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A morphodynamic modeling study on the formation of the large-scale radial sand ridges in the Southern Yellow Sea

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Key Points:

- The fan-shaped morphology of the large-scale radial sand ridges is numerically simulated.
- The formation of radial sand ridges requires specific conditions primarily characterized by the tidal wave system.
- The mechanism underlying the asymmetric spatial pattern of the radial sand ridges is revealed.

Abstract

The governing factors underlying the formation of the fan-shaped large-scale radial sand ridges (denoted as "RSRs" hereafter) off the Jiangsu Coast, China, are investigated using an idealized morphodynamic model. A series of simulations are performed to analyze the effects of the M_2 tidal constituent along the boundary, the Coriolis forcing, the bed resistance and the sediment availability on the morphodynamic behavior of the RSRs. Numerical results indicate that the tidal regime, characterized by the rotational and progressive tidal wave systems, is dependent on the east coastline of China as well as their specific geographic latitude. Through the comparison between the simulated and the measured morphology, this tidal regime is demonstrated to be the key driver in forming and maintaining the present-day RSRs. The sensitivity runs further suggest that the asymmetric pattern of the RSRs, which shows larger northern sand ridges than the southern ones, results from both the asymmetric distribution of the tidal wave systems and unequal sediment supply. Overall, this study highlights the delicate balance, predominantly represented by the special tidal wave systems and the sediment availability, required to shape the striking large-scale RSRs in the Southern Yellow Sea.

Keywords: Radial sand ridges; Morphodynamic modeling; Tidal wave systems; Jiangsu Coast; Southern Yellow Sea

1 Introduction

Sand ridges are geomorphological features widely distributed in estuaries (e.g., the Thames Estuary, Harris, 1988), coastal bays (e.g., the Gulf of Korea, Off, 1963), the ends of straits (e.g., the Dover Straits, Caston, 1981) and continental shelves (e.g., the North Sea and the East China Sea, Belderson et al., 1982; Stride, 1982; Yang, 1989). The formation of sand ridges favors an environment where abundant sediment is available and the hydrodynamic regime is sufficiently strong to transport sediments (Dyer & Huntley, 1999; Liu & Xia, 1985; Off, 1963; Pattiaratchi & Collins, 1987; Swift, 1975). Most sand ridges around the world are hidden subaqueous landscapes characterized by striking and intricate morphologies, which have received considerable Holocene shelf deposits and/or fluvial sediment supply. These sediments are subsequently reworked by both terrestrial and marine processes, including river inflows (Giosan et al., 2005), wind waves (Hulscher et al., 1993), tidal currents (Van de Meene & Van Rijn, 2000a, 2000b), and storm surges (Calvete et al., 2001; Swift, 1975; Trowbridge, 1995).

Sand ridges typically exhibit horizontal length scales ranging from several kilometers (mostly in estuaries or river deltas) to hundreds of kilometers (generally on continental shelves), and are characterized by a "wave-length" of several kilometers and an inter-ridge depth of tens of meters (Gao & Collins, 2014). In most cases, the crests of sand ridges are parallel or subparallel to the main tidal current direction (Dyer & Huntley, 1999; Gao & Collins, 2014; Liu & Xia, 1985). At the end of straits or coastal bays where flow diverges or converges, sand ridges often show a fingered or radial planar pattern, such as the sand ridges observed at the Dover Straits (Caston, 1981) and the Southern Yellow Sea (Liu et al., 1989).

