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Settling particle fluxes across the continental margin of the Gulf of Lion: the role of dense shelf water cascading

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Abstract

Settling particles were collected using sediment traps deployed along three transects in the Lacaze-Duthiers and Cap de Creus canyons and the adjacent southern open slope from October 2005 to October 2006. The settling material was analysed to obtain total mass fluxes and main constituent contents (organic matter, opal, calcium carbonate, and siliciclastics). Cascades of dense shelf water from the continental shelf edge to the lower continental slope occurred from January to March 2006. They were traced through strong negative near-bottom temperature anomalies and increased current speeds, and generated two intense pulses of mass fluxes in January and March 2006. This oceanographic phenomenon appeared as the major physical forcing of settling particles at almost all stations, and caused both high seasonal variability in mass fluxes and important qualitative changes in settling material. Fluxes during the dense shelf water cascading (DSWC) event ranged from 90.1 $g\,m^{-2}\,d^{-1}$ at the 1000 m depth station in the Cap de Creus canyon to 3.2 $g\,m^{-2}\,d^{-1}$ at the canyon mouth at 1900 m. Fractions of organic matter, opal and calcium carbonate components increased seaward, thus diminishing the siliciclastic fraction. Temporal variability of the major components was larger in the canyon mouth and open slope sites, due to the mixed impact of dense shelf water cascading processes and the pelagic biological production. Results indicate that the cascading event remobilized and homogenized large amounts of material down canyon and southwardly along the continental slope contributing to a better understanding of the internal dynamics of DSWC events. While the late winter/early spring bloom signature was diluted when DSWC occurred, the primary production dynamics were observable at all stations during the rest of the year and highlighted the biological community succession in surface waters.

1 Introduction

Continental shelves are bypass zones of lithogenic and biogenic material from their source in the continent to their sink in the deep sea floor. In addition, high biological production takes place in shelf regions due to nutrients inputs from land and coastal upwelling. In those environments, settling material is subjected to biological, physical and chemical processes among which the remobilization basinwards supposes the principal way of shelf erosion. Actually, experiments carried out in the Western Mediterranean Sea show differences of three orders of magnitude when comparing settling particles in the slope with the open basin, underlining the importance of continental shelves as a source of material for the adjoining slope environment (Heussner et al., 2006; Martín et al., 2006; Zúñiga et al., 2008, 2009)

Suspended particles on the continental shelf are mainly advected through bottom or intermediate nepheloid layers (Durrieu de Madron and Panouse, 1996), and particulate fluxes on the slope are larger closer to the bottom (Monaco et al., 1990; Heussner et al., 1999, 2006). One mechanism that facilitates that shelf-deep ocean exchange on the Gulf of Lion's margin is dense shelf water cascading (DSWC). It is a gravity current associated to the shelf edge overflow and down-slope sinking of continental shelf waters due to their excess density gained by cooling and evaporation, (Ivanov et al., 2004). The Gulf of Lion (GoL) is one of the few regions in the Mediterranean where this phenomenon occurs (Durrieu de Madron et al., 2005; Canals et al., 2009). It has retained the attention of several recent studies as it seems an efficient way of sediment erosion, transport and deposition (Canals et al., 2006; Palanques et al., 2006; Bourrin et al., 2008; Sanchez-Vidal et al., 2008; Ulses et al., 2008a). Besides lateral (cross-slope) transport of material, particle fluxes from open-ocean surface waters also play an important role in Western Mediterranean continental margins (Heussner et al., 2006; Fabres et al., 2008; Sanchez-Vidal et al., 2009).

In this paper we evaluate the behaviour and characteristics of settling particulate matter collected during the HERMES (Hotspot Ecosystems Research on the Margins of

European Seas) project along the Lacaze-Duthiers and Cap de Creus canyons and the adjacent southern open slope from October 2005 to October 2006. Because a severe DSWC event took place during the experiment we have the opportunity to evaluate the quantitative and qualitative impact of that event on the dynamic of the sedimentary particles.

2 Study area and oceanographic settings

The GoL margin is located in the Western Mediterranean and extends from Cap Croisette in the northeast to Cap de Creus in the southwest (Fig. 1). It is a wide, progressive margin incised by numerous submarine canyons extending down to the Algero-Balearic basin. The continental shelf is fed by different watersheds (Fig. 1): in the northeast, the Rhône River contributes to more than 90% of the total annual liquid and solid inputs of the rivers discharging to the Gulf of Lion mainly during the snowmelt in spring (Bourrin et al., 2006), whereas the southwestern rivers Hérault, Orb, Aude and Têt are subjected to a Mediterranean regime with short and intense flash-flood events (Serrat et al., 2001).

Sea surface circulation is characterized by the anticlockwise flow of modified Atlantic waters that form the Northern Current (Fig. 1). Its structure changes seasonally, becoming thicker and narrower and flowing closer to slope with maximum flow during the winter season (Millot, 1999). The Northern Current is associated to a permanent shelf-slope density front separating shelf and open-sea waters. Its position and meandering is suggested to significantly influence shelf-slope exchanges (Flexas et al., 2002) and organic carbon export (Van Wambeke, 2002). The Northern Current also controls the GoL primary production distribution, separating shelf waters directly influenced by the Rhône river from offshore waters with a clear seasonality in surface and deep chlorophyll *a* concentrations, as revealed by both in situ measurements (Lefevre et al., 1997) and satellite images (Bosc et al., 2004). Main biological features identified in the southwestern GoL are spring mesotrophy when blooms develop (Vidussi et al., 2000) and summer stratified oligotrophic waters followed by autumn blooms (Marty et al., 2008). When winter meteorological conditions are severe, coastal and open-ocean convection occur, and both contribute to the renewal of the Western Mediterranean Deep Water (Bethoux et al., 1999; Fuda et al., 2000).

Within that context, sedimentary processes in the Gulf of Lion's continental shelf and slope have been the principal issue of several projects and are nowadays well understood. Fine sediments on the continental shelf are advected by the mean anticlockwise near-bottom flow, and exit the shelf through the westernmost submarine canyons mainly during E and SE winter storm events and DSWC (Palanques et al., 2006), resulting in an annual inventory budget on the shelf essentially equal to cero (Courp et al., 1990). Submarine canyons represent the preferential pathway (Monaco et al., 1990), as the shelf edge incision interacts with the bottom flow and funnel shelf water and material basinward. Significant increase of near-bottom transport of sediment were detected when storm-induced downwelling interacts with DSWC, transporting resuspended sediments through the westernmost canyons as bottom turbidity layers (Palanques et al., 2006; Bonnin et al., 2008) and eroding canyon floor sediments (Canals et al., 2006; Puig et al., 2008).

3 Material and methods

3.1 Experimental design and data recovery

Nine instrumented moorings were deployed in 3 different transects along the axes of the Lacaze-Duthiers (LDC) and Cap de Creus (CCC) canyons at upper canyon (300 m), middle canyon (1000 m) and lower canyon (1500 m) and at canyon mouth were both canyons converge (1900 m), and along the southern open slope (SOS) at 1000 and 1900 m water depth (Fig. 1). The sampling period was from mid October 2005 to late October 2006 with a maintenance turnaround and sample recovery in mid April 2006. Each mooring was equipped with a PPS3 Technicap sequential sampling sediment trap

(12 collecting cups, 0.125 m^2 opening and 2.5 height/diameter aspect ratio for the cylindrical part) at 30 m above bottom and an Aanderaa current meter (RCM7/8/9) at 5 m above the bottom. In addition, the LDC1000 station included an extra trap-currentmeter pair at 500 m above the bottom (LDC1000-500 mab). Sampling intervals were set at 15 days for traps and 30 min for current meters. Failure of the sediment trap rotating motor resulted in the absence of samples during the first six months at the CCC300 station and during two months at the LDC1000 station. In addition, early January 2006 sediment sampling bottle at the CCC1000 station overflowed and the excess material probably entered into the following cup during the rotation of the carrousel, so consecutive flux values are respectively under and overestimations.

