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River flow control on intertidal mudflat sedimentation in the mouth of a macrotidal estuary

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ABSTRACT

The objective of this study is to analyze the impact of hydrological variability influenced by climatic phenomena upon the sedimentary exchange between the turbidity maximum (TM) and a river mouth intertidal mudflat. This study, carried out over a period of 10 years (1997–2006) in the Seine Estuary (France), is specifically focused on two extreme periods: a wet one from 2001 to 2002 and a drier one from 2005 to 2006. This study is based on an original approach combining data gathered via low-altitude remote sensing with altimeter readings and ground-level measurements.

During this 10 year period, we observed a link between climate change and the sedimentary processes on the mudflat surface. The modifications of sedimentary processes are mainly connected to the multiannual variability of hydrological flow rates that control the positioning of the turbidity maximum, the source of the sedimentary material deposited in this intertidal zone. The TM at the mouth of the Seine estuary is well developed; its maximum mass is estimated to be between 300,000 tons and 500,000 tons (Avoine et al., 1981) with maximum concentrations in the surface waters ranging from 1 to 2 $g \cdot l^{-1}$ (Le Hir et al., 2001). Most of the fine particles stored within the TM have been found to originate from within the catchment area (Dupont et al., 1994). In the Seine estuary, the dynamics of the estuarine TM, in response to hydrodynamic forcings, have been previously described (Avoine et al., 1981) and modeled (e.g. Brenon and Le Hir, 1999; Le Hir et al., 2001). The TM is upstream of the northern mudflat when the river flow is low (<450 $m \cdot s^{-1}$) and nearby the study area when the river flow is higher. Thus during wet periods, the sedimentation rates increase by $+17$ $cm \cdot y^{-1}$, while during the drier one (when the turbidity maximum is located upstream of the estuary) we observed an erosion rate of 7.6 $cm \cdot y^{-1}$. Sedimentation events in the mudflat resulting from spring tides are less frequent during dry periods, and they deposit a smaller quantity of sediment (−23% of total deposition mass per event). Because of the lower flow rates coupled with the impacts of local development, the flood tides have become dominant. This contributes to the addition of sandy or silty sediments on the mudflat, of which the slope has increased 450% over 8 years caused by erosion.

1. Introduction

As a result of their strategic positioning, estuarine areas are privileged ecosystems and the site of considerable socioeconomic activity. One of the challenges is the capacity of the estuarine ecosystem to adapt to varying levels of metals and organic and inorganic contamination. Given the high affinity of these contaminants for the particulate phase, especially fine cohesive particles (<63 μm), we have a specific need to take the sedimentary dynamic of these particles into account.

In estuarine systems, suspended solids and cohesive sediments are subject to complex hydrodynamics, controlled by natural processes such as ocean swell, which is expressed on a large scale (Green et al., 1997; Ryan and Cooper, 1998; Bassoullet et al., 2000; Da Silva, 2002; Verney et al., 2011), tidal cycles (Eisma, 1998), and the hydrological flow rate of the river (Whitehouse and Mitchener, 1998; Christie et al., 1999; Dyer et al., 2000; Deloffre et al., 2005; Prandle et al., 2006; Talke and Stacey, 2008). Furthermore the river flow alters the position of the TM (turbidity maximum) (Avoine et al., 1981; Lesourd et al., 2003; Uncles et al., 2006), contributing to sedimentary mud deposition on the intertidal mudflats at the mouths of macrotidal estuaries (Avoine et al., 1981; Lesourd et al., 2003; Deloffre et al., 2006). Indeed, when the Seine River flow is high (wet period), the position of the TM is closer to the mudflat surface (Lesourd et al., 2003). Massei et al. (2010) demonstrated that the variability of hydrological cycles in the Seine estuary is controlled by meteorological phenomena such as the North Atlantic Oscillation (NAO). The consequences of such mechanisms for sedimentary transfers within the intertidal mudflats in estuarine areas, however,

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have received very little study. The few studies conducted clearly show the definite role of the NAO in estuarine sediment dynamics, which consists in a strong erosional trend when the NAO index is positive (Kirby and Kirby, 2008; Phillips and Crisp, 2010). One of the reasons for this relative lack of studies is the difficulty of conducting sustained, long-term (i.e., decade-long) studies that allow observers to follow the sedimentary evolution of the intertidal estuarine zones. Another obstacle lies in the superimposition of the consequences of human activity on natural forcing. This situation requires taking into account a mainly multiannual time scale, which is necessary for the readjustment of the hydrodynamic conditions in the modified environment (Cuvilliez, 2008). Multiannual and century-long studies led in various estuaries and deltas (Bourman et al., 2000; Chen et al., 2001; Wolanski et al., 2001; Van der Wal et al., 2002; Van der Wal and Pye, 2004; Lesourd et al., 2003; Blott et al., 2006; Kim et al., 2006; Cuvilliez et al., 2009) have also produced morphosedimentary results that vary greatly as a function of the hydrosedimentary context and the nature of human development. They have highlighted the difficulty of defining the impacts because of human development as opposed to those linked to climatic variation (Cuvilliez, 2008).