Off (1963) was probably the first to define sand ridges as rhythmic linear sand bodies induced by tidal currents. Since then, the morphological characteristics and the dynamics of sand ridges have attracted a considerable research effort over the last 50 years, particularly on the tidal shelf seas around the UK, and on sand ridges in the North Sea and the Atlantic coast of North America (Caston, 1981; Collins et al., 1995; Dyer & Huntley, 1999; Houbolt, 1968; McBride & Moslow, 1991; Swift, 1975). Attention has been given to fundamental theories for the formation and long-term evolution of sand ridges, so that quantitative morphological prediction of sand ridges can be modeled (Dyer & Huntley, 1999). Huthnance (1982a) first derived the wavelength and the orientation of linear sand ridges, which were consistent with observed tidal sand ridges. Huthnance (1982b) further explained that the refraction of tidal currents over a sand ridge could generate a residual flow, which resulted in the convergence of sediment toward the crest of the sand ridge. This theory was further extended to explain other bed forms, such as shoreface-connected ridges (Calvete et al., 2001; Trowbridge, 1995; Walgreen et al., 2002), linear sand ridges (De Vriend, 1990), and long bed waves (Blondeaux et al., 2009). However, these highly schematized models cannot correctly evaluate the development of tidal sand ridges, when perturbations grow large and non-linear processes take over.

Recent advances on long-term morphodynamics by solving the non-linear governing equations numerically (Lesser et al., 2004; Roelvink, 2006; Wang et al., 1995) allow us to simulate the morphodynamic evolution of a system and hence to gain fundamental insights into the ontogeny of coastal landscapes (Zhou et al., 2014c; Zhou et al., 2017). Hibma et al. (2003, 2004) simulated the formation of finite-amplitude tidal sand bars in a long straight tidal basin. Marciano et al. (2005) investigated the channel-shoal patterns in a short tidal basin with both theoretical stability analysis and numerical modeling. These studies indicated that the morphological wavelength is related to the bed slope, the Shields parameter and the sediment availability. Moreover, the Coriolis force has also been found to pronouncedly affect the channel-shoal patterns in estuaries (Schramkowski & De Swart, 2002; Van Leeuwen & De Swart, 2002).

The largest sand ridge system along the Chinese coast (Wang et al., 2012b), the radial sand ridges (hereafter referred to as “RSRs”) in the Southern Yellow Sea are morphologically striking because of the remarkable size and radial planar orientation (Figure 1a and 1b). It has been suggested that the RSRs originated from the underlying Holocene strata relict (Li et al., 2001; Wang et al., 1999, 2012b; Yang, 1989) with sediments coming from the neighboring Yangtze River and the Yellow River (Lee & Chough, 1989; Milliman & Meade, 1983; Saito & Yang, 1994). The Jiangsu coastline has advanced seaward for about 20-40 km over the last one thousand years, because of the abundant sediment supply (Wang et al., 2012b; Zhang, 1984). After the Yellow River diverted from the Yellow Sea into the Bohai Sea in 1855, part of the sediments of the Old Yellow River Delta were reworked and reformed into the RSRs (Zhou et al., 2014a), which in turn provided natural shelters for the tidal flats behind the offshore sand ridges.

Although originating in an earlier environment, sand ridges are dynamic systems which are undergoing modification in response to their present environment, especially the hydraulic regime (Dyer & Huntley, 1999). Many studies have been conducted attempting to elucidate the mechanism underlying the formation of the present-day RSRs (e.g., Du & Wang, 2014; Zhang et al., 1999; Zhu & Chang, 2001). The offshore tidal regime along the Jiangsu Coast have been recognized as the key driven forcing shaping the RSRs, which is supported by two observations: (1) both the tidal current fields and the morphology of the RSRs show similarly radial spatial patterns (e.g., Ren, 1986; Zhang et al., 1999; Zhang, 2012) and (2) several authors found that the radial tidal current patterns can be modeled in the absence of the RSRs (e.g., Qian et al., 2015; Xu et al., 2016; Zhu & Chang, 2001; Zhu & Chen, 2005). The radial tidal current fields are governed by the convergence of a progressive tidal wave from the East China Sea and a local reflected tidal wave formed by the obstruction of the Shandong Peninsula (Zhang et al., 1999;

see also Qian et al., 2015; Xu et al., 2016). Other dynamics, such as waves (Xiong et al., 2017) and storm surges (Ren et al., 1985), are considered to be less relevant to the radial morphology of the RSRs, although they can induce considerable short-term sediment transport.

