carbonate fluxes to the deep Sargasso Sea. Deep-Sea Res., Part I 42, 1923–1932.

Diaz, F., Raimbault, P., Conan, P., 2000. Small-scale study of primary productivity during spring in a Mediterranean coastal area (Gulf of Lions). Cont. Shelf Res. 20, 975–996.

Dufau, C., Marsaleix, P., Petrenko, A., Dekeyser, Y., 2004. 3D modeling of the Gulf of Lion's hydrodynamics during January 1999 (MOOGLI 3 experiment) and late winter 1999. WIW formation and cascading over the shelfbreak. J. Geophys. Res. 109 (C11). doi:10.1029/2003 JC002019.

Durrieu de Madron, X., Panouse, M., 1996. Transport de matière en suspension sur le plateau continental du Golfe du Lion- Situation estivale et hivernale. C. R. Acad. Sci., Ser. IIa, Paris 322, 1061–1070.

Durrieu de Madron, X., Radakovitch, O., Heussner, S., Loye-Pilot, M.D., Monaco, A., 1999. Role of the climatological and current variability on shelf–slope exchanges of particulate matter. Evidence from the Rhône continental margin (NW Mediterranean). Deep-Sea Res., Part I 46, 1513–1538.

Durrieu de Madron, X., Abassi, A., Heussner, S., Monaco, A., Aloïsi, J.C., Radakovitch, O., Giresse, P., Buscail, R., Kerhervé, P., 2000. Particulate matter and organic carbon budgets for the Gulf of Lions (NW Mediterranean). Oceanol. Acta 23 (6), 717–730.

Durrieu de Madron, X., Denis, L., Diaz, F., Garcia, N., Guieu, C., Grenz, C., Löye-Pilot, M.D., Ludwig, W., Moutin, T., Raimbault, P., Ridame, C., 2003. Nutrients and carbon budgets for the Gulf of Lions during the MOGLI cruises. Oceanol. Acta 26 (4), 421–434.

Durrieu de Madron, X., Zervakis, V., Theocharis, A., Georgopoulos, D., 2005. Comments to cascades of dense water around the world ocean. Prog. Oceanogr. 64, 83–90.

Estournel, C., Durrieu de Madron, X., Marsaleix, P., Auclair, F., Julliand, C., Vehil, R., 2003. Observations and modelisation of the winter coastal oceanic circulation in the Gulf of Lions under wind conditions influenced by the continental orography (FETCH experiment). J. Geophys. Res. 108 (C3), 8059.

Fabres, J., Calafat, A., Sanchez-Vidal, A., Canals, M., Heussner, S., 2002. Composition and spatio-temporal variability of particle fluxes in the Western Alboran Gyre, Mediterranean Sea. J. Mar. Syst. 33–34, 431–456.

Ferré, B., 2004. Comparaison de l'effet des tempêtes et du chalutage sur la resuspension et le transport des matières particulaires dans le Golfe du Lion. Ph.D. Thesis, University of Perpignan, 256 pp.

Ferré, B., Guizien, K., Durrieu de Madron, X., Palanques, A., Guillén, J., Grémare, A., 2005. Fine sediment dynamics study during a winter storm in the Gulf of Lion shelf (NW Mediterranean). Cont. Shelf Res. 25, 2410–2427.

Flexas, M., Durrieu de Madron, X., Garcia, M.A., Canals, M., Arnau, P., 2002. Flow variability in the Gulf of Lions during the MATER HFF Experiment (March–May 1997). J. Mar. Syst. 33–34, 197–214.

Gardner, W.D., 1985. The effect of tilt on sediment trap efficiency. Deep-Sea Res. 32, 349–361.

Gardner, W.D., Walsh, I.D., 1990. Distribution of macroaggregates and ne-grained particles across a continental margin and their potential role in fluxes. Deep-Sea Res. 37, 401–411.

Goni, M.A., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Astor, Y., Varela, R., Muller-Karger, F., 2003. Biogenic fluxes in the Cariaco Basin: a combined study of sinking particulates and underlying sediments. Deep-Sea Res., Part I 50, 781–807.

Guarracino, M., Barnier, B., Marsaleix, P., Durrieu de Madron, X., Monaco, A., Escoubeyrou, K., Marty, J.-C., 2006. Hydrodynamic control of the transfer of particulate matter on a Northwestern Mediterranean margin: from observations to modelling. J. Mar. Res. 64, 195–220.

