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Physical and sedimentary processes on the tidal flat of central Jiangsu Coast, China: Headland induced tidal eddies and benthic fluid mud layers

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ABSTRACT

An 11-tidal-cycle record time series of current, wave, suspended-sediment, and bed-level characteristics was analyzed to identify physical and sedimentary processes on the tidal flat of Jiangsu Coast, China. A tripod observation system was placed near the transition between mid and upper tidal flat south of a newly constructed harbor for hydrodynamic and sediment dynamic measurements from 27 Apr 2013 to 3 May 2013. The observations confirm the stable longshore northward (ebb direction) current s with residual velocities ~59.2° anti-clockwise from the offshore direction. This phenomenon can be attributed to the effects of headland (the Harbor) induced tidal eddies based on comparable frictional length scale and the headland length scale. Benthic fluid mud layers occurred in 2 of 11 tidal cycles, with the conditions of strong waves during the flood phase. The fine sediment was resuspended by the waves and currents from the lower area, transported upward and concentrated at the observation station, resulting in the formation of a fluid mud layer with thickness of ~15 cm and SSC of ~8 kg/m^3 at 10 cm asb. Once formed, the fluid mud layer dramatically modified the flow structure, showing a large reduction of current speed from 20 cm asb to 10 cm asb, when the gradient Richardson number was around the critical value of 0.25, inferring that sufficient turbulence from waves and currents exists to maintain fluid mud suspension. The fluid mud processes appear to occur episodically and may play an important role of sediment dynamics on the tidal flat.

1. Introduction

Tidal flats are the transition between subaerial and submarine environments, being a key location for land-ocean interactions (Flemming, 2003). They are of importance not only for material circulation, transformation and preservation (Barranguet et al., 1997; Lee et al., 2014), but also for flood defense, coastal protection and ecological conservation (Reise, 2001; Temmerman et al., 2013). Knowledge of tidal flat processes is necessary to form comprehensive land-ocean interaction management strategies, and studies of hydrodynamics and sediment dynamics play a crucial role (Gao, 2009; Friedrichs, 2012). With the impacts of sea-level rise and human interventions (e.g., land reclamation, harbor construction), there is particular interest in the associated tidal flat response to a changing world (Lee et al., 1999; Kragtwijk et al., 2004; Wang Y.P. et al., 2012; Yu et al., 2014). Among a wide range of observation and modelling studies on tidal flat sediment dynamics (Flemming and Bartholomae, 1995; Shi and Chen, 1996; Allen, 2000; Dyer, 2000; Bartholdy and Kvale, 2006; Fagherazzi et al., 2012; Nittrouer et al., 2013; Green and Coo, 2014), the present contribution focuses on two aspects: (1) headland induced tidal eddies, and (2) benthic fluid mud layers.

The first aspect, tidal eddies, is related to the interaction between coastal headlands and oscillating rectilinear tidal currents, which form on alternate sides of headlands with the reversal of the tide (Pingree and Maddock, 1979; Zimmerman, 1981; Geyer and Signell, 1990; Signell and Geyer, 1991). The formation of these eddies has substantial impact on the coastal hydrodynamics and sediment dynamics due to the strongly alternated flow patterns, resulting in sediment trapping in the cores of the eddies (Bastos et al., 2002; Berthot and Pattiaratchi, 2006a, 2006b) and enhanced fluid stirring (Awaji el al., 1980; Chen et al., 2005). Most previous studies, however, are associated with the coastal seas 10 m deep or more, and few studies of headland induced tidal eddies on very shallow areas, including tidal flats, have been reported.

The second aspect under study is related to the processes of fluid mud. Fluid mud is defined as "a high concentration aqueous suspen-

