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Modeling sorting dynamics of cohesive and non-cohesive sediments on intertidal flats under the effect of tides and wind waves

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ABSTRACT

We extend a numerical model to explore the morphodynamics of intertidal flats, with a specific focus on the sorting dynamics of sand and mud. We investigate the effect of tidal currents, wind waves, sediment properties, external sediment supply, flocculation and initial bed composition on the cross-shore profile shape and sediment sorting of intertidal flats. Consistent with existing analytical theories and benchmark simplified numerical solutions, the equilibrium cross-shore profile of intertidal flats simulated by the extended model is convex-up when tidal currents dominate and it progressively becomes concave-up when the strength of wind waves increases. The equilibrium profile is influenced by the external sediment supply which can lead to the seaward advance of intertidal flats. In line with field observations, mud tends to deposit on the upper intertidal flats when wind waves are relatively weak, while sand is mainly distributed on the middle and lower tidal flats. When wind waves are strong, both sand and mud are more easily resuspended and eroded, resulting in a noticeably concave-up profile near the high water mark. The initial bed composition (e.g., percentage of mud and sand fractions) is also found to play an important role: the intertidal flat is more convex-up in a muddier environment. Numerical modeling demonstrates that sediment properties (e.g., critical shear stress for erosion, settling velocity) and flocculation can pronouncedly influence the sediment sorting dynamics by modifying the initiation threshold and the advection distance of entrained sediments. Application of the extended model to a natural study site indicates a qualitative agreement with field observations.

1. Introduction

Tidal flat landforms, periodically submerged and exposed under the action of tides, serve as a critical component in coastal and estuarine systems for their socio-economic and ecological values (e.g., natural buffer against coastal flooding or erosion, wetland conservation). Their formation and long-term evolution are governed by the interplay between a variety of factors, particularly tidal currents, wind waves, sediment supply, fluvial inflow, biological and anthropogenic activities (Friedrichs, 2011; Coco et al., 2013).

Tides usually act as the dominant driver to shape the morphology of tidal flats (Le Hir et al., 2000; Pritchard et al., 2002; Friedrichs, 2011). The direction of tidal currents is determined by the large-scale flow circulation around the flat and can normally be split into a cross-shore and a long-shore component. The relative magnitude of the cross-shore and long-shore components primarily depends on the local geological and hydrodynamic settings, and the cross-shore component is usually considered to be responsible for the accretion and erosion of intertidal flats (Le Hir et al., 2000).

The effects of other physical processes have also been investigated. Wind waves, either depth- or fetch-limited (Fagherazzi and Wiberg, 2009; Mariotti and Fagherazzi, 2013), can lead to large sediment re-suspension on shallow tidal flats (see Green and Coco, 2013 for a review). Existing field measurements and numerical studies suggest that waves generally favor the offshore sediment transport and result in the erosion of tidal flats (Bassoullet et al., 2000; Roberts et al., 2000). Sediment supply (fluvial

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or marine) can pronouncedly alter the width and the overall shape of tidal flats, even at a seasonal scale (Liu et al., 2011). Abundant sediment supply promotes the progradation of tidal flats while insufficient sediment supply results in erosion (Roberts et al., 2000; Pritchard et al., 2002). River inflow has been reported to affect the flow field and the suspended sediment transport pattern and its influence on intertidal flats depends on the magnitude of discharge and associated sediment source (Zhou et al., 2014a). Based on field observations of the Seine estuary, Deloffre et al. (2005) found that accretion of intertidal flats occurred during high river inflow and erosion during low river inflow. This trend might reverse over short time scales depending on local dynamics and specific estuarine conditions (e.g., Deloffre et al., 2006). Last, human-induced influences (land reclamation in particular) have been found to play an increasingly stronger role on the morphodynamics and ecosystems of tidal flats (Flemming and Nyandwi, 1994; Wang et al., 2012).

The cross-shore profile shapes of tidal flats have been extensively studied over the past years. Assuming a uniform spatial distribution of maximum bottom shear stress, Friedrichs and Aubrey (1996) derived elegant analytical solutions of equilibrium profiles of tidal flats for both tide- and wave-dominated environments. They demonstrated that convex-up and concave-up hypsometries of tidal flats with straight shorelines were favored by the dominance of tidal currents and waves, respectively. Roberts et al. (2000) developed numerical models solving mass conservation and momentum balance equations to simulate the mudflat profile shapes and their results qualitatively agreed with those of Friedrichs and Aubrey (1996). Extending the work of Roberts et al. (2000), Pritchard et al. (2002) and Pritchard and Hogg (2003) investigated the long-term morphodynamic behavior of tide-dominated mudflats under different combinations of sediment supply and tidal boundaries. They found that the cross-shore width of tidal flats increased with increasing sediment supply but was independent of tidal range.