3.2 Forcing conditions

Daily fluvial discharges ($m^3 s^{-1}$) of the Rhône and the southwestern rivers (Hérault, Orb, Aude, and Têt) were obtained from *Compagnie Nationale du Rhône* and the *Banque HYDRO* of the French Ministry of Environment. Open ocean chlorophyll *a* (chl *a*) concentration (mg m^{-3}) recorded by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were obtained from the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI) at the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). From OBPG SeaWiFS 8-Day Global 9-km time series, points with maximum resolution of 0.1 degree that cover our study stations were defined and mean temporal evolution of chl *a* was obtained. Surface (3 m of water depth) coastal chl *a* data was obtained from the SOLA monitoring station, located 1 km off Banyuls sur Mer and provided by Service d'Observation en Milieu LIToral (SOMLIT). Finally, significant wave heights H1/3 (m) data from the Sète wave buoy offshore station was provided by the *Centre d'Etudes Maritimes et Fluviales.*

3.3 Sample treatment and analytical procedures

Sediment trap samples were processed in the laboratory according to the procedure described by Heussner et al. (1990). Large swimming organisms were removed by wet sieving through a 1 mm nylon mesh, while organisms <1 mm were handpicked under a microscope with fine-tweezers. Samples were (i) repeatedly split into aliquots using a high precision peristaltic pump robot to obtain 10–20 mg sub-samples, (ii) filtered through glass-fibre prefilters for carbon and nitrogen analysis and 0.45 μm pore size cellulose membranes for total mass determination and biogenic Si analysis, (iii) rinsed with distilled water and, finally, (iv) dried at 40°C during 24 h for dry weight determination. The precision of mass estimates, as measured by the coefficient of variation was 4.1%.

Total and organic carbon, and total nitrogen contents were measured using an elemental analyzer (EA Flash series 1112 and NA 2100). Samples for organic carbon analysis were first decarbonatated using repeated additions of 100 μl 25% HCl with 60°C drying steps in between until no effervescence occurred. Organic matter (OM) content has been estimated as twice the total organic carbon content, and carbonate content was calculated assuming all inorganic carbon is contained within the calcium carbonate ($CaCO_3$) fraction, thus using the molecular mass ratio 100/12. Uncertainties were lower than 0.1% as determined from replicates of the certified estuarine sediment MESS-1. Biogenic Si was analyzed using a two-step extraction with 0.5 M Na_2CO_3 (2.5 h each) separated after filtration of the leachate. Inductive Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) was used to analyze Si and Al contents in both leachates, and a correction of the Si of the first by the Si/Al relation of the second one was applied to obtain the opaline Si concentration (Fabres et al., 2002). Corrected Si concentrations were transformed to opal after multiplying by a factor of 2.4 (Mortlock and Froelich, 1989). Analytical precision of opal measurements was 4.5%. The siliciclastic fraction was calculated assuming % siliciclastic=100−(% OM+% $CaCO_3$+% opal). Grain size analysis of samples was per-

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formed after removal of organic matter with 10% H_2O_2 on a Coulter LS 230 Laser Particle Size Analyzer.

4 Results

4.1 River, waves and Chl *a* measurement on the shelf

The Rhône river main discharge during the monitored period (October 2005 to October 2006) lasted from mid February 2006 to the end of May 2006, with basal discharge of 1000 $m^3 s^{-1}$ and a maximum peak recorded in early April 2006 of 4165 $m^3 s^{-1}$. In contrast, southwestern rivers showed episodic water discharge pulses in autumn and winter, peaking in mid November 2005 and at the very end of January 2006 to 1390 $m^3 s^{-1}$ and 2923 $m^3 s^{-1}$, respectively (Fig. 2a). Significant wave heights (H1/3) were recorded during the experiment period, with an up to 4 m peak reached in early December 2005 and up to 2.5 m in January 2006 (Fig. 2c). Furthermore, spring and autumn were periods of recurrent wave height increases. Coastal chl *a* concentration was high form middle February to middle April 2006, with a major concentration peak of the pigment during early March (4.2 mg m^{-3}). Offshore, the maximum concentrations (up to 2 mg m^{-3}) were reached at the end of March and mid April 2006 (Fig. 2b). Minimum chl *a* concentrations (0.07 at coastal site and around 0.2 mg m^{-3} at open sea) were recorded during summer months. In addition, a weak increase of chl *a* concentration was detected in September 2006 at both locations and during autumn 2005 at the coastal zone.

4.2 Near-bottom temperature and currents measurements on the slope

Current speed, temperatures and directions at 5 m above the bottom recorded by the current meters display two clearly different periods (Fig. 3). From January to March 2006 several pulses of maximum current speeds (punctual peaks of up to 80 m s^{-1} at the CCC300 station) fitted along canyons axis and along slope were recorded. These strong currents were associated with a strong temperature anomaly (i.e. −2.4°C at the CCC300 station) which is the direct evidence of the occurrence of DSWC. Maximum speeds were reached in early and late January 2006 and March 2006. This intense DSWC event was the last up to date recorded, and followed those that occurred in winters 1998-99 (Bethoux et al., 2002) and 2004/05 (Canals et al., 2006; Puig et al., 2008). Out of the main DSWC period current velocity and temperature at middle canyon were relatively stable. At the canyon heads instabilities remained until mid July and increases in current speed and temperature were detected in autumn 2005 and 2006. At lower canyon, canyon mouth and open slope station current velocities and temperatures did not stabilized until August.

4.3 Spatial and temporal variability of downward particle fluxes

Mean total mass flux show a decreasing off-shelf trend (Table 1) with greater values inside canyons compared to the open slope. Values ranged between 11.7 g m^{-2} d^{-1} in CCC1000 m station down to 0.7 g m^{-2} d^{-1} in the CCC1900 station. Mean flux at the upper open slope (SOS1000) was lower (3.4 g m^{-2} d^{-1}) when compared with the stations at the same depth inside the canyons (11.7 and 6.7 g m^{-2} d^{-1} at CCC1000 and LDC1000, respectively). In contrast, the deep open slope SOS1900 station recorded higher mean flux values (0.8 g m^{-2} d^{-1}) than CCC1900 station at the confluence of both canyons (0.7 g m^{-2} d^{-1}).

