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Storm-driven shelf-to-canyon suspended sediment transport at the southwestern Gulf of Lions

A. Palanques [a,*], J. Guillén [a], P. Puig [a], X. Durrieu de Madron [b]

[a] Institut de Ciències del Mar (CSIC), Passeig Marítim de la Barceloneta, 37–49, E-08003 Barcelona, Spain
[b] CEFREM, CNRS, UMR 5110, University of Perpignan, 52 Avenue Paul Alduy, 66860 Perpignan Cedex, France

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ABSTRACT

Shelf-to-canyon suspended sediment transport during major storms was studied at the southwestern end of the Gulf of Lions. Waves, near-bottom currents, temperature and water turbidity were measured on the inner shelf at 28-m water depth and in the Cap de Creus submarine canyon head at 300 m depth from November 2003 to March 2004. Two major storm events producing waves $H_s > 6$ m coming from the E–SE sector took place, the first on 3–4 December 2003 (max H_s: 8.4 m) and the second on 20–22 February 2004 (max H_s: 7 m). During these events, shelf water flowed downcanyon producing strong near-bottom currents on the canyon head due to storm-induced downwelling, which was enhanced by dense shelf water cascading in February 2004. These processes generated different pulses of downcanyon suspended sediment transport. During the peak of both storms, the highest waves and the increasing near-bottom currents resuspended sediment on the canyon head and the adjacent outer shelf causing the first downcanyon sediment transport pulses. The December event ended just after these first pulses, when the induced downwelling finished suddenly due to restoration of shelf water stratification. This event was too short to allow the sediment resuspended on the shallow shelf to reach the canyon head. In contrast, the February event, reinforced by dense shelf water cascading, was long enough to transfer resuspended sediment from shallow shelf areas to the canyon head in two different pulses at the end of the event. The downcanyon transport during these last two pulses was one order of magnitude higher than those during the December event and during the first pulses of the February event and accounted for more than half of the total downcanyon sediment transport during the fall 2003 and winter 2004 period. Major storm events, especially during winter vertical mixing periods, produce major episodes of shelf-to-canyon sediment transport at the southwestern end of the Gulf of Lions. Hydrographic structure and storm duration are important factors controlling off-shelf sediment transport during these events.

1. Introduction

Off-shelf transfer of sediment has been widely studied during the last few decades, and it has been described and quantified on various continental margins within the framework of several integrated research projects (e.g., Carson et al., 1986; Hickey et al., 1986; Walsh et al., 1988; Biscaye et al., 1988, 1994; Monaco et al., 1990; van Weering et al., 1998; Nittrouer and Kravitz, 1996; Nittrouer, 1999). On the continental slope, it is widely recognized that canyons are preferential conduits for the transfer of sediments from the shelf even during the present high sea-level stand (e.g., Drake and Gorsline, 1973; Gardner, 1989a; Durrieu de Madron, 1994), because they have higher downward particle fluxes (Monaco et al., 1990; Puig and Palanques, 1998a; Hung and Chung, 1998; Puig et al., 2003) and sediment accumulation rates (e.g., Carpenter et al., 1982; Thorbjarnarson et al., 1986; Sánchez-Cabeza et al., 1999; Schmidt et al., 2001) than those found on the open slope. However, the shelf-to-canyon sediment transport activity is not always well known because it is variable in time and differs among canyons.

Across-shelf transport is complex and generally involves mechanisms such as wind-driven flows, internal waves, wave orbital flows, infragravity phenomena and buoyant plumes (Nittrouer and Wright, 1994; Sternberg and Nowell, 1999). The energy of such hydrodynamic processes, shelf morphology, latitudinal constraints and the time scale considered are also important factors that determine the shelf-to-canyon transfer. Canyons incised in margins with narrow continental shelves can receive higher sediment inputs. The transfer of these inputs can be mainly controlled by river floods if the wave energy is low, as in

* Corresponding author. Tel.: +34 932309500; fax: +34 932309555.
E-mail address: albertp@icm.csic.es (A. Palanques).

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the Guadiaro Canyon (Palanques et al., 2005) or by storms if the wave energy is high, as in the Eel Canyon (Puig et al., 2004). The importance of short-term processes like floods and storms for sediment delivery and reworking on the shelf has been recently highlighted on the Eel continental margin (e.g., Ogston et al., 2004), where the sediment discharged by the Eel River is resuspended during storms and deposited on the middle shelf (Traykovski et al., 2000). Later, storms can resuspend and transport the sediment again towards the Eel canyon head (Ogston et al., 2000; Puig et al., 2003; Fan et al., 2004). This multi-event storm-induced sediment transport was also observed in the western Gulf of Lions (GoL) towards the Cap de Creus Canyon head (Guillén et al., 2006; Palanques et al., 2006).

The amount of sediment-transferred off-shelf can determine the type of transport processes in the submarine canyons. Some authors have categorized sediment transport processes in submarine canyons into two types: gravity-driven turbidity currents (Shepard et al., 1979; Komar, 1969; Seymour, 1990; Greene et al., 1991), and flow-driven resuspension and transport events among which storms are special occurrences (Hotchkiss and Wunsch, 1982; Gardner, 1989b; Lyne and Butman, 1988; Durrieu de Madron et al., 1999). At the present time, the most frequent processes monitored in submarine canyons by moored instruments are flow-driven resuspension and transport events. Several mechanisms can produce these flows, such as storms, internal waves, tidal motions and dense shelf water cascading (DSWC) (Gardner 1989a, b; Mulder and Syvitski, 1995; Okey 1997; Puig and Palanques 1998b; Johnson et al., 2001; Puig et al., 2004; Palanques et al., 2006; Canals et al., 2006).

Although it is widely known that the most evident mechanisms producing offshore sediment transport are storms and floods, direct relationships of those events with submarine canyon sediment transport are not always found, and few studies combine sediment transport data recorded simultaneously in a submarine canyon and on the adjacent shelf (e.g., Puig et al., 2003). In the GoL, sediment transport during the fall 2003 and winter 2004 period was studied on the SW inner shelf (Guillén et al., 2006) and at the head of seven submarine canyons (Palanques et al., 2006). However, detailed links and timing of the main shelf-to-canyon processes and shelf sediment transport during this period of time were not analyzed. This paper presents combined hydrographic, hydrodynamic and near-bottom suspended sediment concentration (SSC) data collected simultaneously in the Cap de Creus Canyon head and on the inner part of the adjacent continental shelf during the major storm events of the fall 2003 and winter 2004 period. The aim of this paper is to analyze the detailed sequence of forcing processes and the resulting near-bottom shelf-to-canyon suspended sediment transport at the southwestern GoL during these events.

Several papers of this special issue analyze other aspects of the shelf–slope exchange in the GoL. Downward particle fluxes of several GoL submarine canyons during the fall 2003 and winter 2004 are studied in Bonnin et al. (submitted) and Fabres et al. (this issue), and the impact of storms and dense water cascading in the whole GoL during the same period of time was modeled in Ulses et al. (this issue). The effects of an oceanic flood in April 2004 are analyzed in Bourrin et al (submitted). Shelf–slope exchange in the Cap de Creus Canyon during the fall 2004 and winter 2005 period, when intensified DSWC occurred without major storms, are studied in Puig et al., (submitted) and Ogston et al (this issue). Once we know the global role of floods, storms and DSWC in the GoL and that most of the near-bottom sediment transport in the fall 2003 and winter 2004 period occurred during storm events (Palanques et al., 2006; Guillén et al., 2006; Ulses et al., 2008), in this paper we focus on how near-bottom shelf-to-canyon suspended sediment transport occurs in the Cap de Creus Canyon (the most active GoL canyon in terms of sediment transport) during major storms.