The M_2 tidal constituent is dominant in the RSRs (Ren, 1986; Uehara et al., 2002; Zhang, 2012), which has been considered as the major tidal forcing shaping the present-day RSRs (Xing et al., 2012; Xu et al., 2016; Zhang et al., 1999). Previous conclusions about the formation of the RSRs were mainly based on the short-term tidal current fields and the analyses from classical theoretical studies (e.g., Huthnance, 1982a; Off, 1963; Zhang et al., 1999; Zhu & Chang, 2001). Although these indirect proofs are reasonable, a direct evidence lacks to demonstrate the casual relationship between the M_2 constituent and the planimetric shape of the RSRs. In this study, a state-of-the-art morphodynamic model (Delft3D) is employed to investigate the long-term morphodynamic evolution of the RSRs. It is worth noting that this study does not aim to reproduce the exact morphology of the RSRs. We restrict the research questions to: (1) Whether the dominant M_2 tidal constituent can shape the radial planimetric shape of the RSRs or not? (2) How do tidal regime and sediment supply affect the spatial pattern of the RSRs? By resolving these two questions, we intend to gain a more in-depth understanding of the mechanisms underlying the morphodynamics of the RSRs. This morphodynamic study also aims to facilitate further research effort to predict the long-term evolution of the RSRs under threats of sea level rise, reduced sediment supply and increased frequency of coastal storms.

