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Intratidal erosion and deposition rates inferred from field observations of hydrodynamic and sedimentary processes: A case study of a mudflat–saltmarsh transition at the Yangtze delta front

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ABSTRACT

An understanding of erosional and depositional processes in intertidal wetland environments is of great importance to coastal geomorphologists, ecologists, and engineers. To evaluate the morphodynamic response of intertidal mudflats and saltmarshes to tidal inundation, we measured water depth, wave activity, current velocity profiles, suspended sediment concentration (SSC), and sediment composition at a dynamic mudflat–saltmarsh transition on eastern Chongming Island, at the Yangtze delta front, China. Based on these data, we calculated bed shear stresses generated by the combined current–wave action (τ_{cw}), and the critical shear stress required to erode the surface sediments (τ_{ce}), and so were able to calculate the erosional (E) and depositional (D) fluxes. The erodibility parameter (M_E) and settling velocity (w_s) used in the calculations of E and D were calibrated using daily measurements of bed-level change. Our results showed that the mudflat experienced alternating phases of net erosion and net deposition during tidal inundation. The burst-based changes in bed level ranged from −0.92 (net erosion) to +0.43 mm/10 min, and the cumulative bed-level changes over an entire tidal cycle ranged from approximately 0 to −5.4 mm (net erosion), with an average change of −3.4 mm/tide (net erosion) over five consecutive spring tides. In contrast, only net deposition was recorded on the saltmarsh during our observations. The burst-based changes in bed level ranged from around 0 to +0.56 mm/10 min, and the cumulative changes over a tidal cycle ranged from around 0 to +5 mm, with an average of +2.6 mm/tide for the five consecutive spring tides. We conclude that net erosion and net deposition during tidal cycles alternate on the mudflat, but that only net deposition occurs on the saltmarsh.

1. Introduction

Intertidal wetlands are characterized by rapidly varying water depths, and are important coastal depositional systems that play a key ecological role by providing a habitat for benthic communities and shorebirds (Eisma, 1998; Le Hir et al., 2000). Consequently, an understanding of the morphodynamic responses of these systems to changing environmental conditions is required if we are to protect their ecologically valuable habitats (Kakino, 2000). Generally, tidal currents and waves jointly determine sediment transport and morphological behavior in intertidal wetlands (e.g., Janssen-Stelder, 2000; Wang et al., 2006; Salehi and Strom, 2012; Shi et al., 2012; Zhu et al., 2013). Quantitative prediction of bed-level changes under combined current–wave action is necessary for coastal management and the appropriate design of engineering structures. Many studies have sought to understand bed-level changes in intertidal mudflats, including the Dutch Wadden Sea coast (Houwing, 1999), the Baie de Marennes-Oleron in France (Bassoullet et al., 2000), the Rømø Bight in Denmark (Andersen et al., 2006), the Hythe flats, Southampton Water, UK (Quaresma et al., 2007), and the Yangtze Estuary in China (e.g., Yang et al., 2003, 2008; Fan et al., 2006). However, the majority of these studies focused on daily or monthly bed-level changes (e.g., Whitehouse and Mitchener, 1998; Christie et al., 2001; Yang et al., 2001; Andersen et al., 2006; Fan et al., 2006), while few concentrated on intratidal erosion/deposition behavior (e.g., Andersen et al., 2007; Shi et al., 2012; Zhu et al., 2013) owing to the lack of appropriate equipment for measuring bed-level changes during periods of tidal inundation. Furthermore, at present, there are no highly accurate models available that can calculate and predict intratidal bed-level changes, and mudflats are composed of cohesive sediments, and are therefore more complex in morphodynamic terms than sandy beaches (Wang et al., 2006, 2012).

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Currently, there are two principle assumptions that are applied when considering erosional and depositional processes. First, it is assumed that erosion and deposition do not occur simultaneously. Erosion occurs when the bed shear stress (τ_{cw}) exceeds the critical shear stress for erosion (τ_{ce}), whereas deposition occurs when τ_{cw} is less than the critical shear stress for deposition (τ_{cd}) (e.g., Cancino and Ramiro, 1999; Lumborg, 2005; Wang, et al., 2008; Wang, 2009; Shi et al., 2012). Second, it is assumed that bidirectional sediment exchanges occur between the water column and the bed. Net erosion occurs when the erosional flux (E) exceeds the depositional flux (D), whereas net deposition occurs when $D > E$ (e.g., Ariathurai and Krone, 1976; Mehta, 1988; Mehta et al., 1989; van Leussen and Winterwerp, 1990; Sanford and Halka, 1993). Neither of these assumptions has been entirely validated, consequently, further testing is required. Based on the first assumption, Shi et al. (2012) estimated the timing of intratidal phases of erosion and deposition for a mudflat–saltmarsh transition at the delta front of the Yangtze River by comparing the bed shear stress caused by the combined current–wave action (τ_{cw}) with values of τ_{ce} and τ_{cd}. Nevertheless, they did not calculate intratidal erosion and deposition fluxes as well as net bed-level changes. In the present study, we aim to quantify intratidal erosion and deposition, as well as net bed-level changes, for the same intertidal wetland. Our major objectives are to: (1) calibrate the erosion parameter (M_E) and settling velocity (w_s) using measured bed-level changes; (2) compute burst-based erosion (E) and deposition (D) fluxes, as well as net bed-level changes, for individual tidal cycles; and (3) compare intratidal morphodynamic behavior between the mudflat and saltmarsh.

