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Deep sediment transport induced by storms and dense shelf-water cascading in the northwestern Mediterranean basin

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ABSTRACT

Downward particle fluxes and hydrodynamics in the northwestern Mediterranean basin were measured by a sediment trap and a current meter deployed at 2350 m depth, 250 m above bottom, from November 2003 to April 2005. During the winter of 2003–2004 there were high river discharges, two strong E–SE storms and several moderate storms and short periods of moderate dense shelf-water cascading during which dense shelf water did not reach the deep basin. Downward particle fluxes at the basin site were low during most of this winter but increased above one order of magnitude as a consequence of the strong storm and moderate cascading event that occurred in late February 2004. During the winter of 2004–2005, neither important river floods nor strong storms occurred but there were very intense and persistent dense shelf-water cascading events from February to April 2005. Dense shelf water, mixed with offshore convection water, reached the basin site in early March 2005, increasing downward particle fluxes by more than two orders of magnitude for more than 1 month. These observations indicate that events of significant sediment transport to the northwestern Mediterranean basin can be caused by severe winter E–SE storms associated with moderate cascading events or by exceptionally intense and persistent dense shelf-water cascading episodes alone. On the other hand, river floods, severe storms during water column stratification conditions (without cascading) and moderate storms concurrent with moderate dense shelf-water cascading did not generate sediment transport events able to reach the basin.

1. Introduction

Off-shelf particulate matter transfer has major implications for sediment and biogeochemical cycles. The geological record has shown that this transfer increases during low-sea-level stands, when many rivers discharge near the shelfbreak, and decreases during high sea-level stands, when continental shelves are submerged and retain continental sediment inputs. During the present time of high sea-level stand, river sediment inputs accumulate on many continental shelves of the world, and off-shelf exports depend on the balance between sediment inputs, energy of hydrodynamic processes, shelf and slope morphology and sediment instability (McCave, 1972; Milliman and Syvitski, 1992; Nittrouer and Wright, 1994). Several studies have shown that off-shelf sediment transport can be significant, especially through some submarine canyon systems incised in continental margins (Hickey et al., 1986; Gardner, 1989a; Monaco et al., 1990; Heussner et al., 1999; Mullenbach and Nittrouer, 2000; Puig et al., 2003; Martín et al., 2006; Palanques et al., 2006), and modern depocentres have been identified on several continental slopes (Biscaye et al., 1988; Monaco et al., 1990; Sánchez-Cabeza et al., 1999).

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Classically, modern fine sediment transport, on the continental slope and in deep environments, has been defined as produced by "hemipelagic or pelagic processes" that supply biogenic and terrigenous components by vertical or lateral transport. Often, modern increases in sediment fluxes in slope environments have been associated with storms or river flood events (Monaco et al., 1990; Heussner et al., 1999; Walsh and Nittrouer, 1999; Puig et al., 2000; Palanques et al., 2005), but the specific downslope transport mechanisms have not always been recorded and identified. Only in a few cases have the effects of processes such as sediment gravity flows (Paull et al., 2003; Khripounoff et al., 2003; Puig et al., 2003; Xu et al., 2004) and breaking of internal waves (Gardner, 1989b) been directly observed in submarine canyons.

Recently, dense shelf-water cascading (DSWC) has been identified as another mechanism able to generate high sediment fluxes in submarine canyons (Palanques et al., 2006; Heussner et al., 2006; Canals et al., 2006). The sediment transfer induced by this process was recorded and characterized on the upper and mid-slope of the Gulf of Lions (GoL), where seasonal DSWC takes place. However, the modern sediment transfer from the GoL slope toward the deep sea is less known. Studies based on CTD profiles indicate that although cascading usually reaches upper slope depths, in some years it can be stronger, transporting denser water and reaching deeper environments together with its particle load (Bethoux et al., 2002; Canals et al., 2006; Font et al., 2007). In the present paper we demonstrate that both intense DSWC and strong winter storms concurrent with moderate DSWC generate important sediment transport events toward the northwestern (NW) Mediterranean basin.

2. Background information

The GoL is a micro-tidal and river-dominated continental margin (Fig. 1). In winter, the northerly (Mistral) and the northwesterly (Tramontane) winds cause strong cooling and homogenization of the shelf-water column, which facilitate dense water formation (Estournel et al., 2003), although their small fetch cannot generate large waves in the coastal area. On the other hand, the more occasional and brief southeastern and eastern (Marin) wind events are associated with large swell and a significant rise in sea level along the coast, generating longshore currents and downwelling (Monaco et al., 1990). Dispersal of riverine sediment—together with resuspension of fine sediment by waves and its subsequent transport by the shelf circulation—leads to the formation of a mud belt along the inner and mid-shelf (Aloïsi et al., 1976). On the outer shelf, fine sediment does not accumulate and sediment export to the slope is controlled by shelf circulation. Off-shelf sediment transfer is greater in winter than in summer because of enhanced shelf–slope exchange processes (Durrieu de Madron et al., 1990).

The GoL slope is indented by a series of canyons (Fig. 1), and there is a preferential transport of material through these canyons and a westward along-slope flux increase (Monaco et al., 1990, 1999; Heussner et al., 2006). During the EUROSTRATAFORM Project, near-bottom (5 m above bottom—mab) suspended sediment fluxes were recorded simultaneously in seven GoL submarine canyon heads at 300 m depth from November 2003 to May 2004 and showed that more than 90% of the shelf–slope suspended sediment transfer occurred through the westernmost submarine canyon, named Cap de Creus (CC; see Palanques et al., 2006; Ulses et al., 2008b for details; location in Fig. 1). For this reason, further monitoring of suspended sediment fluxes 5 mab in the CC submarine canyon head at 200, 500 and 750 m depth was carried out from October 2004 to April 2005 (see Canals et al., 2006; Font et al., 2007; Puig et al., 2008 for details).