Particle flux time series at all stations display high temporal variability (Table 1, Fig. 4). At the CCC1000 station there was a 90-fold increase in total mass flux in early January 2006 (90.0 g m^{-2} d^{-1}, maximum flux recorded) respect to late July 2006 (1.0 g m^{-2} d^{-1}) (Fig. 4b). The main visible feature of the temporal variability is the total mass flux increase in January 2006 in most of the stations and the maintenance of high values during the following two months, until March-early April 2006, with the exception of LDC300 and presumably CCC300. SOS1000 station, for example, recorded fluxes above 0.6 g m^{-2} d^{-1} in late autumn 2005 that increased to 11.4 g m^{-2} d^{-1} in late March 2006, with punctual peaks of up to 34.1 g m^{-2} d^{-1} in late January 2006 (Fig. 4). In addition, this maximum flux period (from January to March 2006) was characterized by two discrete peaks at most of the stations. The first particle flux peak was registered in early January 2006 (CCC1000, CCC1500 and SOS1000 stations), late January 2006 (LDC1000, LDC1000-500mab, SOS1900) and early February 2006 (LDC1500 and CCC1900), and represented the maximum total mass flux at almost all stations except for the LDC1500 and CCC1900 stations, were the major particle fluxes were recorded during the second peak in late March 2006 (early April at SOS1900 m, and early May in LDC1000-500 mab). Total mass flux in the Lacaze-Duthiers upper canyon (LDC300) displayed an inverse behaviour, with fluxes decreasing from 14.0 g m^{-2} d^{-1} in late December 2005 down to a minimum of 0.3 g m^{-2} d^{-1} in early March 2006. Total mass fluxes were relatively stable at upper canyon stations during late spring to early summer, with mean values of 4.5 g m^{-2} d^{-1} at CCC300 and 4.0 g m^{-2} d^{-1} at LDC300 stations, whereas during late summer (from late August) and autumn seasons (both 2005 and 2006) mean total mass fluxes increased up to 11.9 and 12.6 g m^{-2} d^{-1}, respectively. At lower canyon, canyon mouth and open slope stations particle fluxes decreased down to 1 g m^{-2} d^{-1} after March 2006. In the case of lower Cap de Creus canyon, flux decreased exponentially until the end of the experiment in October 2006, when values recorded were similar to those recorded in October 2005 and <0.1 g m^{-2} d^{-1}.

4.4 Trends in composition of settling particles

Mean flux and concentrations of major constituents (OM, opal, $CaCO_3$ and siliciclastic) are shown in Table 1. The siliciclastic component predominated at all stations, ranging from 59.5 to 68.8%. Siliciclastic mean flux diminished from middle canyon and slope stations while increasing water depth, so relative content of non-siliciclastic components increased along the same direction. Thus, concentration of OM varied from 3.5% at the upper canyons to 4.1% at the canyon mouth, and from 3.0% to 3.8% at the open slope transect. Opal and $CaCO_3$ recorded almost the same off-margin increase.

Temporal variability of main constituents is quite evident, with main fluctuations recorded similarly in all traps during spring. During summer and autumn seasons peaks of biogenic components (OM, opal and $CaCO_3$) (Fig. 5) were higher in lower canyon, canyon mouth and open slope stations. Maximum OM concentrations were recorded during December 2005 and August 2006, with values up to 19.0% at CCC1500, 16.2% at SOS1900 and 13.9% at CCC1900 (Fig. 5a). OM content reached minimum values during January 2006 at all stations and during autumn 2006 at upper canyon and middle canyon stations. Accordingly, minimum opal concentrations were recorded during January–March 2006 at all stations except at both upper canyons, that were recorded during autumn 2005 (LDC300) and autumn 2006 (CCC300) (Fig. 5a, b). Several peaks in opal concentration were detected concomitantly at most of the stations (Fig. 5b), such as in May 2006 (recorded at all stations, maximum values up to 13.11% at the CCC1500 station), and early summer 2006 (up to 14.8% at the SOS1900 station, recorded at all stations except for both upper canyons). In contrast to OM and opal components, the content in $CaCO_3$ increased at lower canyon, canyon mouth and open slope stations during January–March 2006. Punctual peaks were detected in late summer-early autumn 2006, when SOS1900 reached the maximum carbonate content (39.7%) similarly to SOS1000 (35.7%). At lower canyon stations, carbonate peaks were also recorded during mid-late summer.

5 Discussion

5.1 Lateral transport of material by DSWC

5.1.1 Role of DSWC in canyons

The arrival of massive amounts of material (up to $90\,g\,m^{-2}\,d^{-1}$ at the middle Cap de Creus canyon) associated to strong temperature anomalies and increased current speeds (Fig. 3a) reveals that DSWC was the major physical driver of particle fluxes in the southwestern GoL during the monitored period. The occurrence of DSWC caused total mass flux to increase (Fig. 4) and to be dominated by the siliciclastic fraction (up to 63.3%) (Fig. 6). Concomitantly, composition had the tendency to be constant (Fig. 6), thus indicating the downcanyon transport of homogenized material. Mean composition of the non-siliciclastic fraction was 30.0% of $CaCO_3$, 3.2% of OM, and 1.5% of opal (Fig. 5), quite similar values than those reported by Heussner et al. (2006) (31–32% $CaCO_3$, 2% OM, and 1% opal) during maximum fluxes recorded over a 8-year period, and close to the composition of the superficial sediments from the shelf and upper slope (31% $CaCO_3$, 1–4% OM, and opal nearly absent or below the detection limits, Roussiez et al., 2006).

The large amount of material sedimented during the main DSWC period represents up to 83.5% (CCC1000 station) of the total material settling during 1 year (October 2005–October 2006) (Table 2). This represents a mass up to 1 $kg\,m^{-2}$ in lower canyon and middle slope stations, that reach 3.5 $kg\,m^{-2}$ at CCC1000 station. Indeed, total mass accumulated on the seabed by DSWC should have been higher since sediment traps were deployed at 30 m above bottom on the axis of the canyon, and average height of cascading plume is about 50–60 m thick (Canals et al., 2006; Ulses et al., 2008b), so particle fluxes under the trap were not sampled. In addition, the moored traps were located in the axis of the canyon that is the edge of the DSW plume as it mostly flows along the southern wall of the canyons (Ulses et al., 2008b). Thus, we can expect higher mass accumulation on the seabed. Despite the siliciclastic character of material transferred by the DSWC event that diluted relative OM content, there was also an excess of OM during the main DSWC period at all stations (Table 3). For the CCC1000 and SOS1000 station, for example, the DSWC supposed an increase of 50% of the annual inputs of OM that were 80.7 $g\,m^{-2}$ at the CCC1000 station. The impact of that "excess" of organic matter, even diluted, may alter the functioning of deep ecosystems. It has also to be considered that coastal phytoplanktonic blooms were developing during winter time (Fig. 2b) and shelf material transported downward may carry its signal, as suggested by Sanchez-Vidal et al. (2009) by looking at the isotopic composition of organic matter. Indeed, they report increased marine organic matter contribution at the end of the DSWC period. Likewise, Fabres et al. (2008) indicated that the synchronic bloom and 2003/04 DSWC minor event enhanced the downcanyon export of a relatively fresh OM.

Even that material was relatively homogenized, compositional change can be discerned as material was transported downslope, with enrichment in OM, opal and $CaCO_3$, and an impoverishment of the siliciclastic fraction (Fig. 7). That cross slope geochemical gradient of the settling organic particles and the fining of particle size with increasing depth is associated to the current regime as was pointed by Sanchez-Vidal et al. (2008) for the first DSWC peak in January 2006. Temporal differences between canyons concerning the first maximum peak of total mass flux can be detected. At Cap de Creus middle and lower canyon stations it was registered in early January, while at the canyon mouth and middle and lower Lacaze-Duthiers canyon stations, this maximum was recorded at the end of the same month. A weak maximum was detected at lower Lacaze-Duthiers canyon in early February 2006 (Fig. 4), one month later than in Cap de Creus same water depth station (i.e. 1500 m depth). Those differences are related with lower current speeds and temperature anomalies at the LDC1000 station. The narrowing of the shelf towards the Cap de Creus and differences in upper canyon morphology have been the factors attributed by Ogston et al. (2008) for the different behaviour along those two canyons during the previous 2005' DSWC event. The sediment trap located at 500 m above bottom at the Lacaze-Duthiers middle canyon registered also the event, with mean total mass flux of 6.3 $g\,m^{-2}\,d^{-1}$ during the main DSWC period. Similarly to the sediment trap located at 30 m above bottom, the maximum peak at 500 m above the bottom was at the end of January 2006, but showed lower $CaCO_3$ and siliciclastic contents (Fig. 5). Thus, cascading waters loaded with particulate material reached 500 m of water depth, probably as an intermediate nepheloid layer detached from the shelf or around the upper slope and canyon regions.

