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Differentiating the effects of advection and resuspension on suspended sediment concentrations in a turbid estuary

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ABSTRACT

Suspended sediment concentration (SSC) has a significant impact on the estuarine environment and its morphological evolution. At any given location, the temporal variability of depth-averaged SSC is due to a combination of two processes: horizontal advection and local resuspension. In this study, we investigated the sediment dynamics at three anchored monitoring stations close to the maximum turbidity zone of the Changjiang Estuary, and developed a box model to differentiate the effects of advection and resuspension. Further, settling velocities were estimated using the ADV Reynolds flux method, excluding the advection SSC component. We found that predicted changes in advection- and resuspension-induced SSCs were consistent with the bottom shear stress and accretion/erosion observations. The combination of observed bed accretion/erosion changes and the predicted advection-induced SSCs indicates that the advective transport of suspended sediment is an important process in accelerating persistent erosion at the monitoring stations. Although SSC variations due to advection and resuspension are of similar magnitudes, our model results indicate that if resuspension dominates, the resuspension-induced component can reach up to twice the magnitude of the advection-induced component. We conclude that the box model is a valuable tool for evaluating subaqueous delta accretion/erosion in response to sediment reduction caused by upstream dam construction and climate change.

1. Introduction

Estuarine environments are affected by a combination of terrestrial, riverine, and marine processes. Here the characteristics of water flow dynamics and sediment transport processes have profound impacts on the estuarine morphology and ecosystem. As indicators of both flow dynamics and sediment transport processes, fine-grained sediments in estuarine waters play a significant role in shaping the seabed morphology, absorbing organic matter, and determining water clarity, and consequently affect the health of estuarine ecosystems and influence human activities (e.g., navigation and fisheries management) (Dyer, 1997).

The suspended sediment concentration (SSC) is an important variable when fine-grained sediment dynamics are considered. At any given location, the variation in SSC consists of horizontally advected and locally resuspended components (Krivtsov et al., 2008; Weeks et al., 1993). Now it is relatively easy to obtain, by measurements, time series data of SSC at a fixed location or through the entire water column; however, decoupling these data into the components that represent contributions by localized sediment resuspension and horizontal advection is still difficult because the characteristics of specific suspended sediment particles cannot be easily measured *in situ* (Bass et al., 2002; Hill et al., 2003; Hout et al., 2017; Jago et al., 2006). Moreover, because the erodibility of fine-grained sediment is influenced by multiple parameters, such as tidal currents, wind waves, storm events, and wave–current interactions, the impact of resuspension is difficult to predict (Kalnejais et al., 2007). To date, several approaches have been used to distinguish the advection and resuspension components of SSC. For instance, the relationships between SSC and both wave-induced shear stress and current flow have been used to investigate the principal mechanisms associated with high SSCs in specific estuaries (Cloern et al., 1989; Schoellhamer, 1995; Valipour et al., 2017), and vertical SSC profiles are used to predict the fate of suspended sediment (Bass et al., 2002; Li et al., 2016). Using the latter approach, Mitchell et al. (2017) reported that time-dependent SSC profiles covering a complete tidal cycle can help identify the arrival of an advective mobile “plug” of suspended sediment.

Numerical model has the potential to better differentiate the

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horizontal advection and local resuspension process of suspended sediment. Hamblin (1989) proposed a "two-box" model to study the horizontal transport and vertical diffusion of sediment and salt in the upper St. Lawrence Estuary (Canada). In the Irish Sea, a conceptual model established by Weeks et al. (1993) suggested that SSC variations associated with the M2 tide were caused primarily by advection, whereas those associated with the M4 tide were caused mainly by local sediment resuspension in marine environments dominated by the M2 tidal current. Hill et al. (2003) presented a 1-D Lagrangian particle-tracking model, incorporating the advection of a linear "background" concentration gradient, which was applied to the Dover Straits and Mersey Estuary (UK), to decouple the observed SSC time-series into background and resuspension components. Although such model-based studies have revealed the controlling factors for SSC variation, problems remain in terms of the quantitative separation of advection and resuspension components.

From a sediment dynamics viewpoint, settling velocity (w_s) represents an additional primary characteristic of fine suspended sediment and is a key to model the transport of fine-grained sediment (Shi et al., 2003). Shi et al. (2003) and Shao et al. (2010) estimated the settling velocity of suspended sediment in the Changjiang Estuary, China, by using the Rouse equation, assuming that w_s was a constant throughout the water column. Fugate and Friedrichs (2002) proposed the Reynolds flux method, which derives the settling velocity from Acoustic Doppler Velocimeter (ADV) signals; this functioning of ADV to measure both sediment concentration and settling velocity has been widely used (Voulgaris and Meyers, 2004; Friedrichs et al., 2008; Kawanisi and Shiozaki, 2008; Cartwright et al., 2013; Wang et al., 2013). However, the ADV method is unsuitable for areas where advection is significant, because it assumes that the horizontal gradient of SSC is negligible (Maa and Kwon, 2007). Therefore, a more comprehensive and reliable method is needed to differentiate the advection and resuspension effects.