The 2003–2004 and 2004–2005 winters were different in terms of river discharge, storms and off-shelf sediment transport events. The 2003–2004 winter had a relatively high river discharge and was quite stormy, with two strong and several moderate eastern storms. The most important flood (a Rhone river discharge of 10,000 $m^3 s^{-1}$) occurred on 4 December 2003 at the end of the water stratification period, coinciding with a short (9 h) major eastern storm (significant wave height (H_s): 8.4 m). This event induced downwelling of warmer and turbid water for a few hours and generated a cumulative sediment transport of about 350 $kg\,m^{-2}$ at the CC canyon head (Palanques et al., 2006). The other major storm of the 2004 winter (H_s: 7 m), which started on 21 February and lasted for 3 days, induced downwelling and was associated with moderate DSWC. This event generated a cumulative sediment transport of 3000 $kg\,m^{-2}$ at the CC canyon head, one order of magnitude higher than during the December 2003 storm (Palanques et al., 2006). Other short DSWC events and moderate storms occurring during this winter only caused very slight off-shelf sediment transport increases.

The 2004–2005 winter was very windy, cold, relatively dry (a maximum Rhone river discharge of 2800 $m^3 s^{-1}$) and without significant storms ($H_s < 3.2$ m). These conditions favoured the formation of intense and persistent DSWC events at the CC canyon head. Some short DSWC events started in late December 2004—earlier than in the previous winter—but reached the canyon head only at 200 m depth. Later, intense DSWC occurred continuously from late February to early April 2005. The cumulative sediment transport through the CC canyon head during this major DSWC period was about 12,000 $kg\,m^{-2}$, four times higher than in the preceding year (Canals et al., 2006; Puig et al., 2008).

In the open sea, the same cold and dry winds that cause the DSWC also generate the winter convection process at around 42°N 5°E (MEDOC area), forced by heat losses and evaporation. This process involves intermediate water masses, mostly Levantine Intermediate Water (LIW), and presumably Tyrrhenian Deep Water (TDW). After its formation, dense Western Mediterranean Deep Water (WMDW) spreads to fill the entire western basin below 1000 m (MEDOC Group, 1970; Schott and Leaman, 1991).

3. Material and methods

In the context of the research project "EFLUBIO" devoted to studying the oceanographic conditions, biogeochemical fluxes and the structure of the planktonic

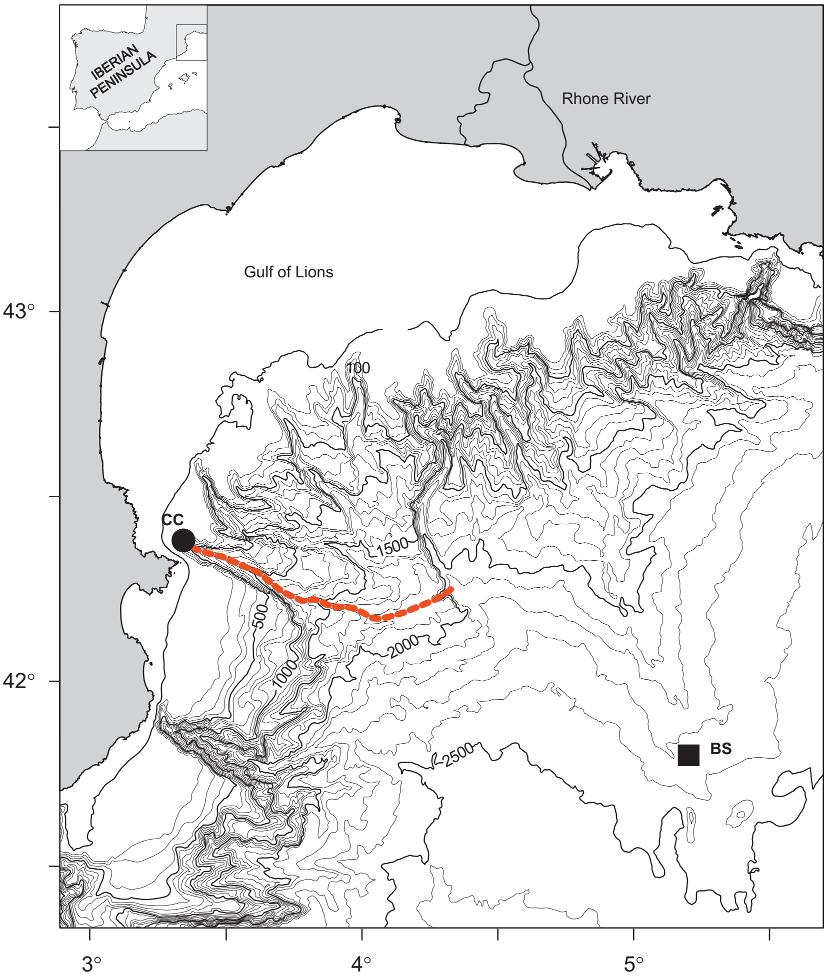

Fig. 1. Bathymetry map of the Gulf of Lions showing the location of the basin site (BS) mooring (square) and the Cap de Creus (CC) canyon head mooring site (circle). The axis of the CC submarine canyon is represented by a discontinuous line.

communities in the North Balearic basin, a moored instrumented array was installed in the North Balearic Basin at 2350 m depth (5°12′; 41°48′; Fig. 1) from November 2003 to April 2005. The array was equipped with an Aanderaa RCM 11 current meter and a Technicap PPS 5/2 conical sediment trap with a 1 m^2 collecting area and 24 receiving cups. The current meter was placed 220 mab and the sediment trap 250 mab to avoid recording local sediment resuspension. The sediment trap collected 48 samples in the two consecutive deployments with a mooring turn around in mid-September 2004. The trap collecting intervals ranged from 5 to 15 days, depending on the season, and the current meter sampling interval was set at 60 min.