2. Study area

The GoL is a micro-tidal continental and river-dominated margin that is fed by several rivers, the most important of which is the Rhône, discharging into the eastern part of the GoL (Fig. 1). The bottom sediment distribution displays a mud belt along the mid-shelf and mixed sandy mud deposits on the inner and outer shelf regions (Aloisi et al., 1973). The GoL continental shelf stores sediment supplied by rivers, which can be subsequently resuspended by storms with waves from the E–SE (E–SE storms) and exported to the slope by storm-induced downwelling and dense water cascading (Palanques et al., 2006; Ulses et al., this issue). The GoL continental slope is incised by numerous submarine canyons. However, most of the near-bottom shelf–slope sediment transfer occurs through the southwesternmost submarine canyon (Cap de Creus Canyon), which is the final outlet before the constriction of the Cap de Creus promontory (Fig. 1). Near-bottom suspended sediment fluxes in this canyon are up to two orders of magnitude higher than in the other GoL canyons (Palanques et al., 2006).

Three small rivers discharge onto the continental shelf northward from the Cap de Creus Canyon head. From north to south, they are the Agly, the Têt and the Tech Rivers (Fig. 1). They have an average water discharge $<10\,m^3\,s^{-1}$, but during exceptional floods their discharge can increase sporadically by up to two orders of magnitude (Palanques et al., 2006).

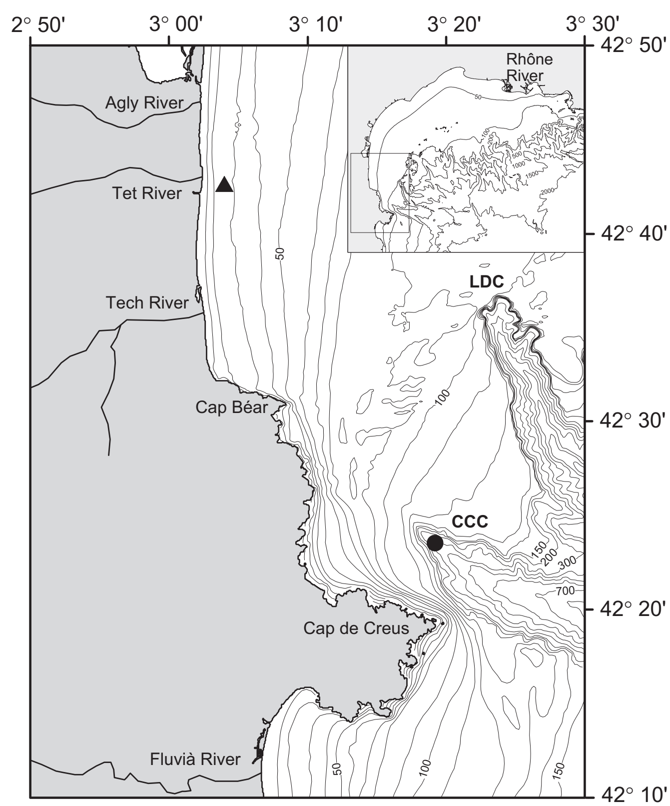

Fig. 1. Map of the NW end of the Gulf of Lions (north-western Mediterranean) showing: the Agly, Têt and Tech Rivers, the position of the tripod installed on the Têt inner shelf (black triangle), the Lacaze Duthier Canyon (LDC) and the Cap de Creus Submarine Canyon (CCC), and the position of the mooring installed at the CCC head (black circle).

From spring to autumn, a seasonal thermocline forms and deepens in the GoL, as in the whole Mediterranean Sea, and during winter this stratification disappears and the waters become homogeneous (Millot, 1990). The main winds in the western part of the GoL are the northwesterly "Tramontane" and the southeasterly "Marin". Estournel et al. (2003) and Ulses et al. (2008) showed that Tramontane and Marin winds induce a cyclonic circulation over the shelf. The cold and dry northerly "Tramontane" is responsible for the strong cooling and homogenization of the shelf water column in winter, which may promote dense shelf water formation.

On this shelf, where tidal currents are negligible, surface waves are the main mechanism causing bottom sediment resuspension and major easterly–southeasterly storms can generate waves with significant wave height (H_s) >6 m and period (T_p) <12 s (Ferré et al., 2005; Guillén et al., 2006). Sediment resuspension during major Marin storms generate large off-shelf particulate matter export specially through the Cap de Creus Canyon by forcing downwelling of turbid shelf water, especially when downwelling is reinforced by DSWC, and when the storm was preceded by a flood event leaving fresh and easily erodible sediment on the shelf (Guillén et al., 2006; Palanques et al., 2006).

A special situation occurs during some years, when intense and persistent action of dry northerly winds in winter intensifies dense shelf water formation in the GoL (Heussner et al., 2006). In this situation, shelf water become denser than usual and cascading can reach the deep slope transporting a significant suspended sediment load towards the basin (Canals et al., 2006). Intensified DSWC occurred in winter 2005 but not in winter 2004.

3. Methods

An Aanderaa current meter (RCM 9) equipped with pressure, temperature, conductivity and turbidity sensors was installed 1 m above bottom (mab) on a tripod deployed 2 km off the mouth of the Têt River on the inner shelf at 28-m water depth (Fig. 1). This tripod was deployed twice, from 26 November 2003 to 12 December 2003 and from 4 February 2004 to 18 March 2004. The sampling interval of the RCM 9 current meter was set to 5 min.

Three D&A Instruments OBS were also mounted on the tripod (see Guillén et al., 2006 for details). These instruments collected data every 3 h in 20-min bursts logged at 2 Hz. Laboratory calibrations were used to convert the signals from these instruments into SSC. In this study, we present the burst-averaged SSC from the OBS mounted at 0.15 mab. In the first deployment, the tripod was knocked over during the peak of a strong storm on 4 December, after 8 days of sampling. The 0.15 mab OBS continued to produce sensible data.

Continuous information on wave conditions was obtained by an autonomous ADCP RDI Sentinel 600 kHz model equipped with a wave pressure sensor and deployed at the shelf study site. It was mounted on a bottom platform with an upward-looking configuration. Waves were measured during 20 min bursts at 2 Hz every 3 h. Currents were measured between wave-burst measurements at 1 Hz and were averaged over that period. In this paper, we show ADCP currents at 2 mab. The ADCP collected data between 26 November 2003 and 16 January 2004, and between 4 February and 26 March 2004. Additional wave data were obtained from a Datawell wave buoy deployed 11 km south of the study area. Bottom shear stress (τ) was estimated using the combined wave and current boundary-layer model of Grant and Madsen (1986). Inputs to the model were wave–orbital velocity (u_{rms}) obtained by applying linear wave theory to the ADCP, H_s and T_p measurements, current speed (u_c) at 2 mab and wave–current angle. The bottom was assumed to be flat and the bottom roughness was given by the sediment grain size (D50) (see Guillén et al., 2006 for details). The Têt River water discharge was obtained from the HYDRO national data bank.