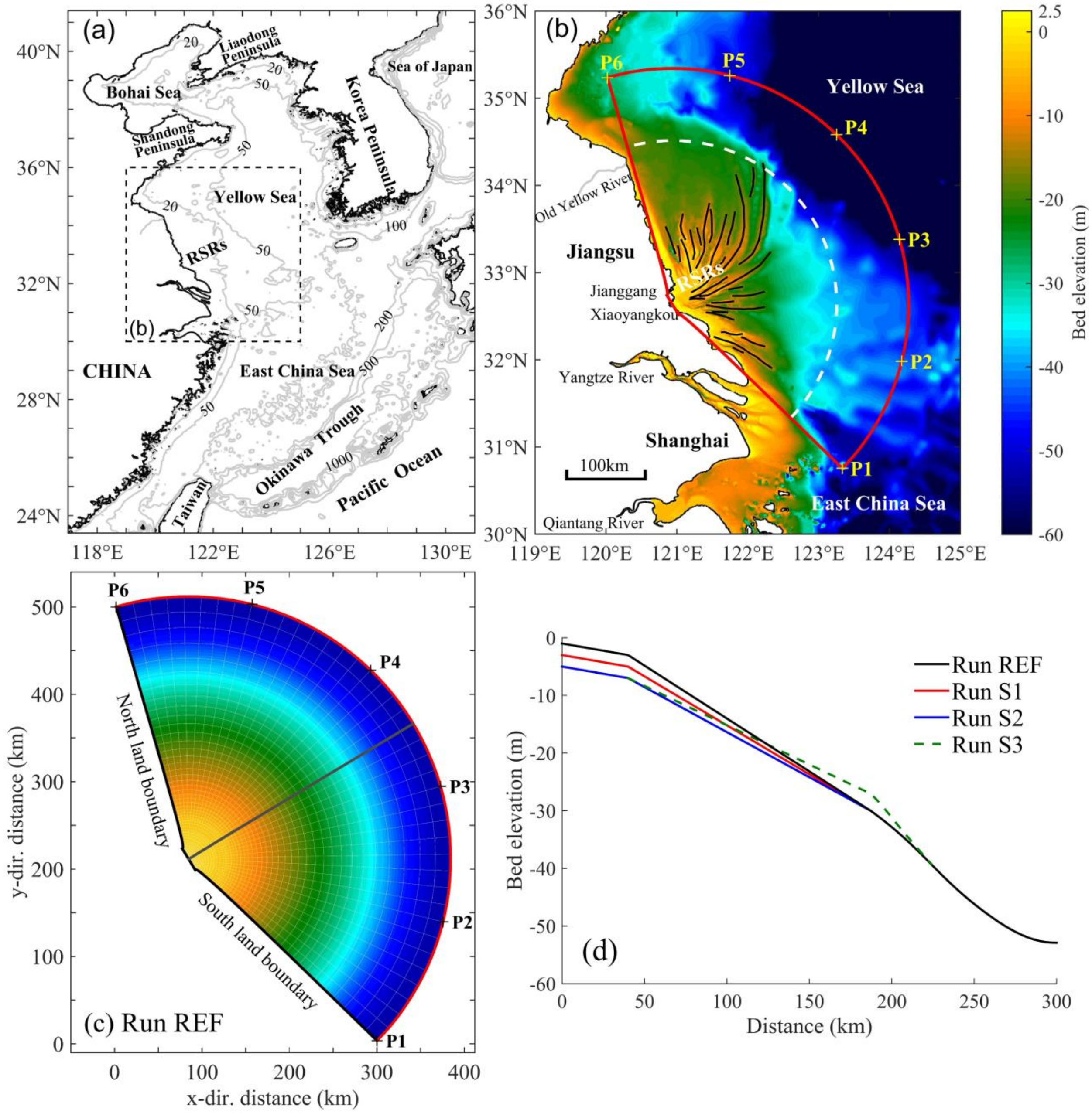

Figure 1. Regional settings of the study area and schematized model configurations. (a) Bathymetry of the Bohai Sea, the Yellow Sea and the East China Sea. The bathymetric data are after the gridded bathymetry data of General Bathymetric Chart of the Oceans (GEBCO) with 30 arc-second interval grid; bathymetry contours are given in m. (b) Bathymetry of the Southern Yellow Sea and the East China Sea. Location indicated by the black dashed box in panel (a). Bathymetric data were measured in 2006. The black lines roughly denote the sand ridges in RSRs system. The white dash sector covers the area of the radial sand ridges (RSRs) and is also the area of morphological change in simulation scenarios. The red lines indicate the schematized model geometry used in this study. The cross markers (P1 to P6) show the nodes for prescribing tidal level along the boundary. (c) Plan view of the geometry, grid and bathymetry of the schematized model. The color bar in panel (c) is the same as that of panel (b). (d) Longitudinal

profiles of the bathymetry with different initial bed levels. Location of the longitudinal profile is indicated by the gray line in panel (c). The bed elevation is relative to mean sea level.

2 Study area

The RSRs off the Jiangsu Coast spread on the seabed on the western margin of the Pacific Ocean, where the long, gentle slope of the coastal plains extends offshore towards the semi-enclosed Yellow Sea (Figure 1a). The subaqueous sand ridges stretch more than 200 km from north to south and approximately 140 km from east to west, showing an approximately 150° fan-shaped spatial pattern centered on Jianggang (Xu et al., 2016). The plane scale of each sand ridge is up to 100 km long and 5-10 km wide (Liu et al., 1989), and the water depth in tidal channels can reach 30 m (Wang et al., 2012b). The spatial pattern of the RSRs is asymmetric characterized by northern sand ridges larger than the southern ones (Xu et al., 2016). The bottom sediment of the RSRs mainly consists of fine to very fine sand, with a mean grain size of 2-4 ϕ (Liu et al., 1989; Wang & Ke, 1997) and the sediment mixture is well-sorted (Liu et al., 2012).

The tide over the sea area of the RSRs is semi-diurnal with a mean tidal range of 4-6 m (Zhang et al., 1999). The tidal currents tend to be radial in a planar pattern and strong in magnitude, with an average spring tidal current depth-average velocity being 1.5-2.0 m/s and a maximum tidal current velocity of over 2.5 m/s (Wang et al., 2012b). Under normal conditions, wave energy progressively decreases when crossing the RSRs so that wave heights of 7-9 m in the open sea are reduced to approximately 0.4 m at the coast. Under extreme wind conditions, although large waves with a wave height of 2 m can occasionally be observed, the probability is only 5% (Wang et al., 2012b). According to the meteorological record from 1949 to 2007, only 5 of the 76 typhoons landed on the Jiangsu Coast or the Yangtze Estuary (Xu et al., 2016).

