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Bed-level changes on intertidal wetland in response to waves and tides: A case study from the Yangtze River Delta

Q. Zhu [a,b], B.C. van Prooijen [b], Z.B. Wang [a,b,c], S.L. Yang [a,*]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[b] Department of Hydraulic Engineering, Faculty Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[c] Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands

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ABSTRACT

Short-term bed-level variability in tidal wetlands has important implication both for ecology and engineering. In this study, we combined in situ measurements with model simulations to quantify short-term bed-level changes on a meso-macrotidal wetland in the Yangtze River Delta. On the middle flat, we observed erosion during neap-to-mean tides under onshore moderate-to-strong winds, and bed recovery during subsequent spring tides, when winds were both offshore and weaker, suggesting that winds can overturn the neap–spring cyclicity of bed-level changes even on meso–macrotidal mudflats. The magnitude of bed-level changes was smaller on both sides of the middle flat, while the smallest changes occurred on the salt marsh. Observed bed-level changes were reconstructed using a single-point bed-level change model, which incorporates in situ measured parameters of hydrodynamics (waves and currents), suspended sediment concentrations, and bed sediment properties. We conclude that the relative importance of waves and tides in intertidal wetland erosion and accretion can vary temporally (due to changes in balance between wave and tidal energies) and spatially (because of changes in elevation and vegetation in the cross-shore profile). Our study also reflects the advantage of combination of in situ measurement with simulation in detecting short-term variability of tidal flats.

1. Introduction

The morphological evolution of tidal mudflats has been extensively studied over recent decades, as healthy mudflats maintain vital ecological and environmental functions as well as protecting shorelines (Costanza et al., 1997; Goodwin et al., 2001; Barbier et al., 2008). Mudflats are sensitive to both natural and human-induced environmental changes. For example, previous research has shown that human activity, including land reclamation, shoreline protection, and the maintenance of navigation routes, in addition to upstream damming, can have a considerable impact on tidal flats (Yang et al., 2005; Chu et al., 2006; Blum and Roberts, 2009; Yang et al., 2011; Wang et al., 2015). In summarising human and climatic influences on meso-to-mega-scale morphodynamic developments, Wang et al. (2015) concluded that the quantitative determination of thresholds associated with regime shifts is vital to the sustainable management of tidal flats. Therefore, it is necessary to understand and predict the response of mudflats to disturbances by both natural and anthropogenic if we are to protect them against the future environmental changes.

However, quantifying the morphological response of tidal flats to human intervention remains challenging. Due to the often slow response times involved, it can be difficult to distinguish among the effects of various source of interference. In contrast, studies of short-term disturbance, such as storm events, are easier to validate and can provide valuable insights into the relationship between environmental changes and bed-level variability.

Numerous studies have sought to clarify the sedimentary processes that act on intertidal mudflats (see Mehta and McAnally (2008) and Friedrichs (2011) for recent overviews). Earlier work on the morphodynamic impacts of combined wave–current action on tidal flats suggests that waves, which are wind-related phenomena, are important agents of mudflat erosion (Green et al., 1997; Christie et al., 1999; Kim et al., 2000; Zhu et al., 2014). Many studies of wave effects on tidal flat morphology have focused on storm events (Ding et al., 2003; Fan et al., 2006; Palanques et al., 2006; Xu et al., 2015). Since moderate wave strength may also deeply affect sediment resuspension and transport (Green and Coco, 2014), study of normal wind effects on tidal flat bed-level variability is also needed. In addition, most studies have been based on either field measurements (Yang et al., 2003; Fan et al., 2006; Siadatmousavi and Jose, 2015) or numerical models (Ding et al., 2003; O'Shea and Murphy, 2013; Hu et al., 2015; Maan et al., 2015).

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* Corresponding author.
E-mail address: slyang@sklec.ecnu.edu.cn (S.L. Yang).

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Studies combining field measurements and modelling are relatively scarce.

Detailed prediction strategies for bed-level changes over small spatial and temporal scales are still prone to considerable uncertainty. On the one hand, several key parameters can be difficult to quantify precisely. For example, the erodibility parameter, the erosion coefficient *M*, can vary by at least an order of magnitude (Whitehouse et al., 2000). Similarly, validation of erosion models can be limited by the techniques employed to measure bed-level changes at high temporal and vertical resolutions. Changes in bed level between each tidal submergences have been widely recorded (Kirby et al., 1992; Allen and Duffy, 1998; Bassoullet et al., 2000; O'Brien et al., 2000; Andersen, 2001; Yang et al., 2003; Andersen et al., 2006; Fan et al., 2006; Quaresma et al., 2007) and these studies provide valuable data to aid our understanding of the intertidal, neap–spring, seasonal, and longer-term evolution of mudflats surfaces. However, such data cannot elucidate the details of intratidal bed-level changes, which are key to understanding the mechanisms of bed evolution. With the development of self-logging instruments, high-resolution measurements of intratidal bed-level changes, together with sedimentary processes (currents, waves, and suspended sediment concentration), have become possible. Bed-level changes, for example, can be determined by repeated acoustic measurements of bed position (Gallagher et al., 1996; Jestin et al., 1998; Thornton et al., 1998; Christie et al., 1999; Saulter et al., 2003; Andersen et al., 2006; Andersen et al., 2007; Turner et al., 2008).