Concurrent with the shelf observations, a RCM11 Aanderaa current meter also equipped with pressure, temperature, conductivity and turbidity sensors was moored 5 mab in the Cap de Creus Canyon head at a depth of 300 m depth from 1 November 2003 to 5 May 2004 with a mooring turnaround from 3 to 5 February. The sampling interval of the canyon-head current meter was set to 20 min.

Temperature and conductivity sensors from the canyon and shelf Aanderaa current meters were calibrated using simultaneous CTD measurements recorded during the mooring deployment. Turbidity data recorded in FTU were converted into SSCs following the methods described in Guillén et al. (2000). Instantaneous and cumulative along-canyon sediment fluxes were obtained by multiplying along-canyon current speed with SSC.

4. Results

To illustrate the storm-driven shelf-to-canyon sediment transport in the SW GoL, two major storms events (H_s>6 m) with waves coming from the E–SE sector during the study period are analyzed in detail: one that occurred in December 2003 while the shelf water was still stratified and concurrent with a flood of all GoL rivers, the other in February 2004 when shelf water was unstratified and DSWC occurred.

4.1. December major storm with water stratification

The first major storm on the Têt inner shelf occurred from 3 to 4 December 2003 (Fig. 2). It was preceded by a 1 °C decrease (from 15.5 to 14.4 °C) in water temperature on 3 December at around 11:30. Six hours later, at 17:30, the storm began and the peak of the storm was at 02:00 on 4 December with H_s of 8.45 m and bottom shear stresses at the study site (28-m water depth) of 3.74 N m^{-2}. The recorded turbidity peak measured by the OBS at 0.15 mab was 1.9 g l^{-1} at 00:00 on 4 December, whereas at 1 mab it was 0.7 g l^{-1} at 01:00 just before the tripod was knocked on its side. Currents 2 mab reached maximum values between 47 and 53 cm s^{-1} after the peak of the storm. The dominant current direction and sediment advection was towards the SSE during the entire event. At 10:30 on 4 December, the storm decreased. The Têt river maximum discharge (363 m^3 s^{-1}) occurred at 12:00 (data not shown), when waves and currents were weak. Therefore, the river flood hardly affected near-bottom turbidity (Fig. 2).

At the canyon head, there was a sudden increase in temperature (from 13.4 to 15.5 °C) and current speed (from 2.5 to >50 cm s^{-1}) at 01:35 on 4 December, which generated the first peaks of bottom shear stress (0.28 N m^{-2}) and turbidity (from 0.8 to 19.2 mg l^{-1}) (Fig. 2). After this first turbidity peak, SSC maintained values between 8 and 15 mg l^{-1} and peaked suddenly up to 48 mg l^{-1} at 04:40. At 9:00, the event ended with a sudden decrease in temperature, currents and turbidity that coincided with the end of the storm on the shelf.

4.2. February major storm without water stratification and with shelf water cascading

The second major storm occurred from 20 to 22 February 2004 (Fig. 3), when river discharge was low (<75 m^3 s^{-1}). On the Têt

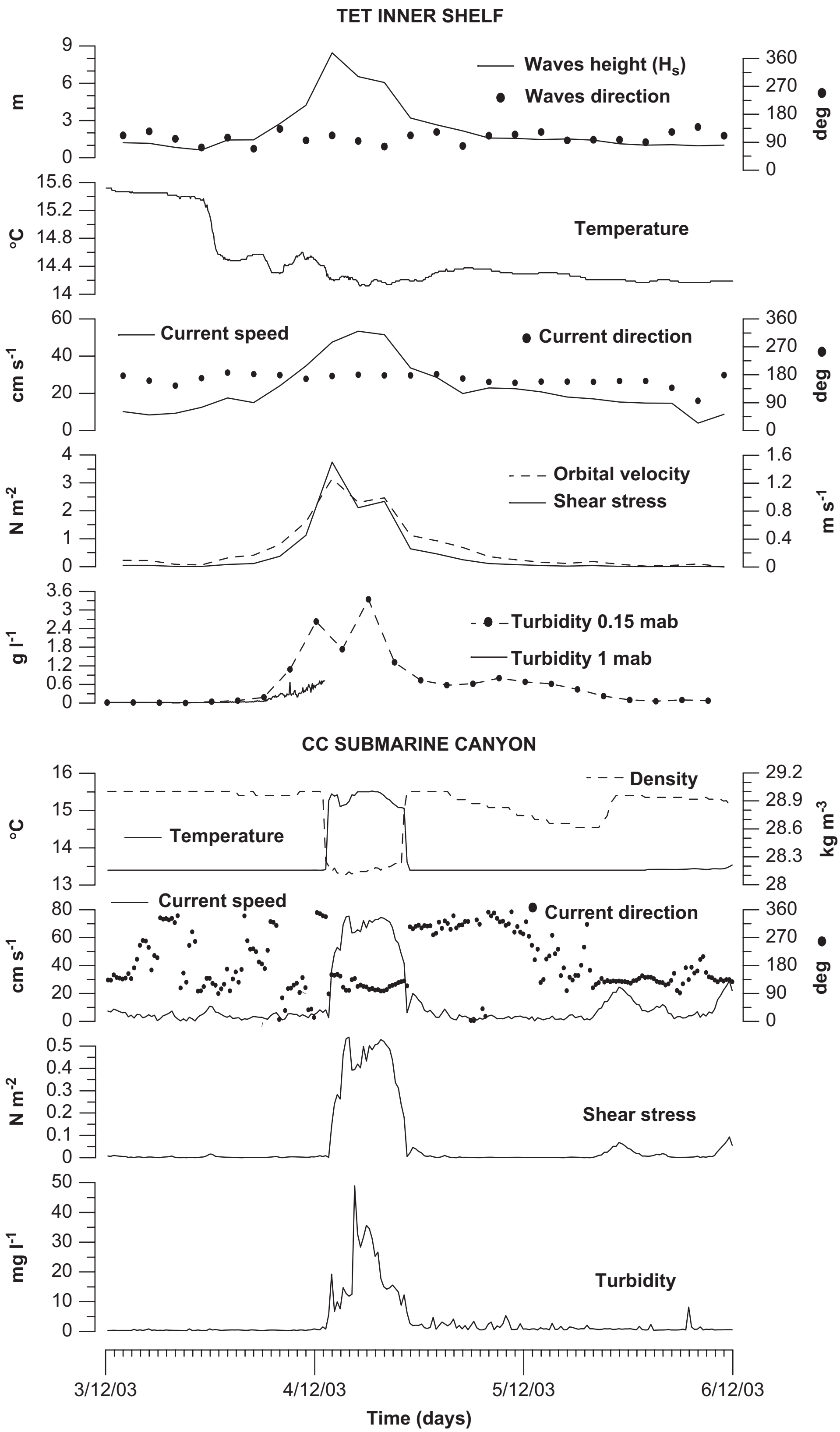

Fig. 2. Time series of waves, near-bottom temperature, near-bottom currents, near-bottom turbidity, orbital velocity and shear stress measured on the Têt inner shelf during the December 2003 event, and time series of near-bottom temperature and density, near-bottom currents, near-bottom shear stress and near-bottom turbidity measured at the head of the Cap de Creus (CC) during the same event.

inner shelf, it began with a temperature decrease of 1 °C and a density increase of 0.15 kg m^{-3} at around 10:40 on 20 February. Seven hours later, at 17:30, the storm began to resuspend sediment on the inner shelf with shear stresses higher than 0.12 N m^{-2}. The peak of the storm ($H_s = 7$ m) occurred at ~03:00 on 21 February, generating the maximum shear stress