Figure 2 shows the co-tidal chart and tidal current ellipses of the M_2 constituent. The area of the RSRs is influenced by two tidal wave systems, including the progressive tidal wave system from the East China Sea and the anti-clockwise rotational tidal wave system characterized by an amphidromic point approximately 220 km to the north of Jianggang (Figure 2a). These two tidal wave systems converge along the Jiangsu Coast, resulting in an approximately stationary tidal wave, of which the phase difference between the current velocity and tidal level is about 90° over the central RSRs (Li et al., 2001; Tao et al., 2018; Xu et al., 2016; Zhang et al., 1999). Both the magnitudes of the current velocities and the tidal amplitudes peak in the central RSRs, due to the convergence of the two tidal wave systems. The tidal current fields in the RSRs show a radial in planar pattern centered in Jianggang (Figure 2b), which is consistent with the fan-shaped morphology of the RSRs (e.g., Tao et al., 2018; Xu et al., 2016). The tidal current ellipses show a bidirectional flow in the north and a rotational flow in the south over the RSRs.

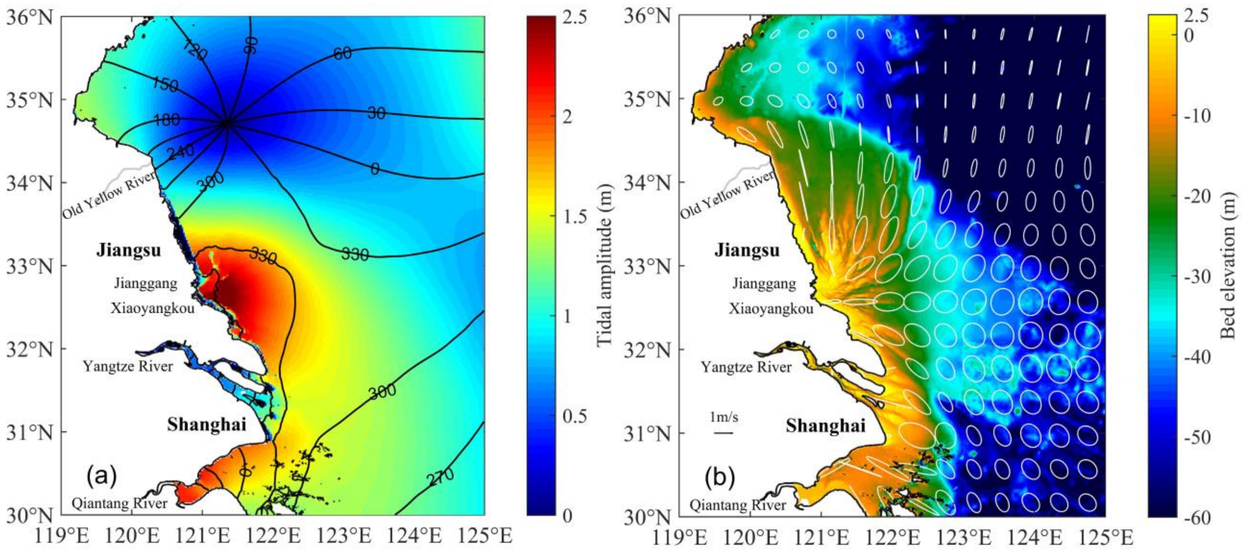

Figure 2. (a) Co-tidal chart and (b) tidal current ellipses of the M_2 constituent in the Southern Yellow Sea (modified after Tao et al., 2018). The color code in panel (a) indicates tidal amplitudes with black co-phase lines in degrees. The color code in panel (b) shows the bed elevation of the Southern Yellow Sea.

3 Methodology

3.1 Numerical model

An open-source morphodynamic model (Delft3D) is employed in the present study (Lesser et al., 2004). Since the model has been described in detail elsewhere (e.g., Van der Wegen & Roelvink, 2008), the governing equations are not introduced herein. The numerical model solves the non-linear 2-D shallow water equations resulting in a detailed description of the flow field (i.e., water levels and velocities) over the model domain. The water level and the velocity fields are then utilized to calculate the sediment transport and the resultant bed evolution.