Heussner, S., Ratti, C., Carbonne, J., 1990. The PPS 3 time series sediment traps and the trap sample processing techniques used during the ECOMARGE experiment. Cont. Shelf Res. 10, 943–958.

Heussner, S., Calafat, A.M., Palanques, A., 1996. Quantitative and qualitative features of particle fluxes in the North-Balearic Basin. In: Canals, M., Casamor, J.L., Cacho, I., Calafat, A.M., Monaco, A. (Eds.), EUROMARGE-NB Final Report MAST II Programme, vol. II. European Union, Brussels, pp. 43–66.

Heussner, S., Durrieu De Madron, X., Radakovitch, O., Beaufort, L., Biscaye, P.E., Carbonne, J., Delsaut, N., Etcheber, H., Monaco, A., 1999. Spatial and temporal patterns of downward particle fluxes on the continental slope of the Bay of Biscay (Northeastern Atlantic). Deep-Sea Res., Part II 46 (10), 2101–2146.

Inthorn, M., Wagner, T., Scheeder, G., Zabel, M., 2006. Lateral transport controls distribution, quality, and burial of organic matter along continental slopes in high-productivity areas. Geology 34 (3), 205–208.

Iseki, K., Okamura, K., Kiyomoto, Y., 2003. Seasonality and composition of downward particulate fluxes at the continental shelf and Okinawa Trough in the East China sea. Deep-Sea Res., Part II 50, 457–473.

Jickells, T.D., Newton, P.P., King, P., Lampitt, R.S., Boutle, C., 1996. A comparison of sediment trap records of particle fluxes from 19° to 48° N in the northeast Atlantic and their relation to surface water productivity. Deep-Sea Res., Part II 43, 971–986.

Karl, D.M., Christian, J.R., Dore, J.E., Hebel, D.V., Letelier, R.M., Tupas, L.M., Winn, C.D., 1996. Seasonal and interannual variability in primary production and particle flux at Station ALOHA. Deep-Sea Res., Part II 43, 539–568.

Karl, D.M., Dore, J.E., Lukas, R., Michaelis, A.F., Bates, N.R., Knap, A., 2001. Building the long-term picture: the US JGOFS time series programs. Oceanography 14 (4), 6–18.

King, P., Kennedy, H., Newton, P.P., Jickells, T.D., Brand, T., Calvert, S., Cauwet, G., Etcheber, H., Head, B., Khripounoff, A., Manighetti, B., Miquel, J.C., 1998. Analysis of total and organic carbon and total nitrogen in settling oceanic particles and a marine sediment: an interlaboratory comparison. Mar. Chem. 60, 203–216.

Knap, A., Michaels, A., Close, A., Ducklow, H. Dickson, A. (eds.), 1996. Protocols for the Joint Global Ocean Flux Study (JGOFS) Core Measurements. JGOFS Report Nr. 19, vi+170 pp. Reprint of the IOC Manuals and Guides No. 29, UNESCO 1994.

Lampitt, R.S., 1985. Evidence for the seasonal deposition of detritus to the seafloor and its subsequent resuspension. Deep-Sea Res. 32, 885–897.

Lampitt, R.S., Newton, P.P., Jickells, T.D., Thomson, J., King, P., 2000. Near-bottom particle flux in the abyssal northeast Atlantic. Deep-Sea Res., Part II 47, 2051–2071.

Lapouyade, A., Durrieu de Madron, X., 2001. Seasonal variability of the advective transport of suspended particulate matter and organic carbon in the Gulf of Lions (NW Mediterranean). Oceanol. Acta. 24, 295–312.

Leblanc, K., Quéguiner, B., Raimbault, P., Garcia, N., 2005. Efficiency of the silicate pump at a coastal oligotrophic site in the Mediterranean Sea. Biogeosciences 2, 219–229.

Lefevre, D., Minas, H.J., Minas, M., Robinson, C., Le B. Williams, P.J., Woodward, E.M.S., 1997. Review of gross community production, primary production, net community production and dark community respiration in the Gulf of Lions. Deep-Sea Res., Part II 44, 801–832.

