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Mechanisms underlying the regional morphological differences between the northern and southern radial sand ridges along the Jiangsu Coast, China

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ABSTRACT

Radial sand ridges (RSRs) spread in a fan-shaped pattern over the seabed of the southern Yellow Sea along the Jiangsu Coast (China) with pronounced differences between the northern and southern channel-shoals (indicated as "NCS" and "SCS", respectively). A depth-averaged nested numerical model is employed to analyze the tidal hydrodynamics and sediment dynamics of the RSRs. Model results show considerable regional differences in terms of tidal current vector ellipses: "eight-shaped" ellipses are typical in the NCS where rotational tidal waves dominate, while the SCS are characterized by "egg-shaped" ellipses because of the dominance of progressive tidal waves. Sand ridges tend to be elongated and straight in the NCS while short and dincontinuous in the SCS. Numerical Lagrange particles released near the ridges in the NCS tend to travel across the crest of the ridges rather than move around them as observed in the SCS. Consistently, the patterns of sediment convergence and divergence indicate that suspended sediments converge over the whole Xiaoyinsha Ridge located in the NCS, while converge to the two sides of the Hetunsha Ridge located in the SCS. Model results also highlight the importance of initial sediment compositions in determining patterns of the net sediment fluxes. The suspended sediment concentration (SSC) time series during one tidal cycle may show single or double peaks depending on the grain size and the related lag effect. Bed load transport is much smaller than suspended load. So sediment compositions should be carefully considered when simulating the SSC field, and the hydrodynamic of the morphological evolution of the RSRs at the regional scale. Overall, this study suggests that the NCS and SCS may be treated as two relatively independent geomorphological systems characterized by different tidal flows and sediment compositions.

1. Introduction

Tidal sand ridges are linear sand bodies often present on the continental shelf with their crests approximately parallel or rotating a certain angle to the principal direction of tidal currents. The formation and evolution of tidal sand ridges result from feedbacks between a variety of processes such as tidal currents, sediment transport and continental topography (e.g., Huthnance, 1982a). By studying 12 systems of linear sand ridges on tide-dominated continental shelves around the world, Off (1963) concluded that tidal sand ridges generally form in coastal waters where the current velocity ranges from 0.5 m/s to 2.5 m/s and where sediment sources are sufficient. The spatial dimension of tidal sand ridges may vary, but they are usually tens of meters high and tens of kilometers long, with a spacing of up to a few kilometers (Stride, 1982; Van Rijn, 1998; Dyer and Huntley, 1999). From 1970s to 1990s, numerous studies were conducted to gain insight into the effect of tides (Smith, 1969; McCave, 1979; Howarth and Huthnance, 1984), waves (Hasselmann et al., 1973, 1980), sediment transport (Caston and Stride, 1970; Stride, 1974; Caston, 1981; McCave and Langhorne, 1982; Collins et al., 1995), underwater landforms (Houbolt, 1968; Kenyon, 1970; Caston, 1972; Berné et al., 1994) and sedimentary processes (Trentesaux et al., 1994; Van de Meene et al., 1996). Huthnance (1982a) firstly modeled the formation of sand ridges, employing simplified two-dimensional shallow water equations and a power-law sand transport formula. A certain angle (about 28°) between the bidirectional tidal current and the sand ridge, was considered to be the necessary condition to form linear sand ridge.

The overall morphology of sand ridges worldwide may differ pronouncedly depending on the local geological history and environmental conditions. In terms of planar shape, some sand ridge systems display a generally periodic channel-ridge distribution while some exhibit a radial shape. Well-documented nearly periodic sand ridges include

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the ones on the North Sea seabed (Dyer and Huntley, 1999) and on the continental shelf of the East China Sea (Liu et al., 2000). Radial sand ridges are mostly found at the entrance or exit of straits (Pattiaratchi and Collins, 1987). An exception is provided by the radial sand ridges (hereafter indicated as "RSRs"), located along the Jiangsu Coast, China, which have developed in an open sea. The large-scale fan-shaped RSRs are considered as one of the most striking coastal landscapes and are the focus of this study.

The RSRs were initially observed in the 1950s, while the first scientific report dates back to the late (He, 1979). Since then numerous research efforts have been devoted to the RSRs also because of their socio-economic importance and because, scientifically they represent the largest system of this type studied. From 1980 to 2010, several large-scale and multi-disciplinary field surveys of the RSRs were carried out and a comprehensive knowledge of the RSRs was attained in terms of terrestrial hydrology, water resources, coastal climate, geological history, sediment composition, suspended matters, stability of wetlands and geomorphic characteristics (e.g., Ren, 1986; Zhang, 1992a, 2012; Bian et al., 2013). More recently, the extensive use of remote sensing and geographic information system (GIS) has further enhanced our ability to monitor the morphological evolution of the RSRs (e.g., Shi and Wang, 2010; Kang et al., 2013).