The sediment transport rate is calculated based on the local instantaneous flow condition using the widely-adopted formula of Engelund and Hansen (1967), which accounts for both bed load and suspended load (following e.g., Marciano et al., 2005; Van der Wegen & Roelvink, 2008; Van Maanen et al., 2013):

$$S = \frac{0.05U^5}{\sqrt{g}C^3\Delta^2 D_{50}} \tag{1}$$

where, S is the sediment transport flux (m^2/s), U is the magnitude of depth-average flow velocity (m/s), g is the acceleration of gravity (m/s^2), $C = H^{1/6}/n$ is the Chézy friction coefficient (m$^{1/2}$/s), H is the water depth (m), n is the Manning coefficient (s/m$^{1/3}$), Δ is the relative density $(\rho_s - \rho_w)/\rho_w$, ρ_s is the sediment density (kg/m^3), ρ_w is the water density (kg/m^3), and D_{50} is the median grain size (m). Effects of longitudinal and transversal bed slope on the sediment transport are accounted for following Bagnold (1966) and Van Rijn (1993) as described in detail by Van der Wegen and Roelvink (2008). The elevation of the bed is dynamically updated linearly by a morphological factor at each hydrodynamic time step according to mass conservation of sediment (Roelvink, 2006).

3.2 Numerical experiments

The computational domain is idealized on the basis of the east coast of China, such that the physical implications of different factors can be analyzed in a more straight-forward manner (Figure 1b). The embayment is a fan-shaped area of approximately 150° open angle. The center of the embayment is a 30-km long line segment, which approximates the distance between Jianggang and Xiaoyangkou (Figure 1b). The lengths of the two lateral closed boundaries are both 300 km. The embayment is discretized using an orthogonal curvilinear grid with 200×220 cells (Figure 1c). The sizes of the grid cells range from 150×200 m^2 at the landward segment to 3.5×4 km^2 along the seaward arc boundary for the consideration of the balance between the numerical precision and efficiency. The computational time to perform each long-term simulation (up to 2000 years) is approximately two weeks using a 3.7 GHz processor, 8.0 GB RAM personal computer.

A reference run (denoted as “REF” hereafter) is designed to reproduce the typical tidal wave system over the RSRs. The tidal amplitudes and the phases of the M_2 constituent at points P1-P6 along the seaward boundary are provided by a well-calibrated large-scale tidal wave numerical model according to realistic shoreline and bathymetry (Tao et al., 2009). Other components and their relevant spring-neap tide are not considered, since the M_2 constituent is dominant in the RSRs. The Coriolis Force is calculated based on realistic latitude spatially varying from 30.7°N to 35.2°N (Figure 1b). For the transparency of the idealized model, the initial water depths are set increasing radially from the central landward segment to the seaward boundary (Figure 1c). According to the overall variation of the bed elevation from the land to the sea (Figure 1b), the radial profile consists of a linear sloping upper-flat segment (0.05‰, Wang et al., 2012a), a relatively steep lower-flat one (0.18‰, Wang & Ke, 1997) and a deep-water one gently reducing the slope to zero (Figure 1d). Notice that the present-day RSRs have portions above the mean sea level that are exposed during low tide, but that those are not represented in the initial model bathymetry. The grain size D_{50} is simply unified as 125 μm. A different value would not affect the simulated morphological patterns when using Engelund and Hansen (1967) formula, as pointed out by many authors (e.g., Dissanayake et al., 2009; Van der Wegen et al., 2008; Zhou et al., 2014c). It can be proved theoretically that only the morphological time scale is changed by changing D_{50}. Other physical parameters, such as the Manning coefficient ($= 0.015$ $\mathrm{s/m}^{1/3}$), and the horizontal eddy viscosity coefficient ($= 1$ m^2/s), are set following previous studies (e.g., Xing et al., 2012; Xu et al., 2016). At the seaward boundary, an “equilibrium boundary condition” technique is employed that the sediment load passing through the boundaries are “perfectly” adapted to the local flow. As a result of considerably large water depths, the erosion or deposition along the seaward boundary is negligible (e.g., Van der Wegen et al., 2008). This technique does not imply that the total amount of sediments is conserved within the computational domain, because sediment fluxes are allowed pass through the boundary.