Sediment trap cups were filled with a borax-buffered 5% formaldehyde solution in 0.20 μm filtered seawater before their deployment, to prevent sample degradation. After trap recovery, pH was measured in each cup to check that there was no acidification on any of them. Samples were stored at 4 °C until analysis. Trapped material was split with a WSD-10 wet sampler divider (McLane) to divide the total sample into several homogeneous aliquots. To determine total mass flux (TMF), sub-samples were filtered through pre-weighed cellulose acetate filters and dried overnight at 40 °C. TMFs were calculated from the sample dry weight obtained with a Cahn microbalance, the collecting trap area and the sampling interval.

4. Results

Time series of in situ temperature and currents recorded by the current meter at 220 mab and downward particle fluxes collected by the sediment trap at 250 mab at the GoL basin site (2350 m depth) are shown in Fig. 2.

Temperature at the study site maintained a relatively constant value of 13.11–13.13 °C from November 2003 to February 2005, increased to 13.20–13.23 °C between 3 February and 3 March 2005, and afterward decreased by about 0.05 °C, to 13.16–13.18 °C, from 3 March 2005 to the mooring recovery on 4 April 2005 (Fig. 2).

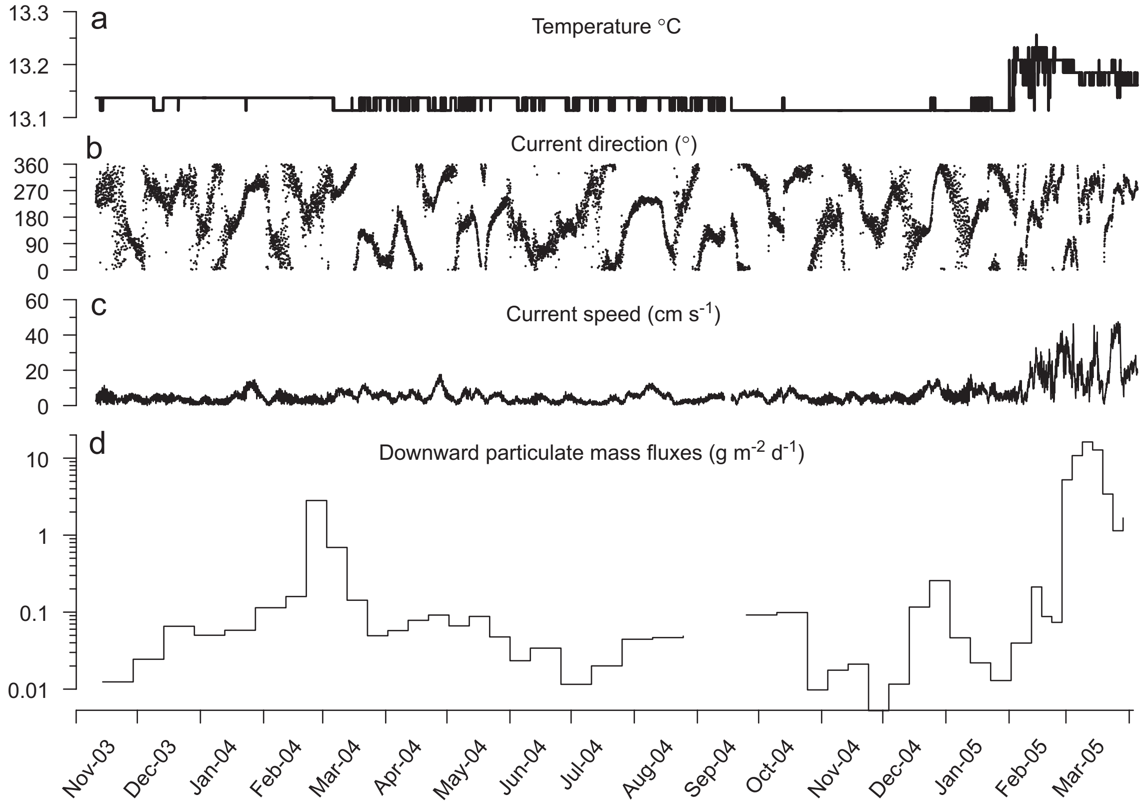

Fig. 2. Time series of (a) temperature, (b) current direction, and (c) current speed recorded 220 mab and (d) downward particle mass fluxes collected 250 mab at the basin site during the study period. See location in Fig. 1.

Current speed from November 2003 to February 2005 ranged between 0.2 and 16.4 cm s^{-1}, being lower than 10 cm s^{-1} most of the time. However, on 11 February 2005 current speed increased to 24.9 cm s^{-1}—a few days after the water temperature increased from 13.11 to 13.23 °C—and fluctuated from this date, reaching peaks of between 35 and 47 cm s^{-1} in late February and March 2005. The strongest current peaks occurred after the slight 0.05 °C temperature decrease during March 2005 (Figs. 2a, c). Current speed oscillated with a 1-week frequency and also with a near-inertial frequency. Current direction oscillated with a lower frequency of between 2 and 4 weeks. The polar diagram shows the high variability of the current direction at the mooring site (Fig. 3).