The general mass flux increase during the DSWC event was not detected at Lacaze-

Duthiers upper canyon station (LDC300), where mean mass flux during the main DSWC period was lower than the rest of the year (1.5 and 8.5 g m^{-2} d^{-1}, respectively, see Table 2). In fact, near-bottom settling fluxes concentrated down canyon as indicates the mass flux increase from 3.5 g m^{-2} d^{-1} at the head of the canyon to 24.5 g m^{-2} d^{-1} at the 1000 m depth station, suggesting that upper canyons acted as bypass areas of material during the period of strong downcanyon currents. Even though no data is available from the Cap de Creus upper canyon station, a similar behaviour has been found in this canyon during the 2004/05' DSWC event, where sedimentary patterns and suspended sediment concentrations evidenced resuspension by strong downcanyon currents of the material temporally deposited in the upper canyon section (DeGeest et al., 2008; Puig et al., 2008). The composition of the material settled during the main DSWC period at Lacaze-Duthiers upper canyon station had low $CaCO_3$ content (Fig. 5), extremely high C/N ratio and a terrestrial isotopic signal of OM (Sanchez-Vidal et al., 2008). The concomitant wave height and southwestern river flow increase in late January 2006 (Fig. 2a, c) suggest the arrival of recent land-derived sediments, mainly from the Pyrenean rivers as suggested by the lower content in carbonates (Roussiez et al., 2006). Indeed, fast transport from the shelf to the slope was suggested by Monaco (1990) inside Lacaze-Duthiers canyon and by Palanques et al. (2008) during the 2004/05' events when storms and DSWC coincide.

Recent studies have described the impact of previous DSWC events such as those occurred in 2003/04 (minor event) and 2004/05 (major event) on sediment transfer through the Lacaze-Duthiers and Cap de Creus canyons (Heussner et al., 2006; Palanques et al., 2006). Total mass flux during the main 2005/06 DSWC period at the middle and lower Lacaze-Duthiers canyon stations (24.5 and 4.1 g m^{-2} d^{-1}) was of the same range than at the middle and lower Cap de Creus canyon (38.7 and 3.5 g m^{-2} d^{-1}) (Table 2). In contrast, current meter and turbidity data from previous DSWC events indicate that the 2003/04 minor events transferred one order of magnitude more sediment through the Cap de Creus canyon than through the Lacaze-Duthiers canyon (Palanques et al., 2006). The same trend was observed during the 2004/05 DSWC event, and was related to higher duration and strength of cascading flows in the Cap de Creus canyon (Ogston et al., 2008). However, our data shows that the cascading waters transported high amounts of material through both canyons. It is most likely that the previous 2004/05 event redistributed the sedimentary deposits, changing the location of the sources of sedimentary material that would be impacted by cascading waters in winter 2005/06. This would explain why there are not such a high differences between total mass fluxes in LDC and CCC during the 2005/06 DSWC event, even the current speeds at the middle Cap de Creus canyon were higher than in the nearby canyon.

5.1.2 Impact of DSWC on the open-slope

At upper open slope station (SOS1000) total mass fluxes increased from late December 2005 ($0.3\,g\,m^{-2}\,d^{-1}$) to early January 2006 ($34.1\,g\,m^{-2}\,d^{-1}$), following the same trend and at the same time than CCC1000 station (Fig. 4) with a 16 h time lag between the first flushing of cold water at CCC1000 and SOS1000 as indicate temperature records (Fig. 3a). While CCC1000 current-meter indicates a clearly along axis direction of the flow during DSWC, the direction of the water flow at the SOS1000 was mainly along slope (Fig. 3). Material settling during the first cascading pulse at both CCC1000 and SOS1000 stations was quite similar (Fig. 7), and closer than comparing CCC1000 and CCC1500 stations. This suggests that during the first pulse the material was transported by cascading waters through the Cap de Creus canyon, probably covering the southern wall of the canyon (Ulses et al., 2008b), and was spread out of the Cap de Creus canyon where the canyon widens at the lower domain. Then, the material was transported southwards, thus impacting SOS1000 station. It is most likely that part of this material remained in suspension and was transported within the along shore current to distal areas. In fact, cascading waters have been detected offshore as anomalies in water mass properties (Bethoux et al., 2002; Lopez-Jurado et al., 2005; Font et al., 2007). Palanques et al. (2009) observed a strong increase of total mass flux in the open Northwestern Mediterranean Basin at 2350 m (250 m above bottom) clearly linked to the 2004/05' intense cascading event. In addition, Zúñiga et al. (2008) found an increase in particle fluxes at 2145 m of water depth in the central Algero-Balearic basin and hypothesized that an important load of material is transported to the deep basin by seasonally controlled deep water formation in the Gulf of Lions.

Lower slope station (SOS1900) recorded higher mass flux values than canyon mouth station (CCC1900) as consequence of the morphologic characteristics and current circulation as explained for the middle slope station. Thus, the deepest part of GoL canyon system loses the constraining effect of the canyon walls and the funnelling effect of canyons.

5.1.3 Post DSWC evolution of particulate fluxes

After maximum mass fluxes recorded again in late March 2006 (early April 2006 at SOS1900 station), total mass flux at lower canyon, canyon mouth and open slope stations decreased progressively, and did not reach values similar to pre-DSWC values (around 0.1 $g\,m^{-2}\,d^{-1}$) until late summer 2006 (Fig. 4). This attenuated tendency was probably due to the addition of vertical settling particles during the spring bloom (see Sect. 5.2) but also because of the settling of material from intermediate or bottom nepheloid layers associated with relatively high current velocities (Fig. 3).

Upper and middle canyon stations out of the main DSWC period (i.e., in autumn 2005, spring and summer 2006) presented a continuous flux of material that ranged from 2.6 $g\,m^{-2}\,d^{-1}$ at CCC1000 station to 8.5 $g\,m^{-2}\,d^{-1}$ at the LDC300 station (Table 2), and with typical values for the Lacaze-Duthiers upper canyon station of 3.4 $g\,m^{-2}\,d^{-1}$ similar to the 3.7 $g\,m^{-2}\,d^{-1}$ value during the long-term measurement at the same station (Heussner et al., 2006). During late summer–autumn 2005 and 2006 months mean total mass fluxes increased and material collected at upper and middle canyon stations was qualitatively similar that the one settled during the main DSWC period (Fig. 8a, c), reflecting downcanyon transfer of shelf homogenized sediments. The intensification of material advection to upper and middle canyon stations was recorded concomitantly with the increase of the waves and western river discharge during late

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summer-autumn months (Fig. 2a, c) as during the 2003/04 period (Palanques et al., 2006). Observations from the HERMES experiment agree with the hypothesis from Bonnin et al. (2008) and Palanques et al. (2008) that suggest that the sedimentation is located mostly at upper canyons during spring and autumn seasons due to the stratification conditions that inhibit the downcanyon descend of the water mass and basinwards in winter non-stratified water column, increasing the erosion capability of the water mass when downwelling interacts with DSWC. It has to be noted that since coastal blooms were developing (Fig. 2b), that fast transference of shelf material may be carrying fresh OM downward.

