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Impact of winter storms on sediment erosion in the Rhone River prodelta and fate of sediment in the Gulf of Lions (North Western Mediterranean Sea)

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ABSTRACT

In this study a three-dimensional sediment transport model was developed. The model accounts for both current and wave forcing on the sediment and was implemented over the Gulf of Lions. A two-way nesting technique was used to focus on the Rhone River prodelta which is considered as a sink for riverine sediment. In addition, to understand the resuspension of trapped sediment over the Rhone prodelta, an *in situ* experiment, called SCOPE, was conducted during the winter 2007–2008. The experiment consisted of measuring hydro-sedimentary parameters using a mooring station comprising a current profiler (ADCP) and an altimeter (acoustic transducer) located in the eastern part of the Rhone prodelta. The three-dimensional transport model was validated using these data, and used to investigate the effect of sediment dynamics at the prodelta and Gulf of Lions scale. Both modelling and data analysis highlighted the impact of the two strong storms from the south-east which characterised the experimental period. Erosion of bed material (about 2 cm) and an increase in suspended material (up to about 50–100 mg/l) in the water were the result of each storm as recorded at the mooring station. The erosion capacity due to waves, combined with a strong current, due to both wind and wave forcing, resulted in strong south-westward export over the whole prodelta. Each storm was responsible for an off-prodelta export estimated at around 2.1 Mt. This study demonstrates that the Rhone River sediments trapped over the Rhone prodelta are subject to strong resuspension during episodic events.

1. Introduction

Like many European river basins, the Rhone River basin covers populated, industrial and agricultural areas. In such environments, human activity often results in the introduction of pollutants into the riverine ecosystem. Some of these pollutants (heavy metals, various radionuclides, etc.) have a high affinity for particulate matter which makes understanding particle behaviour over continental margins particularly important.

Among continental margin systems, river-dominated ocean margins have some of the highest sediment deposition rates of all marine systems (McKee et al., 2004). According to Walsh and Nittrouer (2009), the river-dominated continental margin of the Gulf of Lions (GoL), through which the Rhone River flows, is a proximal-accumulation-dominated system. In such environments characterised by a low tidal range and relatively low mean significant wave height (Walsh and Nittrouer, 2009), fine-grained sediments accumulate rapidly near the river mouth and the accumulation rate is greatly affected by flood events (Hossain et al., 2001). This is particularly true in the GoL where the Rhone River sediment discharge leads to the formation of a prodeltaic structure directly downstream from the river mouth (Roussiez et al., 2005). Up to now, extensive studies have focused on direct dispersion of suspended material from the Rhone river to the prodelta or to the shelf (e.g., Pauc, 1970; Got and Aloisi, 1990; Naudin et al., 1997; Arnoux-Chiavassa et al., 1999; Radakovitch et al., 1999; Thill et al., 2001; Miralles et al., 2006). However, sediments are not always directly dispersed. They can be stored temporarily in prodeltas before being resuspended and transported further away. To better understand the sediment pathways from a river to a continental margin, we need to improve our understanding of sediment resuspension, as this contributes to the transfer of sediment from the prodelta to the shelf.

While several recent observations focused on sediment resuspension events over the GoL shelf (e.g., Ferre et al., 2005; Guillén

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et al., 2006; Palanques et al., 2006, 2011; Bourrin et al., 2008a, 2008b), only a few focused on the Rhone prodelta area (Schaaff et al., 2002; Schaaff, 2003; Lansard, 2005; Lansard et al., 2007; Marion et al., 2010). Moreover, because of the spatial limitation of these observations, resuspension processes on the whole Rhone prodelta remain poorly understood. Numerical models can be used to fill the gap between our understanding of sediment-transport processes provided by local observations, and sedimentation patterns over the prodelta. Sediment transport models have already been successfully used over the GoL (Ulses, 2006; Ferre et al., 2008; Ulses et al., 2008) and have helped to understand off-shelf sediment export through canyons. It is now a key issue to focus on resuspension processes using innovative modelling techniques over the Rhone prodelta, and in particular to develop a high-resolution model specially refined on this area.

In the present study, field measurements performed over a 3-month period were combined with a high resolution three-dimensional sediment transport model to understand the relationship between winter storms, sediment resuspension over the Rhone River prodelta and fate of sediment within the GoL. The hydro-sedimentary experiment, called SCOPE, that took place during the winter 2007–2008 was first used to quantify resuspension processes and validate our model. The model was then used for further investigations focusing on the effect of extreme events on the sediment dynamics of the Rhone prodelta and of the GoL. The paper is structured as follows: after a brief presentation of the study area, we describe the SCOPE field experiment and the sediment transport model developed for the prodelta/GoL case study. In Section 4, we jointly analyse experimental and modelling results and validate the model. This is followed by a discussion on the various results and conclusions.

2. Regional setting

The Gulf of Lions, located in the north-western Mediterranean Sea (Fig. 1), is hydrodynamically complex as several intense and strongly varying processes coexist. Millot (1990) described the main hydrodynamic patterns: (a) the general south-westward circulation along the slope, called the Northern Current; (b) wind-induced currents; and (c) the formation of dense water both on the shelf and offshore. Over the shelf region the wind-driven circulation prevails.