In this contribution, we developed a box model that decomposes observed SSC time series to derive the horizontal advection and local resuspension components. We also suggested approaches to assess the model's validity. Furthermore, we attempted to determine the settling velocity based on the resuspension information obtained from the analysis.

2. Study area

Our study area is located outside the South Passage of the Changjiang Estuary (Fig. 1), a mesotidal estuary with a mean tidal range of 2.66 m and a maximum of 4.62 m at the river mouth (Shen et al., 2003). The multi-year average wind speed is 3.5–4.5 m s^{-1}, with maximum speeds reaching 36.0 m s^{-1} (Yang et al., 2008). Controlled by the monsoon climate, southeasterly winds prevail in summer whereas northwesterly winds dominate in winter (Yang et al., 2008). 67% of the sediment discharged from the Changjiang Estuary is finer than 50 μm and 95% is finer than 100 μm (Yang et al., 2001).

Changjiang is the largest river system in China. After the completion of the Three Gorges Dam, the average water and sediment discharges recorded at Datong (the nearest hydrological station to the Changjiang Estuary; Fig. 1a) were approximately 838 km^3 yr^{-1} and 145 Mt yr^{-1}, respectively (Yang et al., 2015). Sediment dispersal and accumulation in the Changjiang Estuary are controlled by the combined effects of tidal currents, waves and estuarine circulations (Sternberg et al., 1985; Su and Wang, 1986). Characterized by an SSC higher than the upstream and seaward areas, an estuarine turbidity maximum (ETM) is developed at the river mouth (Fig. 1b). The Changjiang ETM is remarkable not only for its high SSCs, but also for the high wash-load content (Li and Zhang, 1998).

3. Methods

3.1. Data collection

Tidal cycle measurements were carried out at three mounted monitoring stations (A, B, and C, Fig. 1b), located outside the South Passage of the Changjiang Estuary on July 2–3, 2016. The distance between stations A and C was 33.4 km. The mean water depths were 10.5, 13.8, and 21.7 m at stations A, B, and C, respectively. Southerly wind speeds reached 11–19 m s^{-1} and contributed to the generation of local waves with a maximum wave height of > 2 m.

Velocity profiles were measured using a downward-looking Acoustic Doppler Current Profiler (ADCP, 1200 kHz) at station A, and two upward-looking ADCPs (600 kHz) at stations B and C. At station A, the velocity profile ranged from 0.85 m below the sea surface to near the seabed, with a vertical resolution (bin size) of 0.2 m. At stations B and C, the profile range extended from approximately 2 m below the sea surface to the seabed, with a bin size of 0.5 m. The sampling

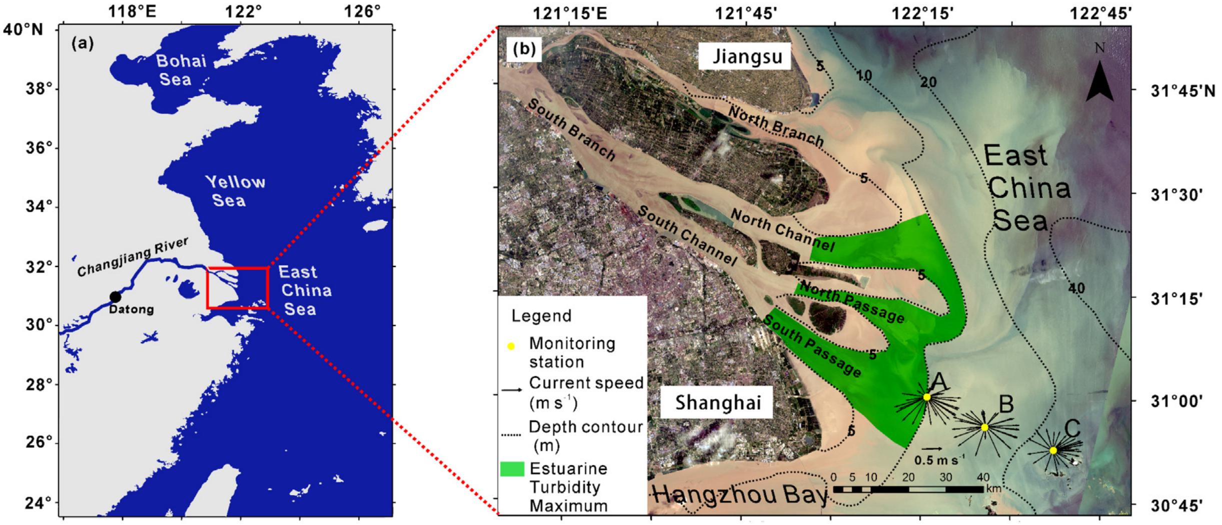

Fig. 1. Maps of the study area, showing (a) the location of the Changjiang Estuary, and (b) monitoring stations (yellow circles). Black arrows represent depth-averaged current speeds in m s^{-1}, measured hourly from 09:00 July 2 to 12:00 July 3, 2016 (UTC/GMT + 08:00). The zone of estuarine turbidity maximum in (b) is from Li and Zhang (1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)