5.2 Pelagic signal in settled material

While dense shelf water was still cascading at the end of March 2006 (Fig. 3), sea surface open ocean chl *a* (Fig. 2b) indicate that a phytoplankton bloom over the study area began (Fig. 2a). The concomitance of OM and opal flux peaks at the end of March 2006 at all stations (Fig. 5a, b) with open ocean chl *a* maximums (Fig. 2b) indicates a fast pelagic sedimentation of organic-rich biological detritus. Fluxes with significant opal fraction have been previously observed during the spring bloom in canyon heads of the Gulf of Lion and Catalan margin (Martín et al., 2006; Fabres et al., 2008). The ratio of essential biogeochemical elements provide a visual knowledge of the interrelated roles that opal, $CaCO_3$ and OM play in the biological pump (Honjo et al., 2008) (Fig. 8). As recorded by Vidussi et al. (2000), the high Si_{bio}/C_{inorg} and C_{org}/C_{inorg} molar ratios indicate that the first primary community developed during the spring bloom is dominated by diatoms. During late summer and autumn, low particulate fluxes and high C_{org}/C_{inorg} ratios recorded at lower canyon, canyon mouth and open slope stations (Fig. 8c) suggest the sedimentation of biological detritus (Fig. 4). During those seasons, OM peaks were recorded associated with both opal and $CaCO_3$ peaks (Fig. 5a, b) and not related to superficial chl *a* increases (Fig. 2b), which is not rare considering the fact that in summer surface layers are almost empty of nutrients and a characteristic deep chl *a* maximum develops below the thermocline (Margalef, 1985). Increases in biogenic components during summer stratification may be related to the development of diazotrophic communities as also indicated by depleted δ^{15}N organic matter found by Sanchez-Vidal et al. (2009). Species responsible are suggested to be associated to diatoms (Garcia et al., 2006), which would explain the increase in opal content detected during July (Fig. 4).

6 Conclusions

Several conclusions may be drawn from this sediment trap experiment that for first time have recorded particle fluxes during a DSWC event, from upper canyons and slope regions to the deep basin, in the Western Mediterranean Sea. Near-bottom particles fluxes reflect a quick response of the system as a consequence of a major physical forcing (i.e. dense shelf water cascading) and in situ primary production. These mechanism induced qualitatively and quantitatively changes in material settled highlighting the different behaviour between shallower stations (upper and middle canyon), primarily affected by cross-slope exchanges with the shelf, and the deeper ones (lower canyon mouth and slope), less affected by that horizontal transferences and with a pelagic particle settling signal typical of an open-ocean regime.

Upper canyons acted as seasonal depocenters of particulate matter of shelf origin during end-summer and autumn, that can possible reach the middle canyon zones linked to storms and river discharges. The severe DSWC event observed during the winter 2005/06 imposed a change of the sedimentation. At the upper canyon, strong downcanyon currents eroded material deposited during the previous months and transported it quickly basinward inducing significant particle fluxes increase, with consequences that lasted for 6 months at the lower canyon, canyon mouth and open slope stations. In contrast to upper and middle canyons where shelf material is advected in autumn and winter seasons, at the lower canyon, canyon mouth and open slope stations it arrives associated to the DSWC event. So, the qualitatively impact of such event on the main composition of the material should be assessed of that deeper stations.

The southern open slope was also directly impacted by DSWC as the dense waters escaped the lower canyons to flow along the isobaths. This denotes the capacity such events to erode shelf material, funnel through canyons and spread it southwardly. Therefore DSWC may become an important factor for the sedimentation in the lower middle and lower slope of the northwestern Mediterranean.

Sedimented material also provide useful information concerning primary production, since particles sink fast through water-column as indicate high-related organic matter and opal components during spring bloom. Settled material reflects community succession at euphotic layers, and not only at superficial waters as satellite data indicate, but also at sub-superficial levels, thus contributing to the understanding of that processes and their link with the environmental factors.

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Table 1. Total mass (TM) flux ($g\,m^{-2}\,d^{-1}$), and main components (OM, opal, $CaCO_3$ and siliciclasts) mean flux ($g\,m^{-2}\,d^{-1}$) and content (%) along the Lacaze-Duthiers Canyon, Cap de Creus Canyon and Southern Open Slope transects. Statistics presented are mean, maximum (Max) and minimum (Min). Mean flux has been calculated as time weighted flux, and mean concentration as flux weighted concentration following Heussner et al. (2006). * Data gaps, see Fig. 3.

Station		TM	OM		Opal		$CaCO_3$		Siliciclastic	
		Flux	Flux	%	Flux	%	Flux	%	Flux	%
LDC300	Max	18.1	0.6	8.2	0.2	3.7	5.3	36.6	12.1	71.6
	Min	0.3	0.0	2.7	0.0	0.1	0.1	23.4	0.2	54.1
	Mean	6.7	0.2	3.5	0.1	1.1	2.0	29.3	4.4	66.1
LDC1000 (500 mab)	Max	11.2	0.4	10.9	0.4	10.0	3.4	42.9	7.4	68.6
	Min	0.6	0.0	3.0	0.0	0.6	0.2	23.1	0.4	40.5
	Mean	2.9	0.1	4.4	0.1	2.7	0.8	28.2	1.8	64.8
LDC1000*	Max	39.9	1.0	5.2	0.3	5.2	12.1	30.7	26.6	67.5
	Min	1.8	0.1	2.3	0.0	0.4	0.6	25.9	1.2	61.4
	Mean	6.7	0.2	3.0	0.1	1.3	2.0	29.6	4.4	66.1
LDC1500	Max	11.9	0.4	10.7	0.3	10.8	3.4	34.9	7.8	65.8
	Min	0.0	0.0	2.8	0.0	0.8	0.0	23.1	0.0	49.9
	Mean	1.4	0.1	3.8	0.0	3.3	0.4	30.1	0.9	62.8
CCC300*	Max	20.0	0.5	6.3	0.3	3.5	5.7	29.0	13.5	67.7
	Min	2.0	0.1	2.6	0.1	0.9	0.6	26.0	1.3	63.4
	Mean	7.0	0.2	3.5	0.1	1.6	2.0	28.0	4.7	66.8
CCC1000	Max	90.1	1.5	7.3	0.3	9.0	25.1	29.9	63.3	73.1
	Min	1.0	0.0	1.7	0.0	0.2	0.3	22.6	0.7	61.2
	Mean	11.7	0.3	2.6	0.1	0.8	3.3	27.8	8.1	68.8
CCC1500	Max	6.3	0.2	19.0	0.2	13.1	1.7	36.3	4.3	68.6
	Min	0.0	0.0	2.9	0.0	1.2	0.0	25.2	0.0	41.2
	Mean	1.3	0.0	3.8	0.0	3.3	0.4	29.6	0.8	63.2
CCC1900	Max	3.2	0.1	13.9	0.1	10.4	1.0	34.7	2.0	63.4
	Min	0.0	0.0	2.7	0.0	1.4	0.0	23.5	0.0	42.8
	Mean	0.7	0.0	4.1	0.0	3.7	0.2	32.2	0.4	60.0
SOS1000	Max	34.1	0.8	8.6	0.1	11.5	9.4	35.7	23.8	69.7
	Min	0.2	0.0	2.3	0.0	0.4	0.0	22.7	0.1	50.0
	Mean	3.4	0.1	3.0	0.0	1.2	1.0	28.0	2.3	67.7
SOS1900	Max	5.7	0.1	16.2	0.1	14.2	2.0	39.7	3.5	62.6
	Min	0.0	0.0	2.4	0.0	1.4	0.0	24.0	0.0	34.8
	Mean	0.8	0.0	3.8	0.0	3.7	0.3	32.9	0.5	59.5

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Table 2. Flux ($g\,m^{-2}\,d^{-1}$), total mass (TM) ($g\,m^{-2}$) and relative contribution of settled mass (%) during the main Dense Shelf Water Cascading (DSWC) period (January, February and March) and out of the main DSWC period recovered at each station. * Data gaps, see Fig. 3.