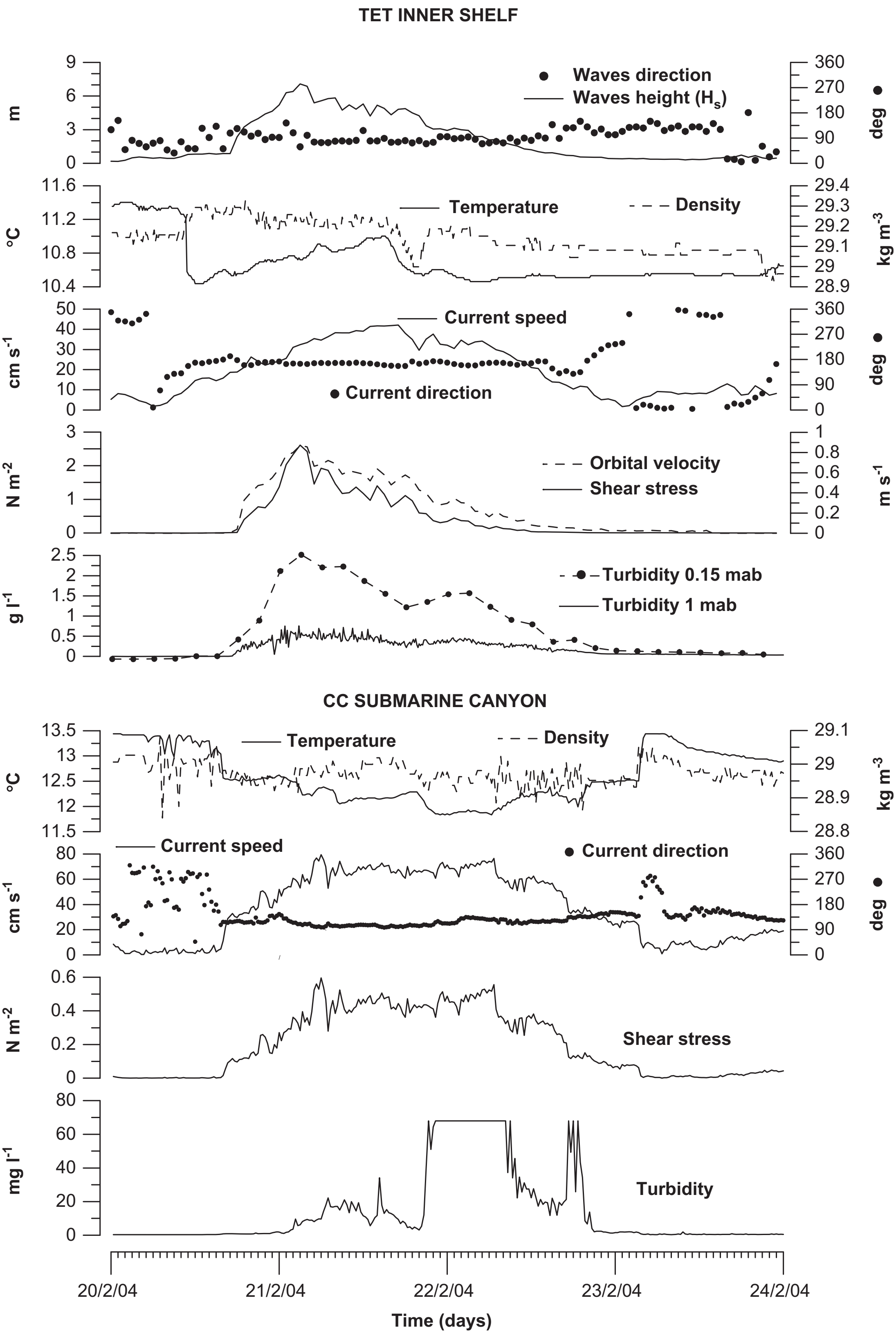

Fig. 3. Time series of waves, near-bottom temperature and density, near-bottom currents, near-bottom turbidity, orbital velocity and wave shear stress measured on the Têt inner shelf during the 21 February 2004 event, and time series of near-bottom temperature and density, near-bottom currents, shear stress, and near-bottom turbidity measured at the head of the Cap de Creus (CC) Canyon during the same event.

(2.61 N m^{-2}) and turbidity (2.5 g l^{-1} at 0.15 mab). During most of the storm, turbidity was >1 g l^{-1} at 0.15 mab and >0.2 g l^{-1} at 1 mab. Simultaneously, currents at 2 mab maintained speeds higher than 20 cm s^{-1} (maximum speed: 42 cm s^{-1}), advecting resuspended sediment towards the S–SE. After the peak of the storm, waves, shear stress and density decreased gradually but turbidity increased again along with a decrease in density and temperature, giving a secondary peak 1 day later, which was not correlated with orbital velocity. All parameters returned progressively to pre-storm values at around 20:00 (Fig. 3).

At the canyon head, the temperature decreased suddenly from 13.1 to 12.5 °C and current speed increased from 3.0 to 21.9 cm s^{-1} at 16:00 on 20 February. For 9 h, current speeds increased progressively and turbidity remained low. Turbidity began to increase at 01:00 on 21 February, when shear stress reached values ~0.14 N m^{-2}. Several turbidity peaks between 20 and 34 mg l^{-1} occurred between 02:00 and 16:00 with shear stresses between 0.27 and 0.59 N m^{-2}. A major turbidity peak began at 22:19 on 21 February and maintained values >68 mg l^{-1} (i.e., turbidity above the sensor range) for 10 h. At the end of the storm, downcanyon currents and turbidity began to decrease progressively. However, turbidity again exceeded 68 mg l^{-1} at 17:00 on 22 February. After this last SSC peak, turbidity decreased drastically and the event ended a few hours later with a sudden increase in temperature and a decrease in current speed (Fig. 3).

5. Discussion

5.1. Resuspension and near-bottom advection on the shelf during the storms

The two major storms analyzed in this paper were exceptional events with relatively similar maximum significant wave height at the study site and recurrence intervals of tens of years (Puertos del Estado). Storm duration was arbitrarily defined as the time when shear stress was higher than 0.12 N m^{-2} at the inner shelf site (Fig. 4), which theoretically, according to Madsen and Grant (1976), could resuspend at least unconsolidated silt and fine sand fractions of the bottom sediment. Following this criterion, the December storm lasted for 26 h and the February storm for 37 h. The peak of the two E–SE storms occurred 9 h after their start. Near-bottom turbidity peaks were correlated with high bottom shear stresses. However, in February there was a second SSC peak between 25 and 50 h after the start of the storm, when waves and shear stresses had already decreased, which was probably due to the advection of sediment resuspended on shallower parts of the