To improve the accuracy of prediction strategies for intertidal mudflats, we report here on the integration of data relating to wave and current regimes, suspended sediment concentrations (SSC), bed sediment properties, and observations of bed-level changes on an intertidal mudflat. The occurrence of strong winds during the measurement period allowed us to directly measure inter- and intratidal changes in bed level caused by wind events. We also describe a single-point BLC (bed-level change) model linking bed-level changes at high temporal and vertical resolutions with erosion and deposition fluxes, using in situ hydrodynamic and sediment property data. By validating the model using observational data, we attempt to: (1) calibrate the erosion coefficient *M* for the present study area; and (2) identify and quantify the main changes in the sedimentary processes during and after wind events. Our aim is to provide a greater insight into the sedimentary processes that operate at the bottom boundary layer of intertidal mudflats and their response to wind events.

2. Material and methods

2.1. Study site

We conducted in situ observations on an exposed tidal mudflat in the Eastern Chongming, which is located in the Yangtze River Delta, China (Fig. 1A). According to records from the Sheshan gauging station located 20 km east of our study site, the tides in the Yangtze Estuary are mixed semi-diurnal with an average range of 2.5 m, reaching up to 3.5–4.0 m during spring tides (Fig. 1A). Wind speed in this region is highly variable, with multi-year averages of 3.5–4.5 m/s and a maximum of 36 m/s (GSCI, 1988; Yang et al., 2008). Monsoon-driven winds are south-easterly during the summer and north-westerly in winter. Several storms hit the study area annually, with >10% of storms having wind speeds >25 m/s (Yang et al., 2003). Tropical cyclones impact the study area almost during every summer (Hu et al., 2007). Wind speed and direction data for 31.5°N 122.3°E were obtained from the European Centre for Medium-Range Forecasts (ECMWF) every 3 h over our study period.

The cross-shore bathymetry profile is shown in Fig. 1B, along with the position of our observation site. Our transect crossed the centre of a secondary channel, which was approximately 2 km in width and 8 m deep (Fig. 1). The cross-shore bathymetirc profile was convex-up, with the innermost 1.4 km being covered by salt marshes and the remainder being unvegetated mudflat. We measured bed-level changes at four sites along the cross-shore profile, corresponding to elevations of −1.21 m (Site 1: lower mudflat), 0.17 m (Site 2: middle mudflat), 0.52 m (Site 3: transition between mudflat and salt marsh) and 1.15 m (Site 4: salt marsh) above the mean sea level (Fig.1B). The dominant species of salt marsh vegetation at Site 4 is *Scirpus mariqueter*. The plant community of the salt marsh was measured to be 30 cm in crown height, 2 mm in stem diameter and 2000/m^2 in density. At Site 2, we conducted systematic measurements of wave, currents, SSC, bed level changes, and the properties of bed sediment.

Bed sediment on the mudflat generally consists of silt (median grain size <63 μm), >50% of which is coarse silt (32–64 μm; (Yang et al., 2008). When the tidal flat was exposed during the measurement periods, we observed only limited evidence of diatoms. In addition, bed ripple structures were not visibly affected by macro benthic species, which, judging by the low density of diatom holes, are relatively scarce at our site. Consequently, we consider the effects of such biological processes on our estimates of erosion and deposition rates to be minimal at this site.

2.2. Field experiments

2.2.1. Instrumentation

We used an Acoustic Doppler Velocimeter (ADV, 6.0 MHz Vector current meter, Nortek AS, Norway) to measure three-dimensional turbulent velocities in a 2.65 cm^3 volume of water. The ADV was fixed firmly to a tripod, with the transmitters oriented downwards and the emitter positioned 25 cm above the sediment surface. The sampled water volume, which was positioned 15.7 cm in front of the emitter, had a height of 9.3 cm. In addition, the ADV collected high-frequency pressure data that could be translated into water depth, wave heights, and wave periods. The measurement period was July 23 to August 3, 2011, during which time the ADV recorded 720 sets at a frequency of 8 Hz, resulting in a 1.5-minute sampling duration every 5 min.

Turbidity in the water column was measured every 5 min using optical back-scatter (OBS) sensors (OBS-3A, D&A Instrument Company, Washington, USA) attached to the tripod, with the probe positioned 15 cm above the sediment surface. Turbidity signals from the OBS sensors were converted into SSC values via calibration with in situ sediment samples. Regression between SSC and OBS-3A-derived turbidity yielded a correlation coefficient of 0.98 (Fig. 2).

2.2.2. Sampling and sediment analysis

Each day, we sampled surface sediment beneath the tripod during periods of daytime emergence. To avoid disturbing bed-level measurement area, we collected those samples at 2–3 m far away from the tripod center, where the ADV was located. Samples consisted of a mixture of at least four scrapes of the topmost 1–2 mm of bed sediment. The grain size distributions of each sample were analysed using a Coulter LS100Q laser diffraction particle size analyser (Beckman Coulter Inc., California, USA). Additionally, we collected mini sediment cores (10 cm long) during typical spring (July 26) and neap (August 2) tides to analyse the vertical distribution of erodibility. Each core was divided into three sections, with the top section being 2 cm long, and the lower two sections each 4 cm long. Except for grain size analysis, water contents of the mini cores were measured. Wet sediment samples were first weighed and then dried at 50 °C in an oven, before being reweighed for 48 h or more to obtain stable weights. We then derived the water content *W* from the ratio of water (the difference between wet and dry sediment weights) to dry sediment weights.

2.3. Bed-level measurements

Two methods were used to determine the bed level variations: the buried-plate method and the echo sounding function of the ADV. We used the former (Fig. 3) to measure relative bed-level changes between