Station	Main DSWC period			Out main DSWC period		
	Flux	TM	%	Flux	TM	%
LDC300	1.5	134.5	5.7	8.5	2208.3	94.3
LDC1000 (500 mab)	6.3	568.9	56.0	1.7	446.8	44.0
LDC1000*	24.5	1102.2	56.0	3.5	866.9	44.0
LDC1500	4.1	366.2	76.2	0.4	114.3	23.8
CCC300*	N.D.	N.D.	–	6.5	1232.5	–
CCC1000	38.7	3487.0	83.5	2.6	691.0	16.5
CCC1500	3.5	315.8	71.7	0.5	124.6	28.3
CCC1900	1.3	117.3	48.1	0.5	126.5	51.9
SOS1000	11.4	1028.6	86.6	0.6	158.8	13.4
SOS1900	2.0	177.3	60.6	0.4	115.2	39.4

Table 3. Total Mass (TM) ($g\,m^{-2}$) settled of OM, Opal, $CaCO_3$ and Siliciclastic fraction during the main DSWC period and the exceeding percentage calculated subtracting relative percentage of the main DSWC period (25% of sampling period, 15% for the LDC1000 station) of the main components studied. * Data gaps, see Fig. 3.

	OM		Opal		$CaCO_3$		Siliciclastic	
Station	TM	%	TM	%	TM	%	TM	%
LDC300	4.4	−19.7	1.7	−18.4	36.5	−19.7	91.8	−19.1
LDC1000 (500 mab)	19.6	19.2	7.9	3.7	160.2	31.0	381.2	32.9
LDC1000*	28.1	32.8	6.6	10.8	332.6	42.1	734.9	41.4
LDC1500	11.9	40.3	6.6	17.5	113.8	53.6	233.9	52.6
CCC300*	N.D.	–	N.D.	–	N.D.	–	N.D.	–
CCC1000	80.7	50.1	15.8	19.5	968.0	58.3	2422.5	59.3
CCC1500	10.1	34.9	5.5	13.2	95.2	48.0	204.9	48.6
CCC1900	3.9	13.4	2.0	−2.1	38.4	23.9	73.0	24.9
SOS1000	26.4	50.5	6.6	20.3	290.1	62.6	705.6	63.1
SOS1900	5.3	23.9	3.0	3.5	60.8	39.0	108.1	38.3

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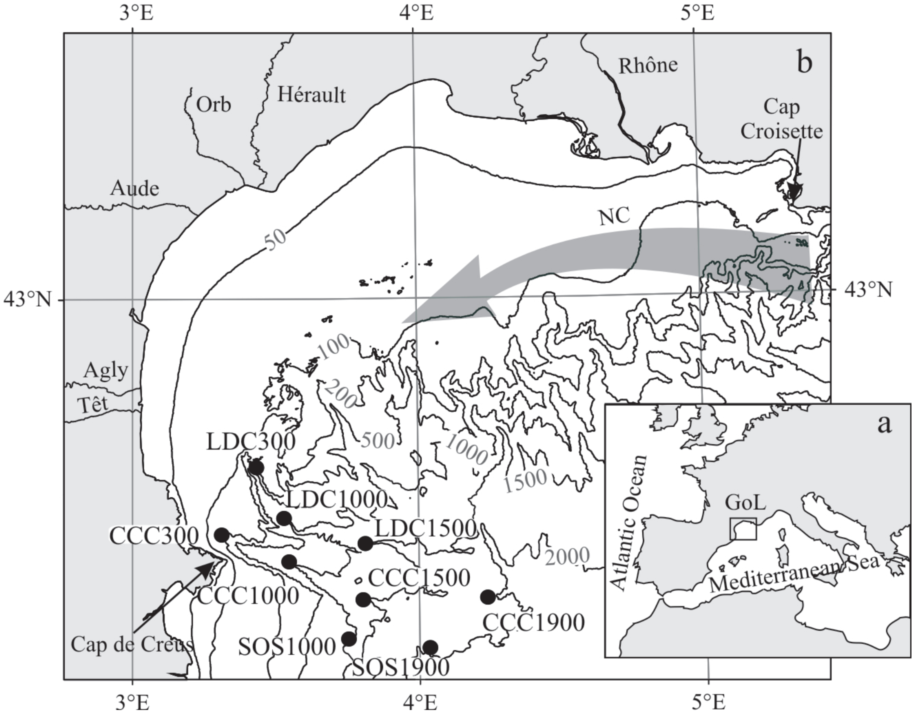

Fig. 1. **(a)** Location of the Gulf of Lion (GoL) in the Western Mediterranean Sea and **(b)** sediment trap mooring stations (black dots) along the tree transects studied: Lacaze-Duthiers Canyon (LDC), Cap de Creus Canyon (CCC), and their Southern Open Slope (SOS). Superficial main oceanic circulation is represented by the Northern Current (NC, grey arrow).

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Settling particles and DSWC in the GoL's margin

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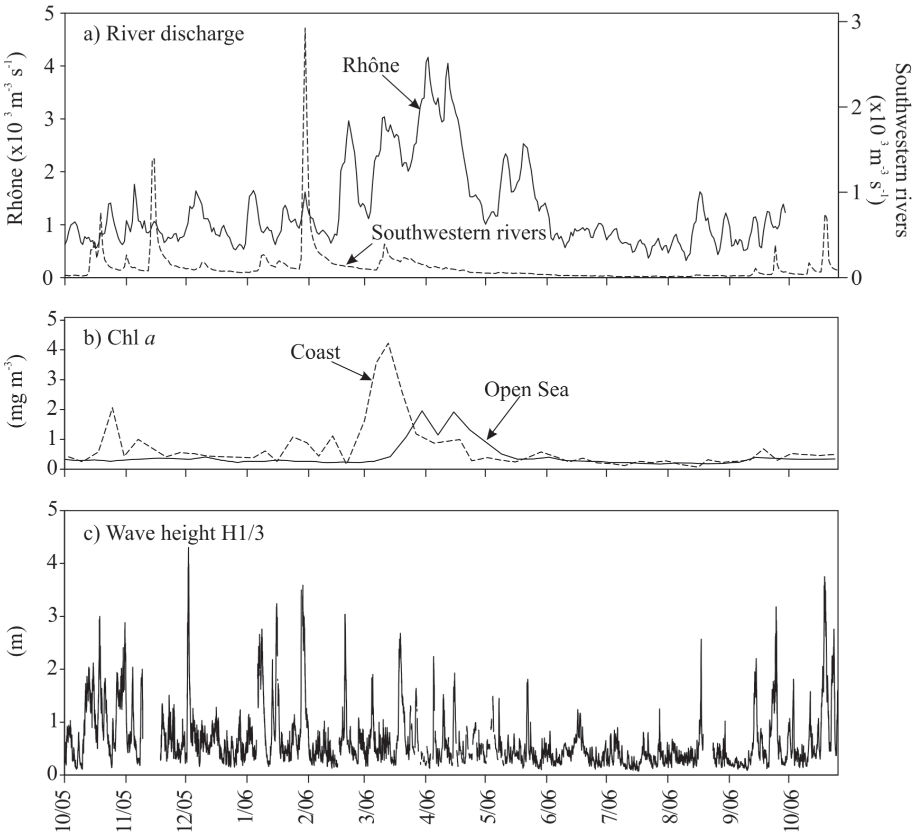

Fig. 2. (a) Daily fluvial discharges ($m^3 s^{-1}$) of the Rhône and the Southwestern rivers (Hérault, Orb, Aude, and Têt), **(b)** mean chlorophyll *a* (chl *a*) concentration ($mg\,m^{-3}$) recorded at coastal station and open sea sites and **(c)** significant wave Heights H1/3 (m).