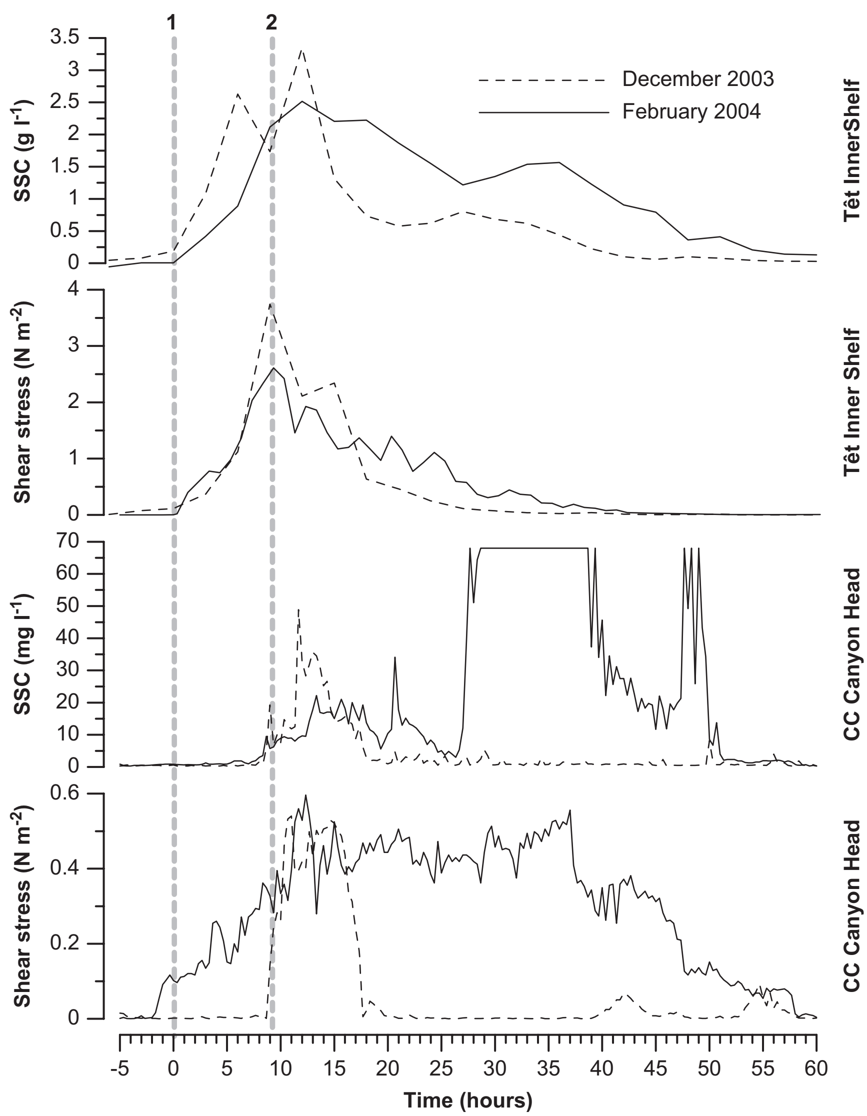

Fig. 4. Time series of near-bottom turbidity and shear stress measured on the Têt inner shelf and at the head of the Cap de Creus (CC) Canyon during the December 2003 event (discontinuous line) and the February 2004 event (solid line) drawn against time since the start of the storm 1: start of wave storms on the inner shelf; 2: peak of the storms.

shelf. Current direction on the inner shelf during the December and February storms was towards the south and southeast. Guillén et al. (2006) estimated from recorded data that in the December event, the dominant sediment transport on the Têt inner shelf was along-shelf towards the south (13 t m^{-2}) with a significant across-shelf component (3 t m^{-2}), whereas in the 21 February event the across-shelf transport was higher and similar to the along-shelf component (15 and 16 t m^{-2}, respectively).

No data were recorded on the middle and outer shelf but considering the peak wave conditions during both major storms, the potential wave shear stresses estimated using the Grant and Madsen (1986) model were higher than 0.12 N m^{-2} down to 110 m depth for the December event and 90 m depth for the February event. This means that resuspension of sandy or unconsolidated fine sediment could have occurred near the shelf break. Ulses et al. (this issue), modeling the combined effect of waves and currents for both storms, also predict sediment resuspension across the outer shelf, where simulated near-bottom currents are >25 cm s^{-1}.

Other more moderate storms such as those occurring on 8 December 2003 (max H_s: 4.5 m) and 13 March 2004 (max H_s: 3.0 m) (Guillén et al. (2006), produced lower sediment resuspension on the inner shelf, and they could not generate bottom shear stresses higher than 0.12 N m^{-2} at depths beyond the middle shelf.

5.2. Shelf water advection at the canyon head during the storms

The shelf cyclonic circulation induced by the December and February major E–SE storms caused a massive convergence of water and suspended sediments at the southwestern end of the GoL. The excess of water that could not escape the GoL's shelf alongshore due to the Cap de Creus promontory was downwelled mainly into the Cap de Creus Canyon (Palanques et al., 2006; Ulses et al., 2008). This water generated a sharp increase in current speed when it reached the canyon head. In both events, the downcanyon water intrusion reached similar maximum current speeds in similar time periods after the beginning of the storms (11 h) but the acceleration and deceleration periods were much shorter and more abrupt in the December event ($\sim$2 h) than in the February 2004 event (13 h) (Figs. 2 and 3).

In the December event, when shelf water was still stratified, the downwelled warmer and lighter shelf water reached the canyon head, suddenly increasing current speed and shear stress 8 h after the beginning of the storm (Figs. 2 and 4). Ulses et al. (2008) and Bonnin et al. (submitted) have shown that this downwelling displaced the upper slope isopycnals downcanyon, giving a strong density contrast between the slope and the shelf waters. The downwelling ended suddenly at the end of the storm because the isopycnals relaxed back to the initial near-horizontal position.

In February, however, during the mixed period, the colder and dense shelf water intrusion arrived at the canyon head increasing current speed and shear stress 90 min before the start of the storm (Figs. 3 and 4) and 5 h after the temperature decrease and density increase that occurred on the Têt inner shelf (Fig. 3). Thus, in February, the intrusion of shelf water at the canyon head started by sinking of dense shelf water before the start of the storm waves at the Têt inner shelf. The lower acceleration was probably due to the small density contrast between the canyon water and the downwelled shelf water (only 0.05 kg m^{-3}). The storm-induced downwelling probably began when current advection by cascading of dense shelf water was already occurring. At the end of the February storm, the advection of shelf water at the canyon head did not end suddenly, but decreased progressively similar to the beginning of the event, also due to the DSWC and low density contrast.

During the moderate storms of the study period, shelf water was advected into the canyon only when associated DSWC occurred during the mixed period (Palanques et al., 2006). This indicates that stratification prevents shelf-to-canyon water advection during moderate storm events.

5.3. Downcanyon sediment transport during the storms

In both the December and the February events, near-bottom turbidity at the canyon head began to increase 9 h after the start of the storms, coinciding with their peaks, when the higher waves produced shear stresses >0.12 N m^{-2} on the outer shelf and simultaneously when canyon current speed increased above 50 cm s^{-1}, generating shear stresses of between 0.14 and 0.59 N m^{-2} at the canyon head (Fig. 4). This suggests that the increases in sediment transported downcanyon during the first few hours could correspond to sediment resuspended either at the canyon head by currents and/or on the outer shelf near the canyon head during the peaks of the storms.

In the December storm, the near-bottom downcanyon sediment transport lasted only for 9 h and ended suddenly along with the storm-induced downwelling as soon as the storm abated and shelf water stratification was restored. However, in the February event, the downcanyon sediment transport lasted for longer (a total of 43 h), continuing even after the end of the storm due to DSWC and lack of water stratification. The highest turbidity increase took place 27 h after the start of the February storm when SSC in the canyon head increased sharply to over 68 mg l^{-1} (Fig. 4). This 27-h time interval is sufficient for advection to transport water and fine sediment over 20–50 km from the inner shelf to the canyon head, given off-shelf bottom water current speeds of 20–42 cm s^{-1} measured during the storm events or 30 cm s^{-1} as resulting from the circulation model of Ulses et al. (2008). Thus, this strong peak was probably produced by shelf-to-canyon advection of the sediment resuspended during the storm on the inner and middle shelf located southward from the Agly River mouth (Fig. 1), where an ephemeral mud layer was previously deposited after the December storm and flood event (Guillén et al., 2006). This major turbidity peak ended after 12 h when waves subsided and inner-shelf and canyon-head current speeds began to decrease (Fig. 3).