2. Study area

Our study is based on in situ observations made at a mudflat–saltmarsh transition on eastern Chongming Island (Fig. 1). Chongming Island is located in the Yangtze Estuary, covers an area of more than 1200 km^2, and is the largest alluvial island in the world (Gan et al., 2009). The island has been created by the rapid deposition of sediments derived from the Yangtze River over the past 1400 years (Yang et al., 2001). However, the progradation rate of the intertidal wetland on eastern Chongming Island has drastically decreased in recent years due to a sharp reduction in sediment supply from the Yangtze River caused by dam construction (Yang et al., 2006). At present, although accretion still occurs on the saltmarsh, the accretion rate has been reduced by around 70% compared with that in the 1980s (Yang et al., 2011). More importantly, erosion has been observed recently on the mudflats of eastern Chongming (Yang et al., 2011; Shi et al., 2012).

The tides on eastern Chongming Island are irregularly semi-diurnal, with an average tidal range of 2.5 m, but reaching 3.5–4.0 m during normal spring tides at the Sheshan gauging station (Fig. 1a), located 20 km east of the study site. The highest recorded water level here is 2.9 m above mean sea level (GSII, 1996). Wind speeds on the Yangtze Delta are highly variable, with multi-year averages of 3.5–4.5 m/s, and a maximum of 36 m/s at Sheshan (GSII, 1996; Fig. 1a). During the period of this study, the wind direction ranged from 29° to 107°, and the wind speed from 6.5 to 8 m/s (Shi et al., 2012). The surface sediment on eastern Chongming Island is composed of very fine sand (63–125 μm) on the lower flats, coarse silt (32–63 μm) on the upper flats, and medium (16–32 μm) to fine (8–16 μm) silt on the saltmarsh (Yang et al., 2008). Suspended sediment concentrations (SSCs) in the mudflat zone range from around 0.5 g/l to more than 10 g/l, but are typically 1–3 g/l (Yang et al., 2008).

The intertidal wetland studied here faces the open waters, and has a maximum width of 7–8 km (Fig. 1a). We examined two locations within the wetland: the Mudflat site located 340 m seaward of the mudflat–saltmarsh border (0.2 m above mean sea level), and the Marsh site located 250 m landward of the mudflat–saltmarsh border (0.7 m above mean sea level) (Fig. 1b). The saltmarsh was 3 km wide, with pioneer vegetation (*Scirpus mariqueter*) occupying the lowermost 0.5 km section. The *S. mariqueter* at our study site was 0.4–0.6 m in height, with a stem diameter of approximately 3 mm and a projective coverage of 70–80%.

3. Methods

3.1. Field measurements

Field measurements were carried out over five consecutive tidal cycles between 22 and 24 September 2009. At both sites (Fig. 1b), water depths and wave heights were measured using a wave–tide recorder (SBE 26 plus SEAGAUGE, Sea-Bird Electronics Inc., USA. Measured accuracy: 0.01% of the full scale). The pressure sensor of this instrument was programmed to measure water depth every 10 min. Wave heights were measured at the same interval using 4-Hz measurements over a 256-s period, giving a total of 1024 measurements per burst. The instrument was mounted horizontally on the bed, with the pressure sensor located 0.15 m above the sediment surface. Using the software provided by the manufacturer, we calculated water depth, significant wave height, and significant wave period. The distance between the pressure sensor and the sediment surface was corrected by adding 0.15 m to all measured water depths.

Current velocity profiles were measured using a Pulse-Coherent Acoustic Doppler Profiler (PC-ADP, SonTek, USA; sampling interval: 5 min) and an Acoustic Doppler Profiler (ADP-XR, SonTek, USA; sampling interval: 5 min). The PC-ADP was fixed to a tripod, with the sensor probe facing downwards at a height of 65 cm above the sediment surface, and the ADP-XR was mounted on the seabed with the sensor probe facing upwards at a height of 10 cm above the sediment surface. Near-bed SSC (15 cm above the sediment surface), salinity, and water temperature were measured using a self-logging turbidity–temperature monitor (OBS-3A, Campbell Scientific, Inc., USA; sampling interval: 2.5 min). The latitude, longitude, and elevation of the two sites (Mudflat and Marsh) were also determined using a real-time kinematic global positioning system (Ashtech, USA; horizontal measurement accuracy: 1.6 cm ± 2 ppm; vertical measurement accuracy: 2 cm ± 1 ppm, ppm: part per million).

Daily surveys of bed level were conducted at both sites after the ebb tide using the double-rods method (Yang et al., 2003). The distance between the two rods was 1 m, and the rods were 30 mm in diameter. During each survey, three bed-level measurements were made from one rod towards the other, at distances of 0.25, 0.50, and 0.75 m. The average of the three relative measurements was then calculated.

At the Mudflat and Marsh sites, wet surface sediments were sampled using a tube-shaped sampler with a diameter of 36 mm, and water samples from the field were used to calibrate turbidity measurements from the OBS-3A. A 600-ml bottle, which opened upwards at a height of 15 cm above the seabed, was fastened to the tripod before the flood, and the bottle was retrieved from the tripod after the ebb.

3.2. Sediment analysis and parameter calculations

3.2.1. Water content and grain size of sediment samples

In the laboratory, the wet surface sediment samples were weighed and oven dried at a temperature of 50 °C to a stable weight (≥ 48 h). The water content of the sediment was defined as