The TMF recorded by the sediment trap deployed at the deep basin site 250 mab varied within a range of more than four orders of magnitude, between 5.23 × 10^{-3} and 16.27 g m^{-2} d^{-1} (Fig. 2d). During most of the time, downward particle fluxes at the basin site were between 0.02 and 0.10 g m^{-2} d^{-1}, decreasing occasionally below 0.02 g m^{-2} d^{-1}. However, there were two periods during which TMF increased by several orders of magnitude: one was in the winter of 2004, when TMF of particles collected between 22 February and 3 March increased to 2.82 g m^{-2} d^{-1}; and the other was in the winter of 2005, when TMF increased to values between 5.24 and 16.27 g m^{-2} d^{-1} from late February to mid-March, and between 1.14 and 3.41 g m^{-2} d^{-1} from mid-March to early April 2005 (Fig. 2d).

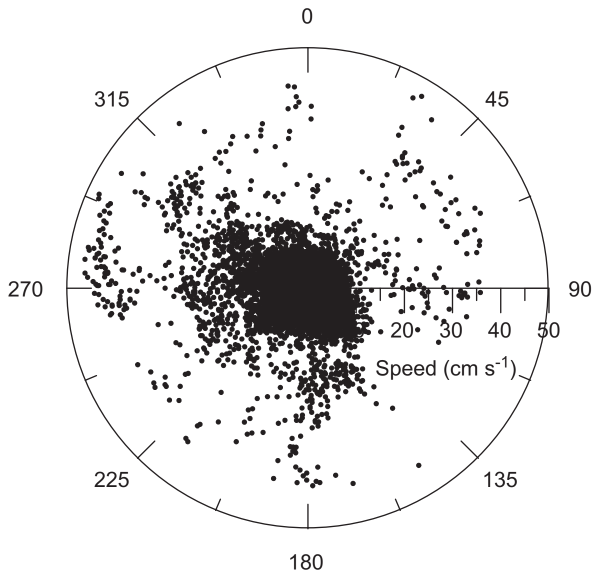

Fig. 3. Polar diagram of the currents recorded at the basin site from November 2003 to April 2005.

5. Discussion

The instruments that recorded the results shown in this paper were not specifically deployed to study sediment transport, but in spite of being more than 200 mab, they were able to record two very significant particle flux increases at the basin site during the 2003–2005 period, one in winter 2004 and another larger in winter 2005.

To study the sediment transfer mechanisms that generated these sharp particle flux increases in the deep basin, the time series of data recorded in this study are analysed together with time series of down-canyon suspended sediment and water transport recorded at the CC submarine canyon head (300–500 m depth) from December 2003 to April 2005. These data were recorded to study shelf–slope water and sediment transfer in the context of the EUROSTRATAFORM Project (see Section 2).

5.1. Winter 2004

The 2003–2004 winter was characterized mainly by a major flood affecting all the GoL rivers and by two major