Liu, K.K., Atkinson, L., Chen, C.T.A., Gao, S., Hall, J., MacDonald, R.W., Talaue McManus, L., Quiñones, R., 2000. Exploring continental margin carbon fluxes on a global scale; EOS Transactions. Am. Geophys. Union 81 (52), 641–644.

Löye-Pilot, M.D., Martin, J.M., 1996. Saharan dust input to the western Mediterranean: an eleven years record in Corsica. In: Guerzoni, S., Chester, R. (Eds.), The Impact of African Dust Across the Mediterranean. Kluwer, pp. 191–199.

Löye-Pilot, M.D., Martin, J.M., Morelli, J., 1986. Influence of Saharan dust on the rain acidity and atmospheric input to the Mediterranean. Nature 321 (6088), 427–428.

Lutz, M., Dunbar, R., Caldeira, K., 2002. Regional variability in the vertical flux of particulate organic carbon in the ocean interior. Glob. Biogeochem. Cycles 16, 91–110.

Marchant, M., Hebbeln, D., Giglio, S., Coloma, C., González, H.E., 2004. Seasonal and interannual variability in the flux of planktic Foraminifera in the Humboldt Current System off central Chile (30°S). Deep-Sea Res., Part II 51, 2441–2455.

McCave, I.N., Hall, I.R., Antia, A.N., Chou, L., Dehairs, F., Lampitt, R.S., Thomsen, L., van Weering, T.C.E., Wollast, R., 2001. Distribution, composition and flux of particulate material over the European margin at 47°–50°N. Deep-Sea Res., Part II 48, 3107–3139.

Millot, C., 1990. The Gulf of Lion's hydrodynamics. Cont. Shelf Res. 10 (9–11), 885–894.

Miquel, J.C., Fowler, S.W., La Rosa, J., Buat-Menard, P., 1994. Dynamics of the downward flux of particles and carbon in the open northwestern Mediterranean Sea. Deep-Sea Res., Part II 41, 243–261.

Monaco, A., Courp, T., Heussner, S., Carbonne, J., Fowler, S.W., Deniaux, B., 1990. Seasonality and composition of particulate fluxes during ECOMARGE-I, western Gulf of Lions. Cont. Shelf Res. 10, 959–988.

Monaco, A., Durrieu de Madron, X., Radakovitch, O., Heussner, S., Carbonne, J., 1999. Origin and variability of downward biogeochemical fluxes on the Rhône continental margin (NW Mediterranean). Deep-Sea Res., Part I 46, 1483–1511.

Mortlock, R.A., Froelich, P.N., 1989. A simple method for the rapid determination of biogenic opal in pelagic marine sediments. Deep-Sea Res. 36, 1415–1426.

Muller-Karger, F.E., Varela, R., Thunell, R., Luerssen, R., Hu, C., Walsh, J.J., 2005. The importance of continental margins in the global carbon cycle. Geophys. Res. Lett. 32, L01602. doi:10.1029/2004GL021346.

Neuer, S., Ratmeyer, V., Davenport, R., Fischer, G., Wefer, G., 1997. Deep water particle flux in the Canary Island region: seasonal trends in relation to long-term satellite derived pigment data and lateral sources. Deep-Sea Res., Part I 44, 1451–1466.

Nittrouer, C.A., Wright, L.D., 1994. Transport of particles across continental shelves. Rev. Geophys. 32, 85–113.

Pace, M., Knauer, G., Karl, D., Martin, J., 1987. Primary production, new production and vertical flux in the eastern Pacific Ocean. Nature 325, 803–804.

Palanques, A., Durrieu de Madron, X., Puig, P., Fabres, J., Guillén, J., Calafat, A., Canals, M., Heussner, S., Bonnin, J., 2006-this issue. Suspended sediment fluxes and transport processes in the Gulf of Lions submarine canyons. The role of storms and dense water cascading. Mar. Geol. 234, 43–61. doi:10.1016/j.margeo.2006.09.002.

Petrenko, A., Leredde, Y., Marsaleix, P., 2005. Circulation in a stratified and wind-forced Gulf of Lions, NW Mediterranean Sea: in situ and modeling data. Cont. Shelf Res. 25, 7–27.

Puig, P., Palanques, A., 1998. Temporal variability and composition of settling particle fluxes on the Barcelona continental margin (Northwestern Mediterranean). J. Mar. Res. 56, 639–654.

