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Formation and structure of the turbidity maximum in the macrotidal Charente estuary (France): Influence of fluvial and tidal forcing

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ABSTRACT

Understanding estuarine sediment dynamics and particularly turbidity maximum dynamics is crucial for the management of these coastal systems. Various processes impact the formation, movement and structure of the turbidity maximum. Several studies have shown that tidal asymmetry and density gradients are responsible for the presence of this suspended sedimentary mass.

The Charente estuary is a highly turbid system (with suspended sediment concentrations often in excess of 5 g/L) that remains poorly understood despite its strong impact on local activities. In this study, a three-dimensional hydrosedimentary model is developed to represent the sediment dynamics of this estuary. Model validation demonstrates good accuracy, especially on reproducing semi-diurnal and spring-neap variability. Several simulations are performed to evaluate the influence of tides and river discharge on the turbidity maximum. Mean and maximum suspended sediment concentrations (*SSC*) and sediment stratification are calculated. *SSC* transects are also used to visualize the suspended sediment distribution along the estuary.

The turbidity maximum generally oscillates between the river mouth and the Rochefort area (20–30 km upstream). The model shows strong variations at different time scales, and demonstrates that *SSC* is mainly driven by deposition/resuspension processes. Spring-neap comparisons show that the turbidity maximum is not well-defined during neap tides for low and mean runoff conditions. Simulations of spring tides and/or high runoff conditions all result in a compact suspended sedimentary mass.

Performing simulations without taking density gradients into account demonstrates that tidal asymmetry is the main mechanism leading to the formation of the turbidity maximum. However, density gradients contribute to maintaining the stability of the turbidity maximum. Vertical stratification traps sediments at the bottom. Longitudinal stratification ensures a sharper edge at the downstream limit of the suspended sedimentary mass, preventing a massive export of sediments.

1. Introduction

Because of their unique location at the interface between land and sea, estuaries are critical ecosystems subject to strong anthropogenic pressures. Macrotidal estuaries characterized by the presence of fine cohesive sediments frequently exhibit a highly turbid zone. This compact suspended sedimentary mass is called a turbidity maximum, and it is sensitive to variations in the tidal and fluvial regime. Understanding the dynamics and characteristics of turbidity maxima is important for the ecology as well as the economy of nearby coastal areas. For example, fine cohesive sediments are noted carriers of pollutants that endanger water quality (Eyre and McConchie, 1993). They are also related to strong siltation rates near harbours or other infrastructure, necessitating regular dredging. For instance, Owens et al. (2005) report that 50×10^6 tons/year of sediment are dredged from coastal areas in the UK. They also show that dredging reaches 4 to 5×10^6 m^3/year in the Elbe river and Hamburg harbour in Germany.

Turbidity maximum processes have been studied in several estuaries (Allen et al., 1980; Brenon and Le Hir, 1999; Cancino and Neves, 1999; Dyer, 1997; Geyer et al., 2001; Sottolichio et al., 2000; Ralston and Geyer, 2009; Uncles and Stephens, 1993; Uncles et al., 2006). The suspended sediment concentration in the turbidity maximum varies on several time scales (following the ebb–flood cycle, spring-neap cycle, seasonal variations). On the 12 h scale of a semi-diurnal tidal cycle, slack waters tend to favour

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sedimentation and deposition, whereas flood and ebb phases favour erosion and resuspension, with mobile bed sediments feeding the turbidity maximum (Allen et al., 1980). Fluctuations on the larger time scale of a spring-neap tidal cycle induced by changes in the current velocities intensity, are also important (Allen et al., 1980; Dyer, 1997). From spring to neap tides, current velocities decrease and sedimentation takes place. The turbidity maximum zone is then reduced, and fluid mud appears (or is supplemented) at the bottom. Seasonal variations related to river discharge also occur. For example, floods can induce a seaward movement of the turbidity maximum (Allen and Castaing, 1973; Geyer et al., 2001; Uncles et al., 2006).

The formation of a turbidity maximum in an estuary is mainly attributed to two processes: density circulation and tidal asymmetry (Allen et al., 1980). Density gradients may generate two-layer circulation (density circulation), with freshwater moving seaward at the surface and saltwater moving landward at the bottom. A turbidity maximum can appear at the density nodal point, where the flow becomes entirely seaward-oriented (Allen et al., 1980; Dyer, 1997). Tidal asymmetry, characterized by uneven current velocities and slack waters (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988), can generate a turbidity maximum at the tidal nodal point. According to Allen et al. (1980) and Dyer (1997), the tidal nodal point is often located upstream from the density nodal point. Uncles and Stephens (1993) showed that the position of the turbidity maximum sometimes corresponds to the freshwater–saltwater interface.

The relative importance of both processes depends on estuary characteristics. Li (1994) suggested that turbidity maximum dynamics are mainly driven by the tides. This behaviour was confirmed by Brenon and Le Hir (1999) and Sottolichio et al. (2000) in the Seine and Gironde estuaries, respectively. However, both studies showed that density gradients are essential to the stability of the turbidity maximum by maintaining a compact sedimentary mass in suspension and preventing strong sediment export.

