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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