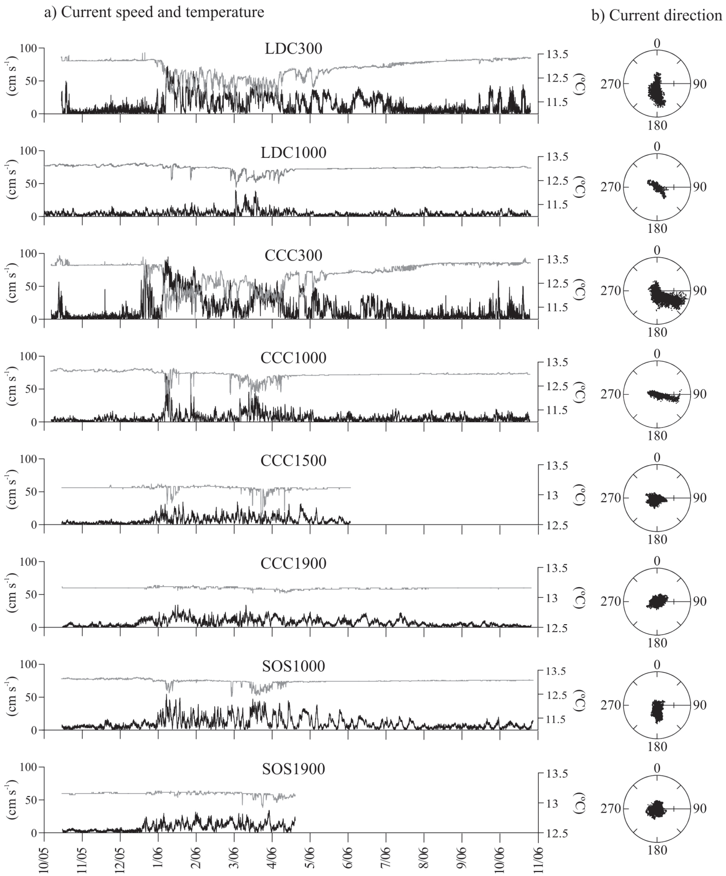

Fig. 3. **(a)** Current speed ($m\,s^{-1}$) (black line) and temperature (°C) (grey line) and **(b)** current directions as a function of the speed (radius limits are 0–100 $cm\,s^{-1}$) recorded at 5 mab at each station location (note different temperature scales).

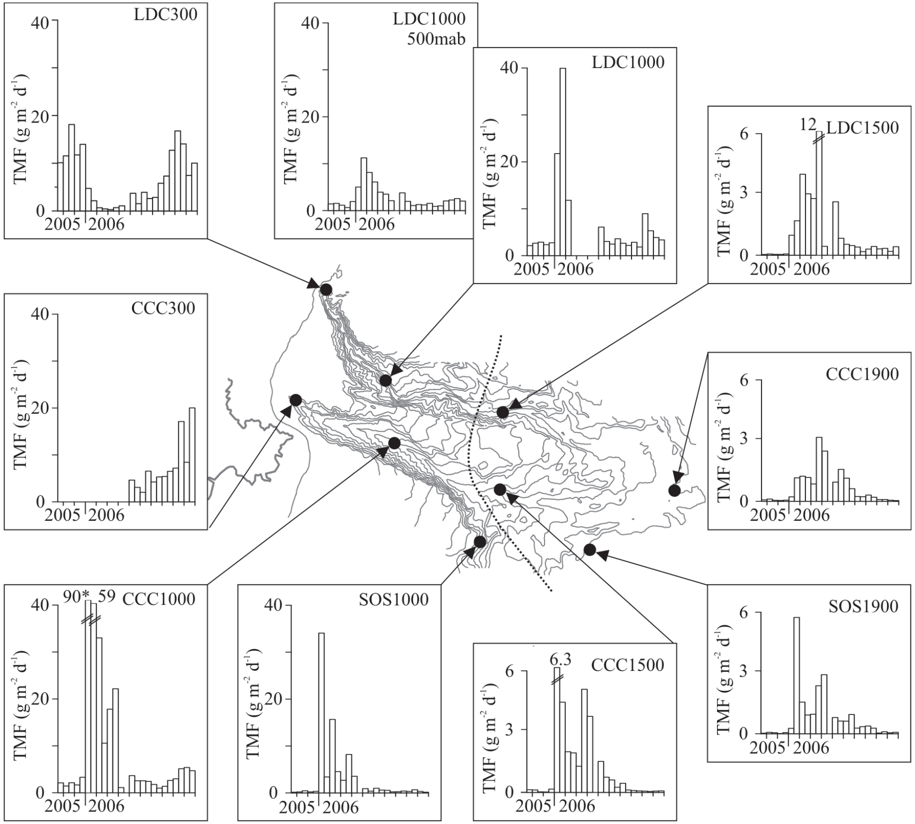

Fig. 4. Time series of total mass fluxes (g m^{-2} d^{-1}) along transects studied: Lacaze-Duthiers Canyon (LDC), Cap de Creus Canyon (CCC) and Southern Open Slope (SOS), at different water depth stations. Contour every 100 m (note that dotted line separate stations with different scale of the TMF axis). *Overflowed.

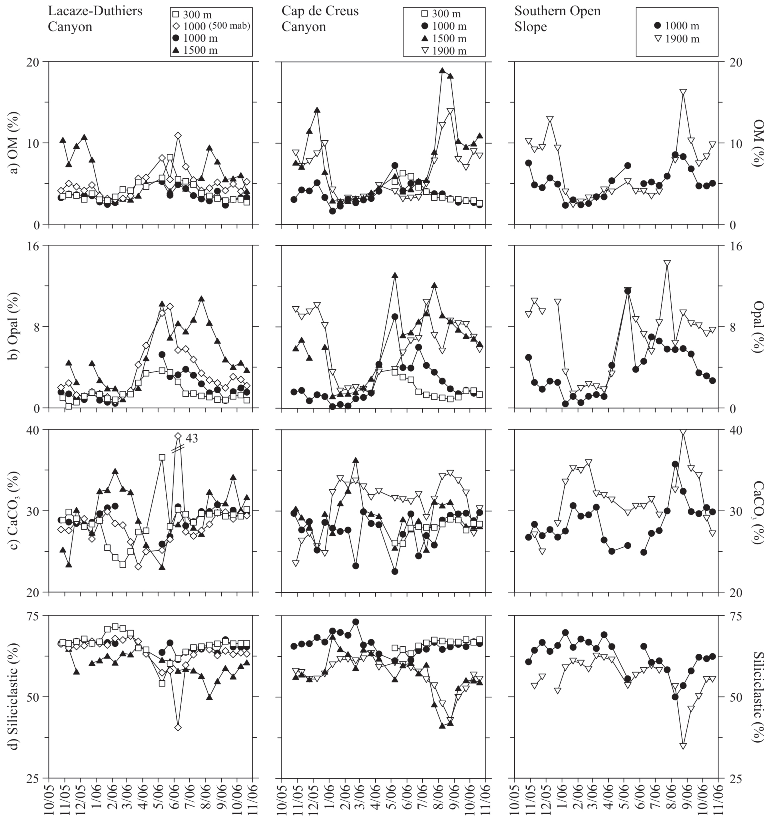

Fig. 5. Temporal evolution of **(a)** organic matter (OM), **(b)** opal, **(c)** calcium carbonate ($CaCO_3$), and **(d)** siliciclastic fractions, in the Lacaze-Duthiers Canyon (LDC), Cap de Creus Canyon (CCC) and Southern Open Slope (SOS) for different water depths stations: 300 m (white squares), 1000 m (black dots), 1000 m (500 mab) (white rhombus), 1500 m (black up triangles) and 1900 m (white down triangles).