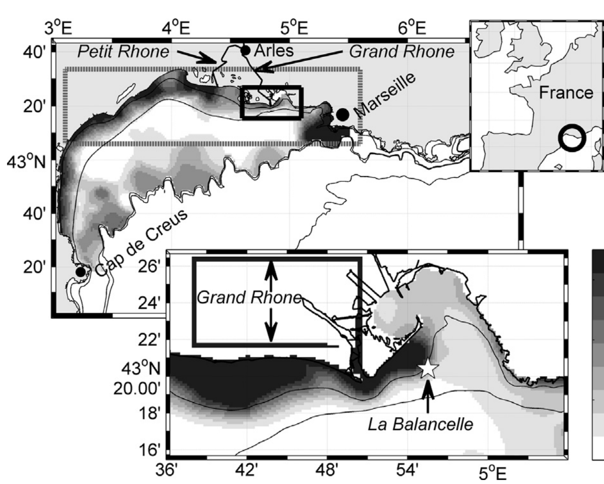

Fig. 1. Study site and sediment facies (% sand fraction) in the coarse resolution model domain GOL and in the fine resolution model domain PRODELTA. The boundaries of the first nested SWAN (into WW3) are shown as grey dotted boxes. The boundaries of the finer nested SWAN and MARS-3D domain are also shown as black boxes. The white star shows the location of the *La Balancelle* station. Isobaths 20, 60, 160, 200 and 2000 are plotted.

Intense and frequent continental winds (the Mistral in the eastern part of the GoL and the Tramontane in the western part) drive the surface waters offshore and induce local upwelling (Estournel et al., 2003). On-shore winds (mainly winds from the east and the south-east) are less frequent and result in the accumulation of water on the coast and the downwelling of surface water (Estournel et al., 2003). The cold dry continental winds which appear during winter also generate dense water on the shelf. This dense water is preferentially formed on the western part of the shelf and sinks on the south-western end part of the shelf causing dense water to cascade through the canyon (Dufau-Julliand et al., 2004).

Both on-shore and off-shore winds also generate waves within the GoL. Due to small fetch, continental winds produce small waves (significant height < 2 m and peak period < 6 s), whereas the north-westward swell induced by less frequent onshore winds, can reach 10 m with a peak period of 12 s (The Medatlas Group: Gaillard et al., 2004; Ulses et al., 2008).

The Rhone River, which divides into two branches (the Grand Rhone and the Petit Rhone) about 50 km upstream the main river mouth near Arles, is a significant source of sediment for the whole GoL. It is responsible for about 94% of total solid fluxes into the GoL with a mean discharge of 10 Mt/year (Bourrin and Durrieu de Madron, 2006). The Rhone River releases 80% of the annual amount of sediments in several days of flooding (Rolland, 2006) and the solid discharge is characterised by a strong seasonal and inter-annual variability (Eyrolle et al., 2012).

High-discharge events of the Rhone river are not coincident with energetic oceanic conditions (strong winds, waves or currents) in the GoL, impacting the deposition of riverine sediments (Drexler and Nittrouer, 2008). Indeed, most of the sediments discharged by the Rhone River are initially deposited close to the river mouth (Noël, 1996; Lansard, 2005; Maillet et al., 2006). Sediments from the Rhone River can also be exported directly to the GoL through the river plume (Naudin and Cauwet, 1997), whose orientation is controlled by the wind. The river plume is directed south-westward and extends far offshore during continental winds, while it moves toward the west of the river mouth, following the coastline, during on-shore wind events (Pauc, 1970; Arnoux-Chiavassa et al., 1999).

Maillet et al. (2006) estimated that 90% of the sediment discharged during a major flood (December 2001) have been deposited on the Rhone prodelta between 0 and 20 m depth. The Rhone prodelta, which covers about 30 km^2 downstream the Grand Rhone river mouth, is characterised by fine-grained sediment downstream from the 20 m isobath (Maillet, 2005; Roussiez et al., 2005). In this area, net sedimentation rates are estimated to range from 30 to 50 cm $year^{-1}$ (Calmet and Fernandez, 1990; Charmasson et al., 1998; Radakovitch et al., 1999; Miralles et al., 2005) and deposition can reach 1 m in some places during exceptional floods (Maillet et al., 2006). The Rhone prodelta acts as a temporary sink for riverine sediment, which can be subsequently eroded and transported south-westward during winter storm from the south-east (e.g., Lansard, 2005; Roussiez et al., 2006; Drexler and Nittrouer, 2008; Ulses et al., 2008; Marion et al., 2010). The sediment erosion process in the Rhone prodelta has been tackled mainly through the estimation of both the erosion rate and sediment shear strength in the vicinity of the Rhone River mouth (Schaaff et al., 2002; Schaaff, 2003; Lansard, 2005; Lansard et al., 2006). At the scale of the whole shelf, studies on sediment resuspension highlighted the role of winds from the south-east and dense water formation on the off-shelf sediment export at the south-western end of the shelf (Ferre et al., 2005; Guillén et al., 2006; Bourrin et al., 2008a; Ulses et al., 2008).

The sedimentological setting of the shelf, described by Got and Aloisi (1990), partly reflects the complex sediment dynamics detailed above (Dufois et al., 2008). The GoL shelf presents various