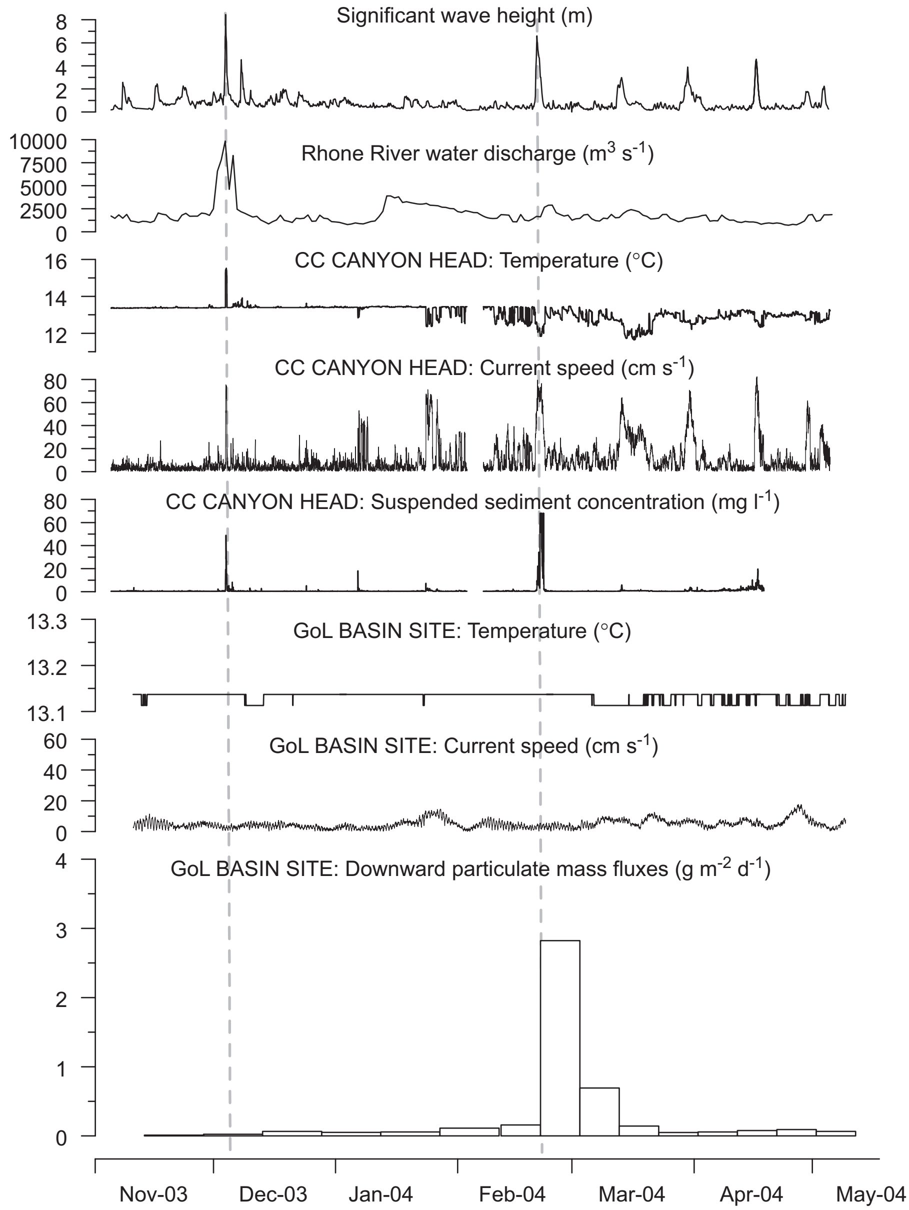

Fig. 4. Time series of significant wave height, Rhone River water discharge, temperature, down-canyon current velocity and suspended sediment concentration recorded 5 mab at 300 m depth at the CC canyon head (from Palanques et al., 2006), and time series of temperature, current velocity and downward particle fluxes at the basin site (see location in Fig. 1) during the winter of 2003–2004. At the canyon head, DSWC events correspond to temperature drops concomitant with current speed increases. Thick dashed lines represent the two major storm events. Downward particle flux increases in late February 2004 are associated with the maximum turbidity increase and DSWC caused by the February 2004 storm event. CC, Cap de Creus; GoL, Gulf of Lions.

E–SE storms (Fig. 4). The early December 2003 river flood and storm event drastically increased the turbidity, temperature and current speed at the CC canyon head but did not affect the sediment fluxes and hydrodynamics at the basin site (Fig. 4). This was a consequence of the still warmer surface water under stratification conditions and the short duration of the storm. According to the hydrodynamic modelling performed by Ulses et al. (2008a), the downwelling of the warmer surface water induced by the December 2003 eastern storm (by water convergence against the coast) could not have reached a depth of more than 300 m. In addition, the duration of this event (9 h) was too short to allow a massive off-shelf export of the sediment resuspended along the coast (Palanques et al., 2008) and it settled mainly on the shelf mixed with sediment discharged by the concurrent river flood, as observed on the inner Tet River prodelta (near the CC canyon head) by Guillén et al. (2006).

After the cooling and vertical mixing of the water column in winter 2003–2004, several short DSWC events began to occur in late January–early February, causing drops in temperature and current peaks at the CC canyon head. However, they neither increased turbidity at the canyon head nor caused sediment export pulses to the basin site (Fig. 4). The major eastern storm occurring in late February induced downwelling reinforced with DSWC, and this event was long enough (43 h) to allow a massive off-shelf export of the sediment resuspended along the inner and mid-continental shelf (Palanques et al., 2008). As a consequence, large amounts of shelf sediment were flushed downslope through the CC canyon, including that accumulated on the shelf after the December flood, and cumulative down-canyon sediment transport reached $>3000\,kg\,m^{-2}$ in only a few hours (Palanques et al., 2006, 2008; Guillén et al., 2006). Almost synchronically, TMF at the basin site increased between one and two orders of magnitude. The following moderate storm and DSWC events occurring in March and April 2004 generated only small turbidity peaks with sharp current speed increases at the canyon head, but did not cause any significant sediment transport pulse at the basin site.

Regarding the February 2004 particle flux increase, the time gap between the sediment transport peak at the canyon head (21–23 February) and the TMF increase at the basin site (sampling period from 22 February to 3 March) indicate that the particles exported through the canyon head reached the basin site within a period $\leqslant 11$ days (2004 was a leap year). The storm-induced downwelling and DSWC generated by this event increased near-bottom currents to more than $80\,cm\,s^{-1}$ at the CC canyon head (300 m depth) for almost 2 days and, according to hydrodynamic modelling, the dense water reached the equilibrium depth at 800 m, maintaining near-bottom current speed higher than $60\,cm\,s^{-1}$ down to 600 m depth (Ulses et al., 2008a). This means that the dense shelf-water plume could have covered the distance from the canyon head to the equilibrium depth (17 km) in less than 7 h.

This event also increased suspended sediment concentration at the CC canyon head to values higher than $68\,mg\,l^{-1}$ at 5 mab, saturating the turbidity sensor for a period of 10 h (Fig. 4), and it could have been significantly higher closer to the bottom. Thus, following the classification of Stow (1994), the down-canyon sediment flow generated during this event could be considered as a low-density turbidity current. Turbidity plumes of this type include suspended particle concentrations in the range of $25–3000\,mg\,l^{-1}$ and can reach a velocity even higher than that of the dense water plume itself if the inclination of the slope is large enough. The density contrast caused by suspended matter of the turbidity plume could have maintained negative buoyancy going deeper than the DSWC equilibrium depth and moving fast down canyon. Turbidity plumes descend ageostrophically (dominated by gravity, friction and inertia) and perpendicular to the slope since any possible decrease of the density difference due to entrainment of ambient water is overridden by an increase in the density difference due to sediment erosion. Turbidity plumes can thus descend faster and deeper into the deep sea (Fohrmann et al., 1998). A loss of its sediment load on smoother slopes could have decelerated the plume and when its density became lower than the density of the ambient water body, the plume could have initiated upward convection, generating detachments of intermediate nepheloid layers (INLs). Either the canyon widening at 1400 m depth or the abrupt slope change (to more than 20°) at the convergence of the CC canyon mouth with the Sète canyon, at 1860 m depth (Lastras et al., 2006), may have worked as an INLs detachment point.