The Charente estuary (Fig. 1), located on the French Atlantic coast, is a useful site in which to study estuarine dynamics. In the recent years, the area has experienced droughts and also hosts a broad spectrum of economic activities (oyster farming, agriculture, tourism, port operations, and so forth), making this estuary particularly sensitive to water quality and siltation issues. Local features, such as the inversion of tidal asymmetry as a function of the spring-neap tidal cycle (Toublanc et al., 2015) are also interesting. More generally, although numerous studies have investigated large macrotidal estuaries, smaller systems such as the Charente remain poorly understood. However, many of these small estuaries strongly influence their surroundings. This study focuses on the turbidity maximum and suspended sediment dynamics in the Charente, at different time scales and under various fluvial and tidal regimes. Several indicators are used to quantify the impact of these forcings on the horizontal and vertical distribution of *SSC* (suspended sediment concentration), and to identify the mechanisms that drive the formation of the turbidity maximum. Changes in its structure are also investigated numerically to delineate the processes controlling sediment escape to the connected bay.

2. Study site

The Charente estuary (45°96N, 1°00W, Fig. 1) is located on the French Atlantic Coast. The river flows into the Marennes-Oléron Bay, in the southern part of the pertuis Charentais. The river's catchment is 10,550 km^2 and its length is 365 km. A dam is located in Saint-Savinien, 50 km from the river mouth. The mean river discharge is estimated to be 70 m^3/s. Discharge can reach extreme values of 600–700 m^3/s during flood events, and drop to less than 10 m^3/s during the summer. Exceptional floods can have caused discharges of up to 1000 m^3/s. The river is shallow, with a maximum depth of 10 m below mean sea level, and the estuary mouth is funnel-shaped.

The Marennes-Oléron Bay's total surface area covers nearly 150 km^2, comprising 60% of intertidal areas. The sediments in the estuary and in the eastern part of the Marennes-Oléron Bay are entirely cohesive, with a very fine grain size (Strady et al., 2011). In the western part of the bay, sediments are sandier (Tesson, 1973; Bertin et al., 2005). The mud ratio decreases and the mean grain size tends to increase upstream, but the latter remains less than 20 μm and the mud ratio is always greater than 80% (Coulombier et al., 2013).

The estuary and the bay are affected by semidiurnal tides. At Rochefort, the mean and maximum tidal ranges are 4.2 m and 6.5 m, respectively. This macrotidal regime is also characterized by the influence of quarter-diurnal constituents (M4, MS4 and MN4), which are strongly amplified shoreward by resonance along the Bay of Biscay shelf (Le Cann, 1990). Bertin et al. (2012) verified this phenomenon numerically and showed that the largest amplification by resonance occurred for the MS4 constituent. In combination with the internal tidal distortion of the estuary, these externally generated overtides result in fortnightly inversions of the tidal asymmetry (Toublanc et al., 2015). Depending on the timing of the spring-neap tidal cycle, and the position in the estuary, the estuary can be dominated either by the flood or the ebb.

Prior to this study, few data were available on the turbidity maximum of the Charente estuary, including only intermittent observations and no numerical modelling. Ravail et al. (1988) recorded *SSC* up to 10 g/L at the river mouth, Auguet et al. (2005) measured concentrations greater than 5 g/L at the surface in Rochefort (20 km upstream from the mouth). Local workers and residents often reported strong suspended sediment concentrations around Rochefort: bathymetric surveys performed by public services revealed on several occasions the presence of a highly concentrated suspended sedimentary mass in front of the harbour. Schmidt et al. (2010) and Le Moine et al. (2012) reported the presence of fluid mud in the proximity of the Saint-Savinien dam. Despite these observations, the spatio-temporal evolution of the turbidity maximum has not been studied yet in the Charente estuary.

The characteristics and movements of the turbidity maximum are very important to management of the area. This is especially true in Rochefort where the harbour is often dredged to compensate for strong sediment accumulation: reports estimate that 160,000 m^3/year of sediment is dredged. Tourism, as well as oyster and mussel farming in the Marennes-Oléron Bay also strongly depend on outflows from the Charente river.

3. Materials and methods

3.1. Numerical modelling

The numerical model MARS-3D (Modelling for Applications at Regional Scales) used in this study has been described in previous work (Lazure and Dumas, 2008). It is a finite differences model that solves the Navier–Stokes equations under hydrostatic and Boussinesq assumptions when used in 3D mode.

The configuration presented here consists of two nested grids. The first one, with 100 m horizontal resolution, is forced by tides computed using the SHOM CST-France model (Le Roy and Simon, 2003). It runs in 2D and provides open boundary conditions at the seaward limit for the second grid. This grid has a 30 m horizontal resolution and runs in 3D with 8 sigma levels. Daily river discharges are prescribed. Bathymetric data (Fig. 1) were provided