The last strong SSC peak at the canyon head occurred after the February storm had ended but while DSWC was still able to advect shelf resuspended sediment towards the canyon (Figs. 3 and 4). After this peak, the downcanyon sediment transport event ended, although cascading of clean dense water continued for 6 more hours.

5.4. Canyon-head near-bottom suspended sediment fluxes during the storms

In the period of autumn 2003 to winter 2004, most of the shelf-to-canyon near-bottom sediment transport occurred by advection of sediment resuspended during major storms. However, we can discriminate between (1) the fluxes of sediment resuspended by surface waves and near-bottom currents on and around the canyon head, which occurred during both the December and February events, and (2) the fluxes of sediment resuspended on the shallower shelf and advected seaward by storm-induced downwelling and/or DSWC, which only reached the canyon head during the February event.

The downcanyon fluxes of sediment resuspended around the canyon head during the peaks of the December and February

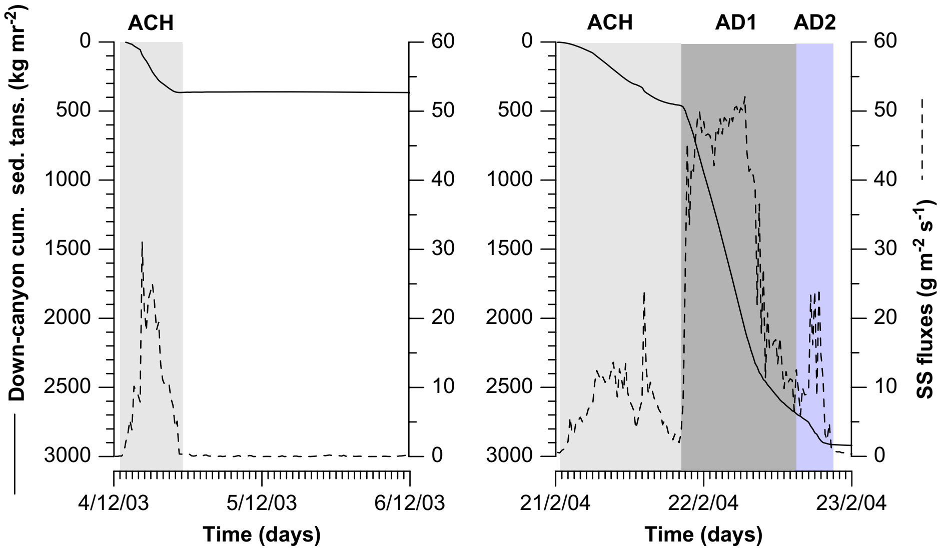

Fig. 5. Time series of downcanyon cumulative sediment transport and instantaneous suspended sediment (SS) fluxes during the December 2003 and February 2004 events. ACH: sediment resuspended around the canyon head; AD1: advection of sediment resuspended on the adjacent inner shelf; AD2: advection of sediment resuspended in more distant areas of the continental shelf.

storms were of similar magnitude. The cumulative sediment transport was slightly less in December (380 $kg\,m^{-2}$) than in February (470 $kg\,m^{-2}$), but the maximum instantaneous fluxes were slightly higher in December (31 $g\,m^{-2}\,s^{-1}$) than in February (23 $g\,m^{-2}\,s^{-1}$) (Fig. 5).

In February, the main peak of suspended sediment advected from the shallower shelf by downwelling and DSWC accounted for a cumulative transport of at least 2230 $kg\,m^{-2}$ and maximum instantaneous fluxes of 50 $g\,m^{-2}\,s^{-1}$. The last peak of sediment advected through the canyon mainly by DSWC produced a cumulative sediment transport of 220 $kg\,m^{-2}$ and maximum instantaneous fluxes of 23 $g\,m^{-2}\,s^{-1}$. Thus, from the total cumulative sediment transport in the February event (2920 $kg\,m^{-2}$), 18% occurred during the first peak of sediment resuspended around the canyon head, 70% during the major peak of sediment resuspended on the shelf and advected by storm-induced downwelling and cascading, and 10% during the last peak of sediment resuspended on the shelf and advected only by cascading. The downcanyon transport of sediment resuspended on the shelf during the last pulses of the February event accounted for more than half of the total downcanyon sediment transport during the whole fall 2003 and winter 2004 period (4350 $kg\,m^{-2}$) estimated in Palanques et al. (2006).

During the December event, near-bottom sediment transport from the inner shelf to the canyon was inhibited by the short duration of the storm and by water stratification. In February, with mixing conditions, the longer storm period reinforced by cascading favored near-bottom sediment advection from inner shelf to the canyon. Another factor that contributed to increase downcanyon near-bottom suspended sediment fluxes was the flood sediment layer accumulated on the shelf after the December flood (Guillén et al., 2006; Ulses et al., this issue), which remained available to be resuspended during the February storm.

Fluxes and processes controlling shelf-to-canyon suspended sediment transport at the Cap de Creus Canyon head can have a strong interanual variability. Most of the downcanyon cumulative fluxes at the canyon head during winter 2003–2004 ($\sim$4350 $kg\,m^{-2}$) occurred during the studied major storms events. However, during the following winter (2004–2005), a larger sediment transport through the canyon head ($\sim$6000 $kg\,m^{-2}$) occurred without major storms, due to exceptionally intensified DSWC working almost permanently from February to early April (Puig et al., submitted). Although intensified DSWC is very important for the off-shelf sediment transport in the GoL (Canals et al., 2006; Puig et al., submitted; Ogston et al., this issue), it is also relevant to point out that only during the 43 h February 2004 storm event, the downcanyon cumulative fluxes at the canyon head were half of those during the 2 months of intensified DSWC in winter 2004–2005. In winters with major storms, downcanyon suspended sediment fluxes at the canyon head can reach at least the same order of magnitude as in winters with intensified DSWC.

5.5. Comparison with other submarine canyons

In canyons located on continental margins with narrow shelves, with significant sediment inputs from rivers and high-energy wave regimes (e.g., Quinault, Monterey and Eel canyons), across-shelf sediment transport is strong and significant amounts of sediment can be temporarily stored at the head of the canyon, therefore providing unconsolidated material for generation of density-driven flows (Xu et al., 2002; Puig et al., 2004). In the GoL, wave regime is less energetic than in the Eel Canyon and the smaller across-shelf sediment transport does not provide enough unconsolidated material to the outer shelf to form density-driven flows. During high-energy events in the SW GoL, sediment bypasses the outer shelf and only an ephemeral veneer of unconsolidated fine sediment can be formed when advection ends (Ogston et al., this issue), which is resuspended at the beginning of the following event.