Four sets of additional runs are presented to analyze the effects of the tidal boundary condition (T1-T3), the Coriolis Force (C1-C3), the Manning coefficient (i.e., the bed resistance, R1-R3) and the sediment availability (S1-S3) on the morphodynamics of the RSRs. All the runs are listed in Table 1 varying one model parameterization based on the reference case (run REF). The sediment availability is determined by the initial water depths in runs S1-S3. Arranging according to the initial sediment availability indicates that REF=S3>S1>S2. Notice that varying the initial water depths in runs S1 and S2 are accompanied by changes of bed slopes, which interfere with the analysis on the sediment availability. Therefore, run S3 is designed with a smaller initial bed slope and the same sediment availability compared with run REF. All the runs are simulated for a 2000-years with the time step of 2 min. Notice that the time scale "2000 years" here is just conceptual for the system to approach a dynamic equilibrium (as argued by Zhou et al., 2017). Considering the gap in the time scales between hydrodynamic and morphodynamic processes time scales, the morphodynamic evolution is scaled up linearly by a morphological factor ($=200$) (Roelvink, 2006). Typical values of this factor for sandy environments may range from tens to hundreds (e.g., Dastgheib et al., 2008; Ranasinghe et al., 2011; Van der Wegen & Roelvink, 2008).

Table 1. Model configurations, including the tidal boundary conditions, the geometric latitudes (i.e., testing the Coriolis Force), the Manning coefficients and the initial bed slopes (the blanks indicate the same parameter as run REF).

Run ID	Tidal boundary							Latitude (°N)	Manning coefficient (s/m$^{1/3}$)	Initial bed slope (‰)
	M2 tide	P1	P2	P3	P4	P5	P6			
REF	AMP (m)	1.0	1.05	0.75	0.60	0.45	1.05	real	0.015	0.180
	phase (°)	0	12	45	90	180	270			
T1	AMP (m)	1.0	1.05	0.75	0.60	0.45	1.05			
	phase (°)	0	54	108	162	216	270			
T2	AMP (m)	0.75	0.75	0.75	0.75	0.75	0.75			
	phase (°)	0	12	45	90	180	270			
T3	AMP (m)	0.75	0.75	0.75	0.75	0.75	0.75			
	phase (°)	0	0	0	0	0	0			
C1								20		
C2								10		
C3								0		
R1									0.010	
R2									0.020	
R3									0.025	
S1										0.167
S2										0.153
S3										0.130

Note. "AMP" denotes amplitude; REF is the reference run, of which the simulated configurations at the end look most like the real RSRs. The "real latitude" means that the latitude varies spatial depending on the position of the cells in the model (from 30.7°N to 35.2°N). The "initial bed slope" represents the second part of the profile as shown in Figure 1d.

4 Results

4.1 The simulated morphodynamic evolution

The simulated morphological patterns of run REF at years 100, 500, 1000 and 2000 are shown in Figure 3. At year 100, a series of thin sand ridges are formed near the landward apex, where the tidal current velocities are relatively large due to the convergence of the tidal waves. The sand ridges are elongated in the north and relatively short in the south. This spatial variation in the length of the sand ridges is related to tidal flow pattern: bidirectional in the north and rotational in the south (Xu et al., 2016), see Figure 2b. Sediments continuously accrete in the central region of the RSRs and the sand ridges near the apex gradually merge, leading to the formation of several huge sand bodies (Figure 3b and 3c). At year 2000, the spatial patterns of the sand ridges tend to be stabilized and show similarly radiated planar forms as the current RSRs.