Roussiez, V., Ludwig, W., Monaco, A., Probst, J.L., Bouloubassi, I., Buscail, R., Saragoni, G., 2006. Sources and sinks of sediment-bound contaminants in the Gulf of Lions (NW Mediterranean Sea): a multi-tracer approach. Cont. Shelf Res. 26, 1843–1857.

Sanchez-Vidal, A., Calafat, A., Canals, M., Fabres, J., 2004. Particle fluxes in the Almeria-Oran Front: control by coastal upwelling and sea surface circulation. J. Mar. Syst. 52, 89–106.

Sempéré, R., Charrière, B., Van Wambeke, F., Cauwet, G., 2000. Carbon inputs of the Rhône River to the Mediterranean Sea: biogeochemical implications. Glob. Biogeochem. Cycles 14, 669–681.

Siegel, D.A., Deuser, W.G., 1997. Trajectories of sinking particles in the Sargasso Sea: modeling of statistical funnels above deep-ocean sediment traps. Deep-Sea Res., Part I 44, 1519–1541.

Strickland, J.D.H., 1960. Measuring the production of marine phytoplankton. Fish. Res. Board Can. Bull. 122, 1–172.

Suess, E., 1980. Particulate organic carbon flux in the ocean-surface productivity and oxygen utilization. Nature 288, 260–263.

Swart, H.D., 1974. Offshore Sediment Transport and Equilibrium Beach Profiles. Delft Hydraulics Laboratory Doctor's Thesis, Publication No. 131, 318pp. The Netherlands.

Thunell, R.C., 1998. Seasonal and annual variability in particle fluxes in the Gulf of California: a response to climate forcing. Deep-Sea Res., Part I 45, 2059–2083.

Tusseau-Vuillemin, M.H., Mortier, L., Herbaut, C., 1998. Modelling nitrate fluxes in an open coastal environment (Gulf of Lions): transport versus biogeochemical processes. J. Geophys. Res. 103 (C4), 7693–7798.

Ulses, C., 2004. Dynamique océanique et transport de matière particulaire dans le Golfe du Lion: Crue, tempête et période hivernale. Ph.D. Thesis, University Paul Sabatier, Toulouse, 247 pp.

Unger, D., Ittekkot, V., Schäfer, P., Tiemann, J., Reschke, S., 2003. Seasonality and interannual variability of particle fluxes to the deep Bay of Bengal: influence of riverine input and oceanographic processes. Deep-Sea Res., Part II 50, 897–923.

US GOFS, 1989. Sediment trap technology and sampling. In: Knauer, G., Asper, V. (Eds.), Report of the US GOFS Working Group on Sediment Trap Technology and Sampling. Planning Report, vol. 10. US GOFS Planning Office, Woods Hole, MA, 94 pp.

Van Wambeke, F., Heussner, S., Diaz, F., Raimbault, P., Conan, P., 2002. Small-scale variability in the coupling/uncoupling of bacteria, phytoplankton and organic carbon fluxes along the continental margin of the Gulf of Lions, Northwestern Mediterranean Sea. J. Mar. Syst. 33–34, 411–429.

Van Weering, T.C.E., de Stigter, H.C., Boer, W., deHaas, H., 2002. Recent sediment transport and accumulation on the NW Iberian margin. Prog. Oceanogr. 52, 349–371.

Walsh, I.D., Fischer, K., Murray, D., Dymond, J., 1988. Evidence for resuspension of rebound particles from near-bottom sediment traps. Deep-Sea Res. 35, 59–70.

Waniek, J.J., Schulz-Bull, D.E., Blanz, T., Prien, R.D., Oschlies, A., Müller, T.J., 2005. Interannual variability of deep water particle flux in relation to production and lateral sources in the northeast Atlantic. Deep-Sea Res., Part I 52, 33–50.

Wong, C.S., Whitney, F.A., Crawford, D.W., Iseki, K., Matear, R.J., Johnson, W.K., Page, J.S., Timothy, D., 1999. Seasonal and interannual variability in particle fluxes of carbon, nitrogen and silicon from time series of sediment traps at Ocean Station P, 1982–1993: relationship to changes in subarctic primary productivity. Deep-Sea Res., Part II 46, 2735–2760.