Puig et al. (2003) also pointed out that in submarine canyons located on continental margins with relict or coarse-grained sediments on the shelf edge around the canyon head (e.g., Baltimore and Foix canyons), contemporary sediment transport mechanisms within the upper canyon section appear to be mainly dominated by internal wave resuspension along the canyon axis and by storm-induced intermediate nepheloid layer detachments at the shelf break (Gardner, 1989a, b; Puig et al., 2000). In the case of the Cap de Creus submarine canyon, with relict sand around its head, intermediate nepheloid layer detachments at the shelf break are probably induced by storms but a dominant sediment transport caused by internal wave resuspension has not been observed (Ogston et al., this issue). In this area, the off-shelf transport is dominated by storm-induced downwelling, which is restricted during water stratification periods, and by DSWC that occurs during unstratified conditions. Therefore, hydrographic structure is an important factor controlling the dominant shelf-to-canyon sediment transport processes.

6. Conclusions

In the Cap de Creus Canyon, different pulses of near-bottom shelf-to-canyon suspended sediment transport can be produced during major storms coming from the E–SE sector. The first pulses can be only sediment resuspended in the canyon itself and the nearby outer shelf area during the peak of the storm. Later, other pulses of sediment resuspended on the inner shelf can reach the slope and be funneled through the canyon head.

During the December event, there was only one main down-canyon pulse of sediment resuspended on the canyon head and the adjacent outer shelf by the highest waves and the increasing canyon near-bottom currents during the peak of the storm. As this event was short and restricted by water stratification, inner shelf resuspended sediment could not be transferred near the bottom towards the canyon head.

During the February storm, there were several pulses of downcanyon near-bottom sediment transport. The first pulses were of sediment resuspended in the canyon head and the adjacent outer during the peak of the storm as during the December event. However, the February event was reinforced by DSWC and was long enough to transfer resuspended sediment from the shallow shelf to the canyon head in two different pulses. The first and most intense occurred at the end of the storm and the last just after the storm when only DSWC was still going on.

Downcanyon cumulative transport of sediment resuspended in and around the canyon head during the December event and during the first sediment transport pulses of the February event was similar. However, the downcanyon transport of shelf resuspended sediment during the last pulses of the February event was one order of magnitude higher and accounted in less than 1 day for more than half of the total downcanyon sediment transport during the fall 2003 and winter 2004 period.

The hydrographic structure and the storm duration are factors that determine the intensity and the pattern of the storm-driven shelf-to-canyon sediment transport events. The combination of different mechanisms such as waves, storm-induced downwelling and cascading during storms can generate various downcanyon sediment transport pulses. Detailed observations recorded simultaneously on the shelf and submarine canyons are required in order to better understand off-shelf sediment export.

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References

Aloisi, J.C., Got, H., Monaco, A., 1973. Carte géologique du précontinent languedocien au 1/250000ième. International Institute for Aerial Survey and Earth Sciences (I.T.C.), The Netherlands.

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. Continental Shelf Research 8, 855–904.

Biscaye, P.E., Flagg, C.N., Falkowski, P.G., 1994. The shelf edge exchange processes EXPERIMENT, SEEP-II: an introduction to hypotheses, results and conclusions. Deep-Sea Research II 41, 231–252.

Bonnin, J., Heussner, S., Fabres, J., Calafat, A., Palanques, A., Durrieu de Madron, X., Canals, M., Puig, P., Avril, J., Delsaut, N. Effect of storms on temporal and spatial variability of downward particle fluxes across canyons of the Gulf of Lions (NW Mediterranean), Continental Shelf Research, submitted.

Bourrin, F.P., Friend, L., Amos, C.L., Durrieu de Madron, X., Thompson, C.E., Manca, E., Ulses, C., Palanques, A., Sediment dispersal from a typical Mediterranean flood: the Têt River, Gulf of Lions (NW Mediterranean, France), Continental Shelf Research, submitted.

Canals, M., Puig, P., Durrieu de Madron, X., Heussner, S., Palanques, A., Fabres., J., 2006. Flushing submarine canyons. Nature 444, 354–357.

Carpenter, R., Peterson, M.L., Bennett, J.T., 1982. ^{210}Pb-derived sediment accumulation and mixing rates for the Washington continental slope. Marine Geology 48, 135–164.

Carson, B., Baker, E.T., Hickey, B.M., Nittrouer, C.A., DeMaster, D.J., Thorbjarnarson, K.W., Snyder, G.W., 1986. Modern sediment dispersal and accumulation in Quinault submarine canyon—a summary. Marine Geology 71, 1–13.

Drake, D.E., Gorsline, D.S., 1973. Distribution and transport of suspended particulate matter in Hueneme, Redondo, Newport and La Jolla submarines canyons. Geological Society of America Bulletin 84, 3949–3968.

Durrieu de Madron, X., 1994. Hydrography and nepheloid structures in the Grand-Rhone canyon. Continental Shelf Research 14, 457–477.

Durrieu de Madron, X., Castaing, P., Nyffeler, F., Courp, T., 1999. Slope transport of suspended particulate matter on the Aquitanian margin of the Bay of Biscay. Deep-Sea Research II 46, 2003–2027.

Estournel, C., Marsaleix, P., Auclair, F., Julliand, C., Vehil, R., 2003. Observations and modeling of the winter coastal oceanic circulation in the Gulf of Lion under wind conditions influenced by the continental orography (FETCH experiment). Journal of Geophysical Research 108 (C3), 8059.

Fabres, J., Tesi, T., Velez, J., Batista, F, Lee, C., Calafat, A., Heussner, S., Palanques, A., Miserocchic, S. Seasonal and event-controlled export of organic matter from the shelf towards the Gulf of Lions continental slope, Continental Shelf Research, this issue, doi:10.1016/j.csr.2008.04.010.

Fan, S., Swift, D.J.P., Traykovski, P., Bentley, S., Borgeld, J., Reed, C.W., Niedoroda, A.W., 2004. River flooding, storm resuspension, and event stratigraphy on the northern California shelf: observations compared with simulations. Marine Geology 210, 17–41.

Ferré, B., Guizien, K., Durrieu de Madron, X., Palanques, A., Guillén, J., Grémare, A., 2005. Fine-grained sediment dynamics during a strong storm event in the inner-shelf of the Gulf of Lion (NW Mediterranean). Continental Shelf Research 25, 2410–2427.

Gardner, W.D., 1989a. Baltimore canyon as a modern conduit of sediment to the deep sea. Deep-Sea Research 36, 323–358.

Gardner, W.D., 1989b. Periodic resuspension in Baltimore canyon focusing of internal waves. Journal of Geophysical Research 94, 18185–18194.

Grant, W.D., Madsen, O.S., 1986. The continental shelf bottom boundary layer. Annual Review of Fluid Mechanics 18, 265–305.

Greene, H.G., Gardner-Taggart, J., Ledbetter, M.T., Barminski, R., Chase, T.E., Hicks, K.R., Baster, C., 1991. Offshore and onshore liquefaction at Moss Landing spit, central California—result of the October 17, 1989 Loma Prieta earthquake. Geology 19, 945–949.

Guillén, J., Palanques, A., Puig, P., Durrieu de Madron, X., Nyffeler, F., 2000. Field calibration of optical sensors for measuring suspended sediment concentration in the Western Mediterranean. Scientia Marina 64 (4), 427–435.

Guillén, J., Bourrin, F., Palanques, A., Durrieu deMadron, X., Puig, P., Buscail, R., 2006. Sediment dynamics during 'wet' and 'dry' storm events on the Têt inner shelf (SW Gulf of Lions). Marine Geology 234, 129–142.