It is worth noting that a sediment trap deployed only 4 mab with a current meter on the lower Sète Canyon, near its confluence with the CC canyon, 80 km away from the basin site, also recorded a TMF increase during the 18 February–2 March sampling interval (Henko Stiger, personal communication). The magnitude of this TMF peak at this location ($2.52\,g\,m^2\,d^{-1}$) was very similar to that of the basin site and the current velocities at both sites were low (between 0.8 and $6.2\,cm\,s^{-1}$) without any significant hydrographic change. This suggests that the sediment load of the turbidity plume left the dense water plume and became detached somewhere in the lower CC canyon, spreading over a large area, and that particles collected 250 mab at the basin site were detached particles that settled from upper water levels and proceeded from this sediment transport pulse and not from local sediment resuspension or local sediment gravity flows.

To reach the basin site in less than 11 days, if particle detachment had been from the CC canyon around 800 m (equilibrium depth), 140 km away from the basin site, particles should have travelled at a mean speed of $15\,cm\,s^{-1}$. However, it is very likely that the sediment was transported down to the lower CC submarine canyon at significantly faster speeds, reaching that area in 1 or 2 days, and that a deeper spreading had occurred afterwards. In that case, if the detachment point was located at 1900 m (CC canyon mouth), 80 km away from the basin site (nearly half way from the canyon head to the basin site), the detached particles should have been transported from one site to the other at a mean speed of around $9\,cm\,s^{-1}$.

There are no good estimates of offshore flows associated with spreading INLs. Horizontal flows of slope INLs have been estimated to range from 1 to 20 cm s^{-1} (McPhee-Shaw and Kunze, 2002). Detachments of INLs below 800 m depth have been found in some submarine canyons extending up to some tens of km from their detachment region (Hickey et al., 1986; Gardner, 1989a; Durrieu de Madron et al., 1990). Thorpe and White (1988) suggested that gravitational collapse and restratification subsequent to mixing events near a boundary lead to enhanced lateral dispersion and described a large (100 km in along-slope extent) INL spreading seaward from the slope at 2500 m depth off the Porcupine Bank.

In the GoL, the circulation deeper than 800 m depth is complex, especially around the basin site, which is in the deep convection area described by the MEDOC Group (1970). Numerous eddies (both anticyclonic and cyclonic) drift far away from this area and might last over 1 year. Most of these eddies first drift toward the southwest and later turn northeastward at mean drifting speeds of 5–6 cm s^{-1} and maximum orbital velocities between 12 and 18 cm s^{-1} (Testor and Gascard, 2006), which are close to the estimated velocities if the particles were detached near the CC canyon mouth. In addition, there are other processes, such as the topographic Rossby waves, affecting the GoL deep continental slope (Millot and Monaco, 1984; Millot, 1985) that could contribute to the redistribution of the particles reaching the basin. The progressive vector of the currents at the basin site during the 2004 winter period shows this complexity (Fig. 5). We must consider that these currents do not reflect the transport conditions, but instead reflect the settling conditions at the sediment trap emplacement. Overall, this finding shows for the first time that a strong winter E–SE storm associated with a moderate DSWC can generate a major event of sediment transfer toward the NW Mediterranean basin. The TMF

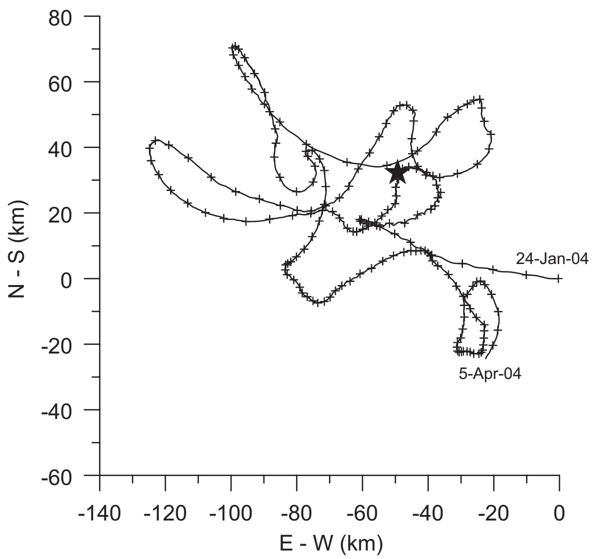

Fig. 5. Progressive vector plot of the currents measured at the basin site during the 2004 moderate cascading period. The star represents the time when the February major storm and associated DSWC event occurred. Crosses represent time periods of 1 day.

collected between 22 February and 3 March (10 d) was 28.2 g m^{-2}, which is 52% of the annual total flux from 14 November 2003 to 14 November 2004 (54.3 g m^{-2}).