Apart from extensive field surveys, various numerical models have also been developed and applied to study the RSRs. By simulating the propagation of the M_2 tidal constituent together with the ancient coastline, Zhang et al. (1999) demonstrated that the moving stationary tidal wave system on the southern Yellow Sea provided plausible hydrodynamic conditions for promoting the growth of underwater bars. Tidal currents were suggested to be the major hydrodynamic factor inducing the formation and maintenance of the RSRs, while storms and typhoons could only cause short-term modifications. Therefore, tidal currents play a major role in the formation and evolution of the RSRs, while occasional storms could induce considerable instantaneous change which can be gradually recovered as a result of sediment transport by tidal currents. Zhu and Chang (2001) simulated the M_2 tidal constituent in the RSRs with a two-dimensional model using a schematic topography. They found that the results were generally in agreement with field data and hence argued that flood and ebb tidal current fields were not significantly influenced by the bottom topography. More recently, Tao et al. (2011) developed a three-dimensional model to simulate the response of the tidal wave system to a large-scale land reclamation project carried out on the Jiangsu tidal flats including the RSRs. They found that the amphidromic point moved about 3 km northeastward and tidal ranges increased at several locations, leading to pronounced local morphological changes. In line with Tao et al. (2011); Song et al. (2013) used a different numerical model and also suggested that large-scale tidal flat reclamation could cause the displacement of the amphidromic points and redistribution of tidal energy in the East China Sea. Xing et al. (2012) simulated the fine-grained suspended sediment transport in the RSRs and argued that tidal current is the dominant factor shaping the RSRs while the effects of other factors such as waves, winds and river discharges were more localized. Recently, Zhang et al. (2013) calculated the suspended sediment fluxes in the RSRs using a depth-averaged numerical model and their results indicated that the RSRs were still in a growing/accretionary phase.

Although remarkable progress has been achieved during the last five decades, all the above mentioned numerical studies were primarily focused on the global properties and dynamics of the RSRs patterns, while the local differences within the sand ridges have received little attention. The planar morphology of the RSRs appears to be symmetrically fan-shaped, with sand ridges radiating seaward from Jianggang (Fig. 1). However, there are evident differences between the northern and southern parts of the RSRs, in terms of topography, sediment compositions and hydrodynamic conditions (see Section 2 for details). The model domain of most of the previous numerical studies tended to be large-scale with relatively coarse grid sizes (e.g., 1–10 km), lacking a detailed description of local characteristics within the RSRs. The bottom sediment parameters (e.g., settling velocity and critical shear stress) were usually considered to be constant over the entire model domain when the SSC fields were simulated. However, those parameters are highly dependent upon the grain size (Van Rijn, 1984a, 1984b), which differs pronouncedly over the RSRs, an aspect which so far has not been explored. In this study, we aim to unravel the mechanisms underlying the regional differences between the northern and southern parts of the RSRs using a two-dimensional numerical model with much smaller grid size (300 m) than any previous study. Specifically, the research questions we try to address are: (1) What are the major hydrodynamic differences within the fan-shaped RSRs? (2) How do patterns in tidal currents contribute to the maintenance of the sand ridges and troughs differently between the northern and southern parts of the RSRs? (3) What role does the sediment composition play in the morphological evolution of the RSRs? Understanding these questions is critical to improve our knowledge of the morphodynamics of these features to make sustainable development strategies and to predict future morphological changes, particularly under the threat of increasingly climatic change and human activities (e.g., harbor operations, land reclamations and nearshore fisheries).

2. Study area

The RSRs spread over the Jiangsu Coast which is located between the abandoned Yellow River Estuary and the Yangtze Estuary (Fig. 1a), covering an area of more than 200 km from north to south and approximately 140 km from east to west (Wang et al., 1999). The RSRs consist of more than 70 sand ridges with various dimensions radiating from the Jianggang towards the open sea. Within the fan-shaped RSRs, there are pronounced morphological differences between the northern and southern features. The northern sand ridges are elongated and tend to bend northwards, while the southern ones are shorter and straighter (Fig. 1b). In the center of the RSRs, three main sand ridges (named Dongsha, Tiaozini and Gaoni Ridges, respectively) are present and they emerge from the water during low tidal levels. These three sand ridges, separated by small troughs, roughly divide the RSRs area into two geomorphic units, i.e., the northern and southern channel-shore systems (hereafter referred to as "NCS" and "SCS").

The NCS is considered as the region to the north of the Tiaozini Ridge, with the Xiyang Trough being the major tidal channel (Fig. 1c). The Xiyang Trough is bounded by land on the west side and characterized by large width and depth. The average width is about 15 km and the maximum depth is up to 35 m. The Xiyang Trough is further separated by a narrow sand ridge (the Xiaoyinsha Ridge) and is located between the West Xiyang Trough and the East Xiyang Trough (Fig. 1c). The West Xiyang Trough is much deeper with larger flow velocities than the East Xiyang Trough. Measured tidal current velocities in the West Xiyang Trough can reach 2.5 m/s (Yan et al., 1999a). Compared to the NCS, the SCS are characterized by the presence of a large number of sand ridges and troughs characterized by smaller size (Fig. 1d). The main tidal channels in the SCS are the Lanshayang and Huangshayang Troughs which have a water depth comprised between 10 and 20 m.

The RSRs are controlled by a large-scale tidal wave system which is determined by the land boundaries of China and the Korean Peninsula (Zhang et al., 1999). The tidal wave first enters the southern Yellow Sea and part of the wave is reflected by the Shandong Peninsula, forming an anticlockwise rotational tidal wave system. The rotational wave meets the following progressive wave from the southern Yellow Sea, resulting in the formation of an approximately stationary tidal wave, where the phase difference between the current velocity and tidal level is about 90° (Zhang et al., 1999). However, due to the large tidal range in the RSRs, the wavelength varies as the tidal level fluctuates. As a result, the tidal wave appears to be not completely stationary (see the phase lines along the Jiangsu Coast in Fig. 2b). This explains why the tidal wave system has been defined a moving stationary tidal