Heussner, S., Durrieu de Madron, X., Calafat, A., Canals, M., Carbonne, J., Delsaut, N., Saragoni, G., 2006. 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). Marine Geology 234, 63–92.

Hickey, B.M., Baker, E., Kachel, N.B., 1986. Suspended particle movement in and around Quinault Submarine Canyon. Marine Geology 71, 35–83.

Hotchkiss, F.S., Wunsch, C., 1982. Internal waves in Hudson Canyon with possible geological implications. Deep-Sea Research 29, 415–442.

Hung, G.W., Chung, Y., 1998. Particulate fluxes, ^{210}Pb and ^{210}Po measured from sediment trap samples in a canyon off northeastern Taiwan. Continental Shelf Research 18, 1475–1491.

Johnson, K.S., Paull, C.K., Barry, J.B., Chavez, F.P., 2001. A decadal record of underflows from a coastal river into the deep sea. Geology 29, 1019–1022.

Komar, P.D., 1969. The channelized flow of turbidity currents with application to Monterey deep-sea fan channel. Journal of Geophysical Research 74, 4544–4558.

Lyne, V.D., Butman, B., 1988. Sand transport and fine particle suspension within and around Lydonia Canyon. In: North Atlantic Slope and Canyon Study, vol. 2, Open-File Report 88-27B. US Geological Survey, Woods Hole.

Madsen, O.S., Grant, W.D., 1976. Sediment transport in the coastal environment. Report No. 209, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, MIT, 105pp.

Millot, C., 1990. The Gulf of Lions' hydrodynamics. Continental Shelf Research 10 (9–11), 885–894.

Monaco, A., Biscaye, P.E., Soyer, J., Pocklington, R., Heussner, S., 1990. Particle fluxes and ecosystem response on a continental margin: the 1985–1988 Mediterranean ECOMARGE experiment. Continental Shelf Research 10, 809–839.

Mulder, T., Syvitski, J.P.M., 1995. Turbidity currents generated at mouths of rivers during exceptional discharges to the world oceans. Journal of Geology 103, 285–299.

Nittrouer, C.A., 1999. STRATAFORM: overview of its design and synthesis of its results. Marine Geology 154, 3–12.

Nittrouer, C.A., Kravitz, J.H., 1996. STRATAFORM: a program to study the creation and interpretation of sedimentary strata on continental margins. Oceanography 9, 146–152.

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

Ogston, A.S., Cacchione, D.A., Sternberg, R.W., Kineke, G.C., 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. Continental Shelf Research 20, 2141–2162.

Ogston, A.S., Guerra, J.V., Sternberg, R.W., 2004. Interannual variability of near-bed sediment flux on the Eel River shelf, northern California. Continental Shelf Research 24, 117–136.

Ogston, A.S., Drexler, T.M., Puig, P. Sediment delivery, resuspension and transport in two contrasting canyon environments in the southwest Gulf of Lions. Continental Shelf Research, this issue, doi:10.1016/j.csr.2008.02.012.

Okey, T.A., 1997. Sediment flushing observations, earthquake slumping, and benthic community changes in Monterey Canyon head. Continental Shelf Research 17, 877–897.

Palanques, A., El Khatab, M., Puig, P., Masqué, P., Sánchez-Cabeza, J.A., Isla, E., 2005. Downward particle fluxes in the Guadiaro submarine canyon depositional system (north-western Alboran Sea), a river flood dominated system. Marine Geology 220 (1–4), 23–40.

Palanques, A., Durrieu de Madron, X., Puig, P., Fabres, J., Guillén, J., Calafat, A., Canals, M., Bonnin, J., 2006. Suspended sediment fluxes and transport processes in the Gulf of Lions submarine canyons. The role of storms and dense water cascading. Marine Geology 234, 43–61.

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

Puig, P., Palanques, A., 1998b. Nepheloid structure and hydrographic control on the Barcelona continental margin, northwestern Mediterranean. Marine Geology 149, 39–54.

Puig, P., Palanques, A., Guillén, J., García-Ladona, E., 2000. Deep slope currents and suspended particle fluxes in and around the Foix submarine canyon (NW Mediterranean). Deep-Sea Research I 47, 343–366.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Sternberg, R.W., 2003. Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California). Marine Geology 193, 129–149.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Parsons, J.D., Sternberg, R.W., 2004. Storm-induced sediment gravity flows at the head of the Eel submarine canyon, northern California margin. Journal of Geophysical Research 109 (C3), C03019.

Puig, P., Palanques, A., Orange, D.L., Lastras, G., Canals, M. Dense shelf water cascading and sedimentary furrow formation in the Cap de Creus Canyon, northwestern Mediterranean Sea. Continental Shelf Research, submitted.

Sánchez-Cabeza, J.A., Masqué, P., Ani-Ragolta, I., Merino, J., Frignani, M., Alvisi, F., Palanques, A., Puig, P., 1999. Sediment accumulation rates in the southern Barcelona continental margin (NW Mediterranean Sea) derived from ^{210}Pb and ^{137}Cs chronology. Progress in Oceanography 44, 313–332.

Schmidt, S., de Stigter, H.C., van Weering, T.C.E., 2001. Enhanced short-term sediment deposition within the Nazaré Canyon, North-East Atlantic. Marine Geology 173, 55–67.

Seymour, R.J., 1990. Autosuspending turbidity flows. In: Le Mehaute, B., Hanes, D.M. (Eds.), The Sea, vol. 9, pp. 919–940.

Shepard, F.P., Marshall, N.F., McLoughlin, P.A., Sullivan, G.G., 1979. Currents in Submarine Canyons and Other Seavalleys. AAPG Studies in Geology No. 8. American Association of Petroleum Geologists, Tulsa, OK, 173pp.

Sternberg, R.W., Nowell, A.R.M., 1999. Continental shelf sedimentology: scales of investigation define future research opportunities. Journal of Sea Research 41, 55–71.

Thorbjarnarson, K.W., Nittrouer, C.A., DeMaster, D.J., 1986. Accumulation of modern sediment in Quinault submarine canyon. Marine Geology 71, 107–124.

Traykovski, P., Geyer, W.R., Irish, J.D., Lynch, J.F., 2000. The role of density driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. Continental Shelf Research 20, 2113–2140.

Ulses, C., Estournel, C., Bonnin, J., Durrieu de Madron, X., Marsaleix, P., 2008. Impact of storms and dense water cascading on shelf–slope exchanges in the Gulf of Lion (NW Mediterranean). Journal of Geophysical Research, 113, C02010, doi:10.1029/2006JC003795.

Ulses, C., Estournel, C., Durrieu de Madron, X., Palanques, A., Suspended sediment transport in the Gulf of Lions (NW Mediterranean): Impact of extreme storms and floods. Continental Shelf Research, this issue, doi:10.1016/j.csr.2008.01.015.

van Weering, T.C.E., McCave, I.N., Hall, I.R., 1998. Ocean margin exchange (OMEX I) benthic processes study—preface. Progress in Oceanography 42, 1–4.

Walsh, J.J., Biscaye, P.E., Csanady, G.T., 1988. The 1983–1984 shelf edge exchange processes (SEEP)-I experiment: hypotheses and highlights. Continental Shelf Research 8, 435–456.

Xu, J.P., Noble, M., Eittreim, S.L., Rosenfeld, L.K., Schwing, F.B., Pilskaln, C.H., 2002. Distribution and transport of suspended particulate matter in Monterey Canyon, California. Marine Geology 181, 215–234.