This study was carried out over a period of 10 years (1997–2006) on an intertidal mudflat located at the mouth of the Seine River estuary (upper Normandy, France, Fig. 1). During these 10 years, two periods of slightly more than one year each were chosen because they illustrate the impacts of climate change on the sedimentary dynamics of the mudflat at the mouth of the Seine estuary. One was a wet period; the other was a dry period. In these cases climate appeared as a dominant factor in the sedimentary dynamics because the mudflat connection with the river remained the same before and after 2005 (Fig. 1). The objectives of this study are (i) to understand and quantify the role of multiannual climate cycles in the sedimentary dynamics of this area, notably during extremes of hydrological flow rate; and (ii) to decipher the impact of natural processes on different time scales. To reach these objectives a low altitude remote sensing technique was coupled with selective (ALTUS) and global (LIDAR) altimetric measurements at the level of the mudflat. Recordings of the hydrodynamic conditions and sedimentary sampling followed by analysis were also made.

2. Study area

The Seine estuary is a macrotidal estuary with a tidal range maximum reaching 8.5 m during the highest tides. Located in the watershed of Paris, whose surface of 78,650 km^2 represents 14% of the French continental territory, the estuary of the Seine, 160 km long, drains the river waters of which the average flow of 450 m^3·s^{-1} varies between 60 and 2600 m^3·s^{-1}. According to Meybeck et al. (1998) the flood threshold is reached at a rate of 800 m^3·s^{-1}. The northern mudflat is located on the right bank of the Seine River mouth estuary (Fig. 1), accounting for an area of 3.1 km^2 (Cuvilliez, 2008). Its easternmost limits are set by the Normandy bridge, built between 1988 and 1995; to the west it abuts against a hook dyke and the Port 2000 dyke, finished in 2004. To the north it is bordered by a salt marsh that has ceased its extension into the mudflat as of 1998, which notably correlates to the impact of the construction of the Normandy bridge (Cuvilliez et al., 2009). Its southern limits historically correspond to the Northern Trench.

The hydrological cycle plays a very important role in the morphosedimentary dynamic of the estuarine northern mudflat as it influences the positioning of the TM (Brenon and Le Hir, 1999; Le Hir et al., 2001), the principal source of cohesive sedimentary material in this section of the estuary (Avoine et al., 1981; Dupont et al., 1994). On the annual scale, Lesourd et al. (2003) have shown that subtidal deposits in the Bay of the Seine occur when flooding (flow > 1200 m^3·s^{-1}) induces the expulsion of the TM from the estuary. During low river flow, sediment deposits are redistributed according to tidal range and ocean swell periods. Furthermore, Deloffre et al. (2006) demonstrated that the sedimentary deposits on the northern mudflat originated in the TM.

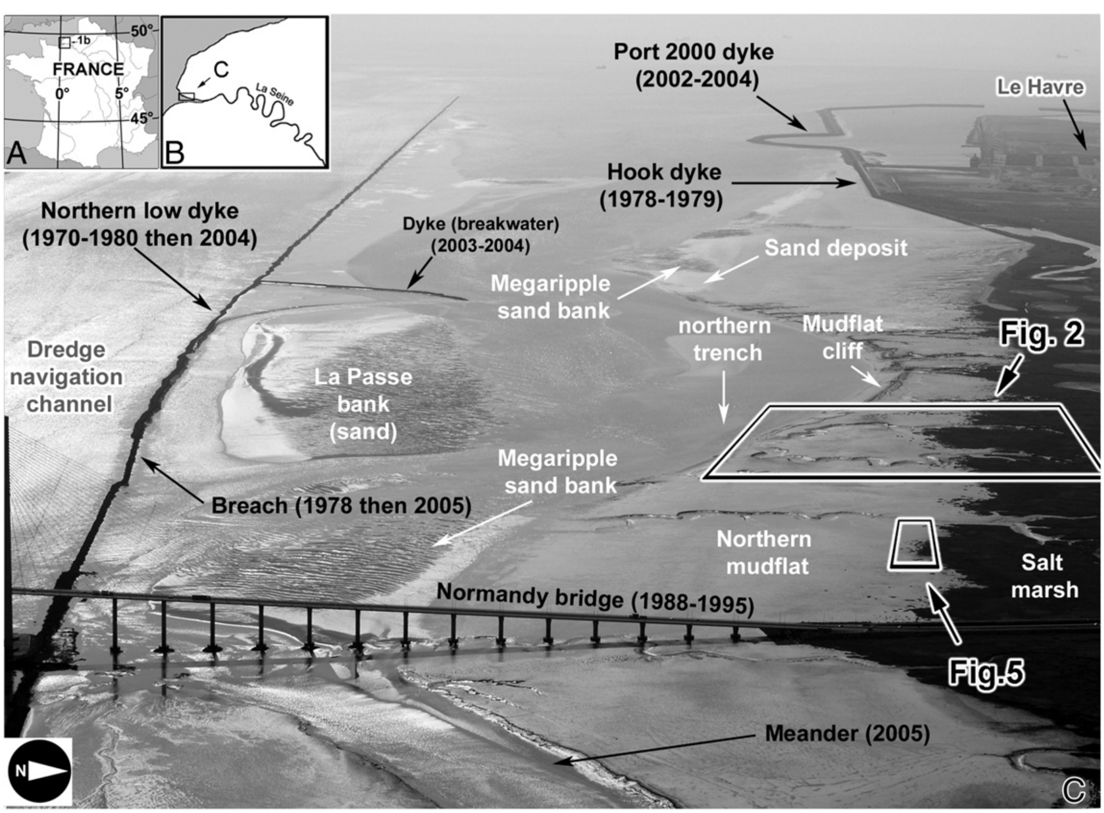

Fig. 1. (A and B) Location of the studied area. (C) Right bank of the Seine estuary mouth with dates of the environmental planning (black) and morphologic units of the studied area (white). Black frames show the location of the areas of Figs. 2 and 5.