5.2. Winter 2005

During winter 2005, there were no major storms and floods, but in late January–early February 2005, DSWC became intense, causing drops of temperature and sharp peaks in down-canyon current velocities and turbidity at the CC canyon head. This occurred almost simultaneously with the arrival of warmer water and the increase of current speed at the basin site (Fig. 6). At the same time, Font et al. (2007) also recorded similar temperature and current increases southward from the study area on the Catalan deep slope south of the Palamós Canyon, at 1890 m depth. They deduced that the conditions were suitable for the simultaneous triggering of offshore convection and shelf-water cascading in the region. The same persistent cold and dry winds that enhanced DSWC also caused a winter convection process in the open sea more intense than average (López-Jurado et al., 2005). This process extended over an unusually large area (Salat et al., 2006) giving a mixed LIW–TDW saltier and warmer than in preceding years (Schröder et al., 2006). Similarly, we can assume that the intrusion of warmer deep water at the basin site corresponds to the arrival of offshore dense water with a larger contribution of more saline and warmer LIW and TDW than usual.

From 24 February 2005, DSCW began to flow uninterruptedly along the CC canyon to depths greater than 750 m (Canals et al., 2006; Puig et al., 2008). Five days later (1 March), DSWC mixed with offshore convection waters arrived to the Catalan deep slope, producing a temperature drop of 0.2 °C (Font et al., 2007). This drop was smaller (0.05 °C) and occurred 2 days later (3 March) at our basin site (Fig. 6), indicating that dense shelf waters reaching this region were more mixed with offshore convection waters than on the Catalan deep slope. At both sites, this temperature drop was associated with higher current speed peaks and lasted to the end of both deployment periods in early April 2005. The progressive vector of the currents at the basin site during this period is shown in Fig. 7.

The particle flux increase at the basin site sediment trap began during the February 26–March 3 sampling interval. Considering that DSWC flowed deeper than 750 m depth from 24 February, the estimated downbasin mean current speed necessary to reach the basin site from that depth (145 km away) would have been between 21 and 54 cm s^{-1}. Given that down-canyon current speeds were between 60 and 80 cm s^{-1} at 750 m depth and between 20 and 47 cm s^{-1} at the basin site during most of the deep cascading period, it is evident that the arrival of deep cascading water with its sediment load at the basin site produced the particle flux increase of two to three orders of magnitude from 26 February until early April 2005 (Fig. 6). The total particle flux during this period (35 days) was 251.1 g m^{-2}, which is 93.2% of the annual TMF from 3 April 2004 to 3 April 2005 (269.5 g m^{-2}).

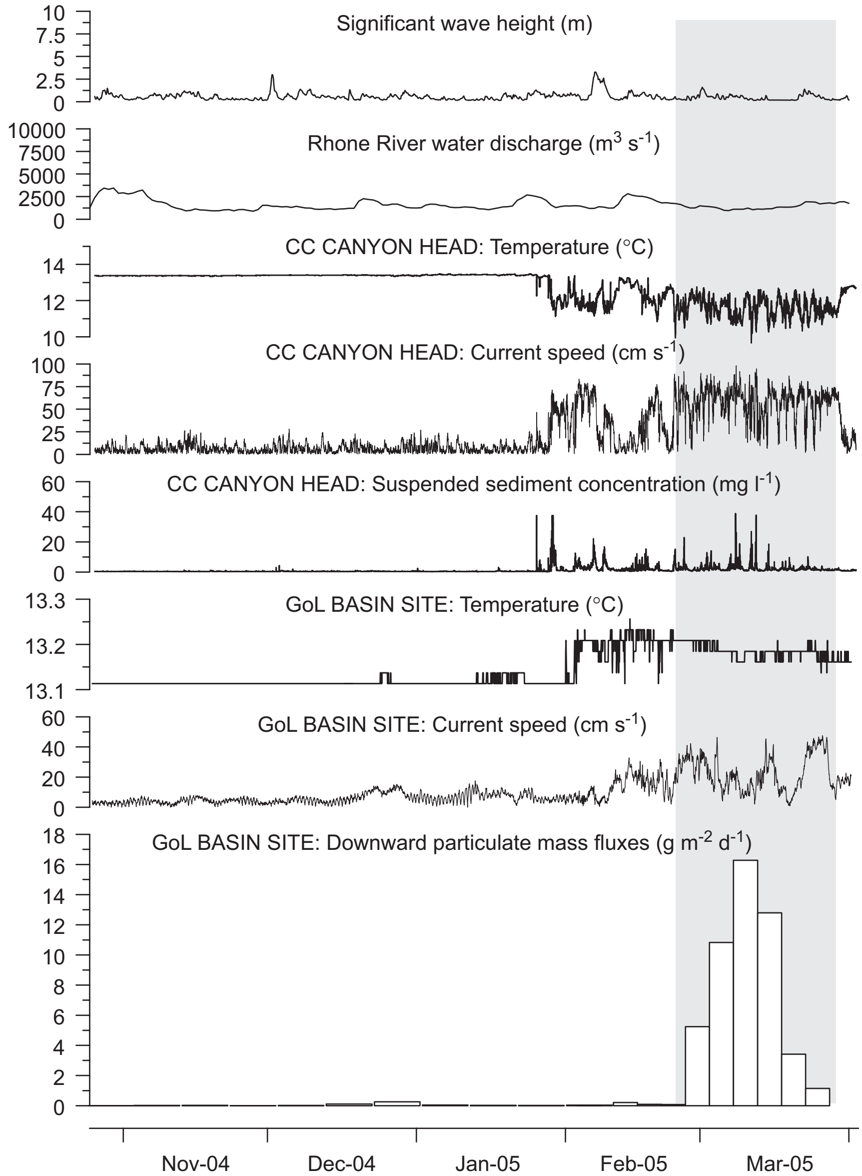

Fig. 6. Time series of significant wave height, Rhone River water discharge, temperature, down-canyon current velocity and suspended sediment concentration recorded 5 mab at 500 m depth at the CC canyon head (from Puig et al., 2008) and time series of temperature, current velocity and downward particle fluxes at the basin site (see location in Fig. 1) during the winter of 2004–2005. At the canyon head, DSWC events correspond to temperature drops concomitant with current speed increases. Gray bands correspond to the period of time during which DSWC was continuously flowing into the deep waters. The downward particle flux increase in March 2005 is associated with the arrival of DSWC mixed with offshore convection water in the basin. CC, Cap de Creus; GoL, Gulf of Lions.