Compared to the existence of a wide literature on intertidal profile shapes, the investigation on the spatial distribution of sediment mixtures on tidal flats is mainly limited to qualitative and conceptual descriptions based on field observations. A clear cross-shore sediment zonation has been observed at various intertidal flats of different sizes (Evans, 1965; Wang and Ke, 1997; Friedrichs, 2011) and it generally displays the trend shown in Fig. 1. From the mean low water spring level (MLWS) to the mean high water spring level (MHWS), many intertidal flats are successively covered by sand, mixed sediments, mud and salt marshes, showing a gradual landward sediment fining (Friedrichs, 2011; Fan, 2012). Over an annual cycle particularly in a tidally-dominated environment, the distribution of sediments is generally stable and consistent with the cross-shore tidal energy gradient (Friedrichs, 2011).

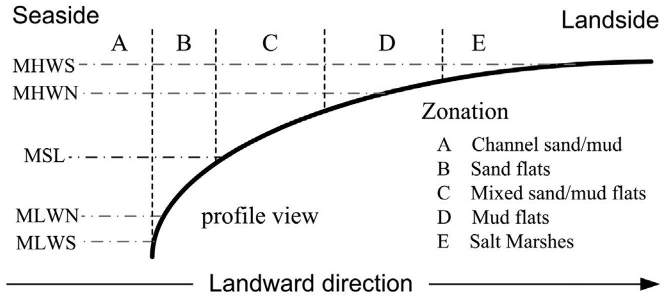

Fig. 1. A profile view of sediment zonation. The regions above the mean high water spring level (MHWS) and below the mean low water spring level (MLWS) are respectively called supratidal and subtidal zones, and the region between MHWS and MLWS is the intertidal zone. The other abbreviations MHWN and MLWN stand for mean high and low water neap level, respectively.

In the past decade, increasing efforts have been made to more realistically simulate sediment dynamics, particularly sediment sorting and bed stratigraphy. However, most of the studies primarily focused on the sorting dynamics of sandy beaches, rivers, deltas, tidal basins, and inner continental shelves (e.g., Coco et al., 2007a,b; Frings, 2008; van der Wegen et al., 2011; Goldstein et al., 2011, 2014; Viparelli et al., 2014), while intertidal flats received much less attention. To the authors' knowledge, there is currently no numerical study specifically addressing intertidal sediment sorting dynamics. Nevertheless, the zonation of multiple sediments has been found to bear significant implications also for the ecosystem of tidal landforms (e.g., Gray, 1981). At the same time, sediment composition (e.g., percentage of cohesive sediment) is a key factor to assess the environmental impact when nearshore engineering works are carried out (e.g., dredging, dumping and land reclamation). Therefore, there is a need to gain fundamental insights underlying the transport and distribution of intertidal sediments.

Here, we extend a state-of-the-art numerical model (Delft3D) to investigate the morphodynamics of intertidal flats, with a specific focus on sediment sorting. The extended model is first compared with an existing benchmark model developed by Roberts et al. (2000), in terms of cross-shore profile shapes under the effect of tides and wind waves. To examine the applicability of the model, we then test the model against the morphodynamics of a measured intertidal profile in the Jiangsu coast, China. Overall, we aim to unravel the mechanisms underlying sediment sorting of intertidal flats and our specific objectives include (a) examine the relative importance of tides and wind waves, (b) explore the effect of sediment parametrizations (e.g., critical stress for erosion, settling velocity, median grain size and flocculation), (c) investigate the influence of the initial bed sediment composition (i.e., the percentage of mud and sand), and (d) understand the role of sediment sources on the shape and sediment distribution of intertidal flats.

2. Methods

An open-source morphodynamic model (Delft3D, Lesser et al., 2004; van der Wegen and Roelvink, 2008) is utilized and extended to consider the effect of wind waves. A description of the extended model is provided in this section.

2.1. Modeling of tidal currents, wind waves and bottom shear stresses

We follow previous published studies and assume alongshore uniformity (Roberts et al., 2000; Pritchard et al., 2002; Pritchard and Hogg, 2003; Liu et al., 2011; van Maren and Winterwerp, 2013), so that tidal flow is simulated by solving the one-dimensional shallow water equations describing mass conservation and momentum balance

$$\frac{\partial \eta}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} + \nu\frac{\partial^2 u}{\partial x^2} - g\frac{u|u|}{C^2 h} \tag{2}$$

where u is the depth-averaged velocity in the x direction (m/s); t is the time (s); h is the water depth (m); η is the water level with respect to datum (e.g., MSL) (m); ν is the horizontal eddy viscosity coefficient (m^2/s); C is the Chézy friction coefficient ($m^{1/2}/s$) and g is the gravitational constant (m/s^2).