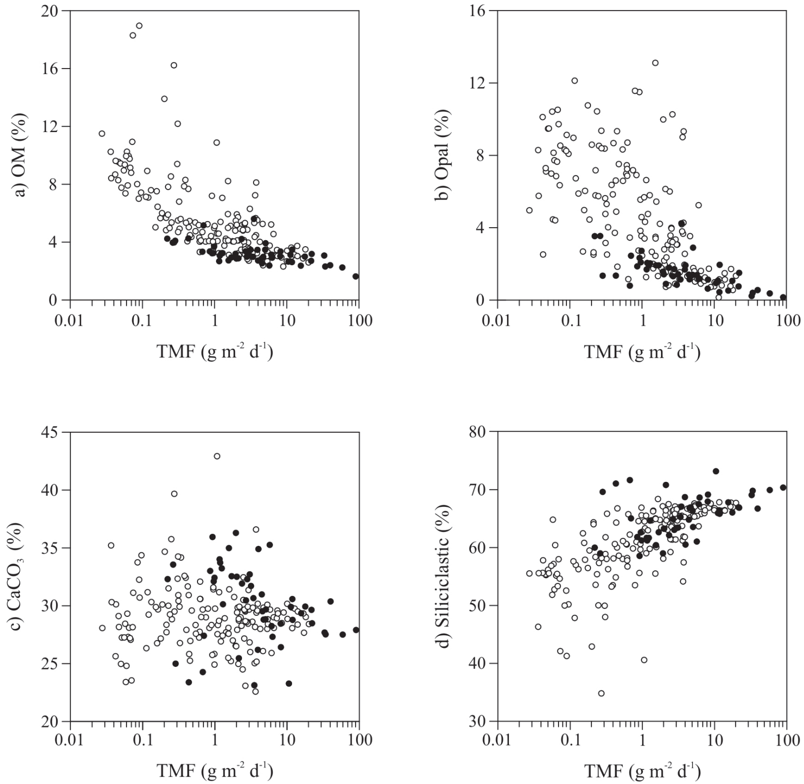

Fig. 6. Content of **(a)** organic matter (OM), **(b)** opal, **(c)** calcium carbonate ($CaCO_3$), and **(d)** siliciclastic versus total mass flux (TMF) ($g\,m^{-2}\,d^{-1}$) for samples recovered during the main DSWC period (black dots) and out of the main DSWC period (white dots).

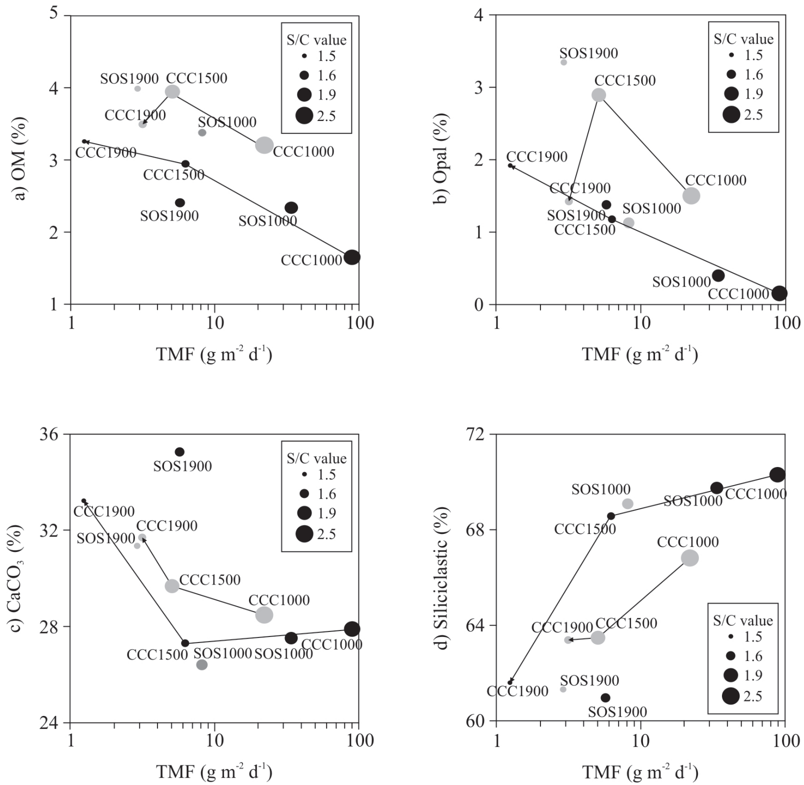

Fig. 7. Content of **(a)** organic matter (OM), **(b)** opal, **(c)** calcium carbonate ($CaCO_3$), and **(d)** siliciclastic versus total mass flux (TMF) ($g\,m^{-2}\,d^{-1}$) of the samples recovered during the maximum arrival of material of each DSWC pulse (first pulse: black dots; and second one: grey dots). Arrows represent the along Cap de Creus transect. Size of the dot represents the value of the silt/clay ratio (S/C).

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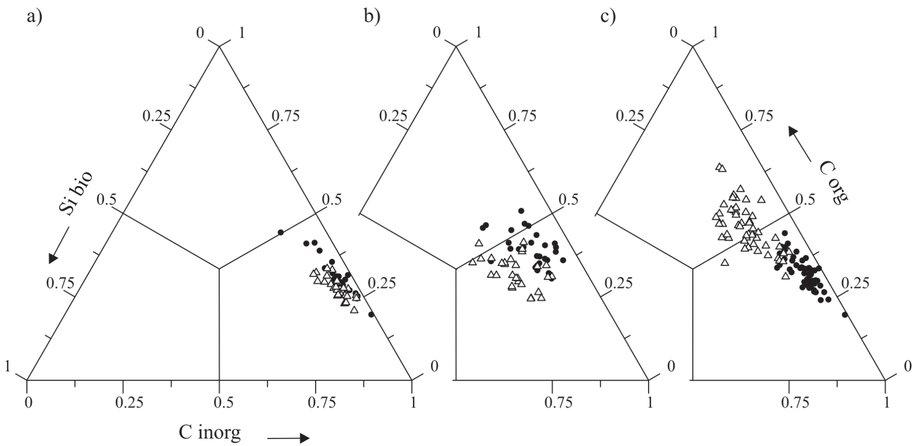

Fig. 8. Correlations of essential biochemical elements organic carbon, inorganic carbon, and biogenic silica, expressed in molar units during **(a)** the main DSWC event, from January to March 2006, **(b)** from April to middle July 2006 and **(c)** the remaining period. Samples from the upper and middle canyon stations are plotted in black dots and samples from the lower canyon, canyon mouth and open slope stations in white up triangles.