5.3. Recurrence period and magnitude of the sediment transport events reaching the basin

This is the first time that such large increases in downward particle fluxes generated by very strong E–SE winter storms and by deep DSWC have been observed so deep (2350 m) and affecting several hundreds of mab in the NW Mediterranean. In addition, the data series obtained show the timing of the particle flux peaks generated by these processes.

Different events in winter 2004 and winter 2005 gave similar current speeds, turbidity increases and temperature decreases at the CC canyon head, but they did not have the same effect in the basin. Particles can reach the deep environment transported in the dense water plume when cascading is intense enough to be spread over the basin, but they also can reach the basin as turbidity plumes independently from dense water spreading, when extreme storms combined with moderate cascading inject enough sediment through the CC submarine canyon.

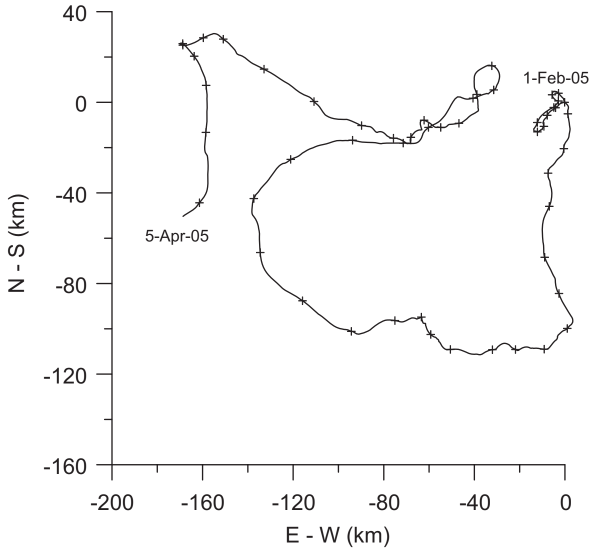

Fig. 7. Progressive vector plot of the currents measured at the basin site during the 2005 intense and persistent deep cascading period. Crosses represent time periods of 1 day.

These events are controlled by climatic and hydrographic factors and have a recurrence interval of several years. In the case of the February 2004 storm (H_s: 7 m) the recurrence interval is 10 years (Puertos del Estado), and deep DSWC was reported to occur in the GoL in 1999 (Bethoux et al., 2002) and in 2005 (Canals et al., 2006; Font et al., 2007; Puig et al., 2008), indicating that these extreme events can take place on a decadal scale.

The magnitude of the downward particle flux peaks recorded 250 mab at the basin site (2350 m depth) is similar to that of the highest downward particle flux peaks recorded only 30 mab at several canyon heads of the NW Mediterranean (Puig and Palanques, 1998; Palanques et al., 2005; Martín et al., 2006; Heussner et al., 2006) and to that of peaks recorded near the bottom on the shelf and upper slope of the mid-Atlantic Bight (Biscaye et al., 1988; Biscaye and Anderson, 1994). The particle flux peaks recorded in the present study are several times greater than those recorded near the bottom at similar depths on the continental slope of the Bay of Biscay (Heussner et al., 1999), and orders of magnitude higher than those recorded in the Mid-Atlantic Bight (Biscaye et al., 1988). Excluding the particle flux peaks of February 2004 and late February–early April 2005, all the remaining fluxes recorded at the basin site in the present study are similar to those recorded in the open Algero–Balearic basin at 2850 m depth (Zúñiga et al., 2008) and on the continental rise of the Mid-Atlantic Bight (Biscaye et al., 1988).

6. Conclusions

Major particle transport events cause increases in downward particle fluxes of more than two orders of magnitude in the NW Mediterranean basin. These events occur as a consequence of several processes. The sharp increase in particle flux recorded in February 2004 in the basin was generated by a major storm that flushed resuspended shelf sediment, mainly through the CC submarine canyon. This storm induced downwelling and occurred simultaneously with DSWC, which injected dense water with resuspended sediment into the submarine canyon. However the particle load moved down-canyon beyond and deeper than the dense water and was transported 160 km seaward from the CC canyon head, in less than 11 days, reaching the basin and affecting deep particle fluxes several hundred mab. This could be explained by a combination of a low-density turbidity current that could have reached the lower CC submarine canyon relatively fast, and by a later detachment of INLs that would have been spread by the deep circulation, reaching the basin site.

In March 2005, the sharp increases in particle flux in the basin were produced by an exceptionally strong and persistent DSWC. This process started in late February, and dense shelf water reached the basin site 1 week later, well mixed with offshore convection water and transporting a large particle load several hundred meters above the bottom. Both offshore convection and cascading increased the near-bottom current speed in the basin, although the strongest peaks were recorded during the deep DSWC period.

This study shows that significant events of sediment transport into the deep basin can be produced both by exceptionally intense and persistent DSWC events, and by strong S–SE winter storms associated with moderate DSWC. Strong storms alone, if they occur during the water stratification period and without DSWC like the December 2003 one, and moderate DSWC events without strong storms like the winter 2004 ones, do not directly increase sediment transfer to the deep basin.

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