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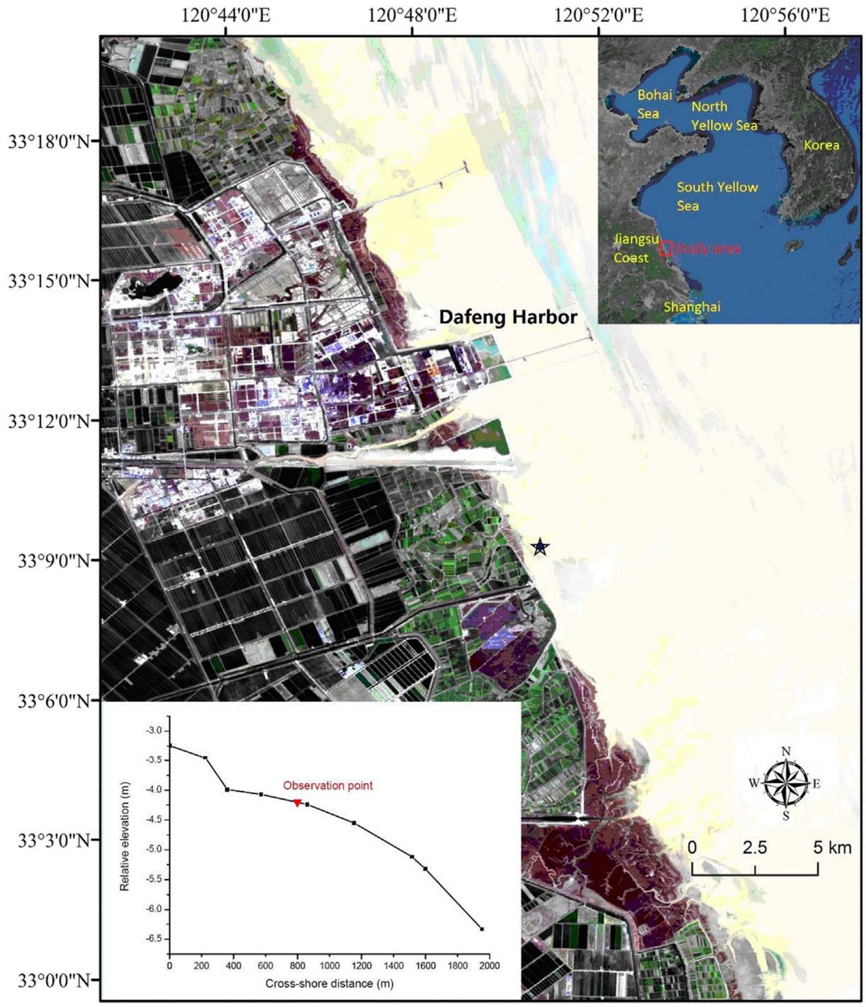

Fig. 1. The study area of the middle Jiangsu coast. The black star denotes the observation station. Subfigure shows the cross-shore tidal flat elevation profile from the offshore foot of sea dike (X =0 m) measured by RTK-GPS.

sion of fine-grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs, but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility" (McAnally et al., 2007). Fluid mud and associated gravity flows have been comprehensively investigated on estuaries and continental shelves by means of field observation (Nichols, 1985; Wright et al., 1988; Kineke at al., 1996; Sternberg et al., 1996; Ogston et al., 2008; Hale and Ogston, 2015), numerical modelling (Scully et al., 2003; Harris et al., 2005; Traykovski et al., 2007; Hsu et al., 2009), and theoretical analysis (Mehta, 1991; Trowbridge and Kineke, 1994; Wright et al., 2001).

Based on the earlier works of Trowbridge and Kineke (1994), the analytical theory of Wright et al. (2001) suggests that wave-current suspension of sediment supports the fluid mud layer when the gradient Richardson number (Ri) is approximately 0.25. The feedback mechanism herein is: for $Ri < 0.25$, turbulence suspends additional sediment, increasing suspended sediment concentration (SSC) and Ri, while for $Ri > 0.25$, reduced shear instabilities inhibit turbulence and result in sediment settling. The physics of Wright et al. (2001)'s theoretical framework is shown in Fig. 2. The thickness and concentration of the fluid mud layer are associated with the velocity scale composed of the wave orbital velocity, current velocity, and the gravity current velocity. This framework was used to analyze the observational data.

Fluid mud has been found to be formed on tidal flats. Benthic fluid mud layers on tidal flats, with a typical thickness of ~10 cm, have been detected by direct sampling and pressure measurements (Wells and Coleman, 1981), differences of reflection distances observed by high and low frequency acoustic altimeters (Christie, et al., 1999; Bassoullet et al., 2000; Andersen et al., 2006), and by isotope (^{210}Pb and ^{7}Be) evidence in sediment cores (Gouleau et al., 2000). Zhu et al. (2014) measured high SSC (~8 kg/m^3) with near-bed OBS observations on the tidal flat of the Changjiang River Delta, where near-bed fluid mud layers had been suggested. However, compared with the studies of continental shelf fluid mud processes, the detailed analysis of the interactions between hydrodynamics and fluid mud behavior on tidal flats is still limited.

The present study reports on an observational program carried out on the tidal flats of the central Jiangsu coast. The tidal-flat system extends approximately 600 km along the coast of the South Yellow Sea, with a typical cross-shore width of several kilometers and the surface sediment of mud and fine sand. It is sheltered on the north by a large radial-shaped tidal ridge (or linear sandbank) system (Ren, 1986; Liu et al., 1989; Wang, Y., et al., 2012). Erosion of the abandoned Yellow River delta erosion supplies sediment to the adjacent coast (Zhang et al., 1992). The coastal waters are characterized by strong tidal currents and generally weak waves. Extensive harbor construction (Dafeng Harbor), initiated in 2008, represents an artificial headland complex at the northern end of the tidal flats and has significantly changed the previously smooth coastal bathymetry.

The proximity of this tidal flat to the recently constructed Dafeng Harbor headland provides a unique opportunity to investigate hydrodynamic and sedimentation characteristics in a changing coastline. The