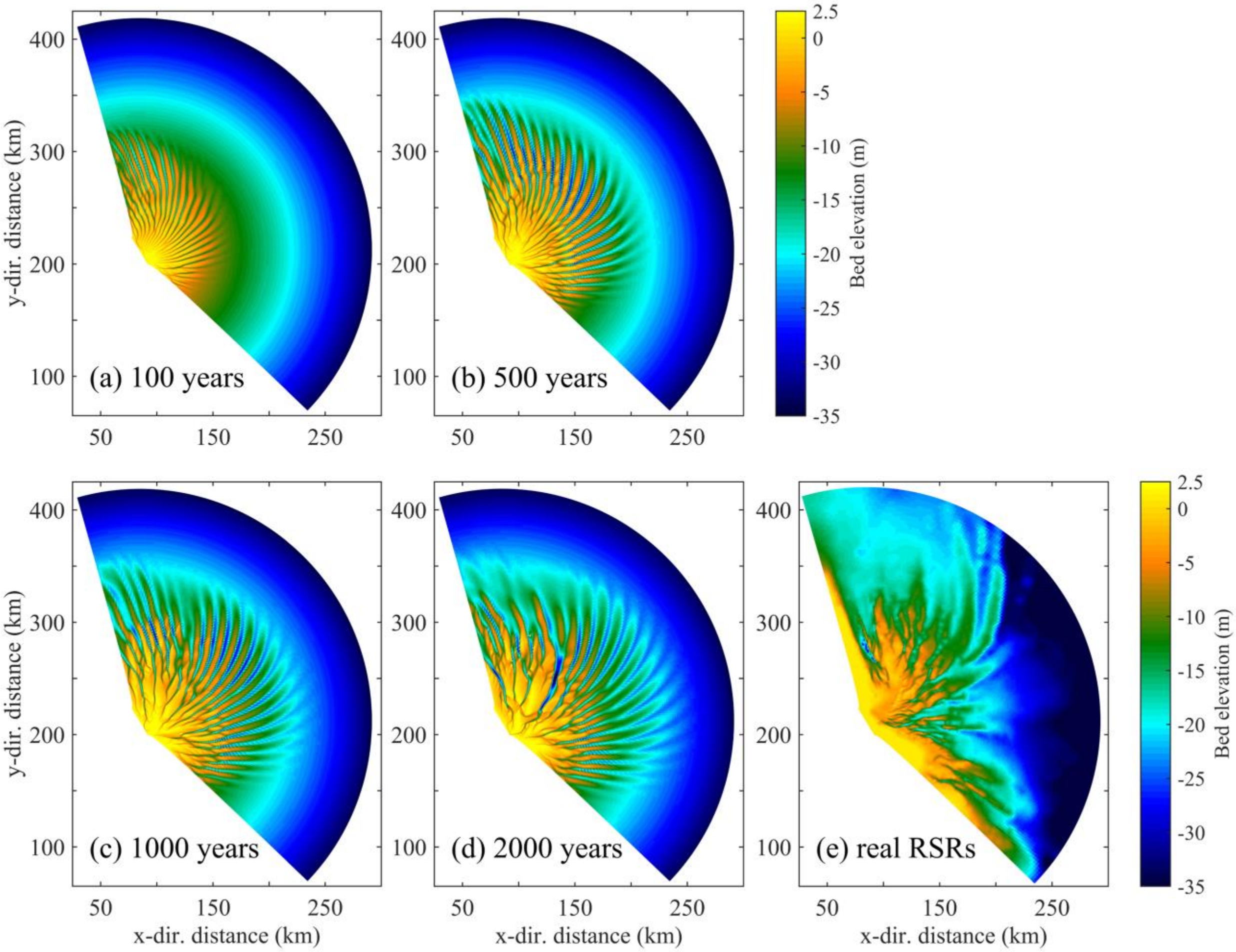

Figure 3. Morphologies simulated in (a-d) run REF and of (e) the real RSRs.

To clarify whether the present system converges to a morphodynamic equilibrium (Zhou et al., 2017), we quantify the morphodynamic evolution using the mean square root of the overall variations in bed level relative to the initial state (as e.g., Garnier et al., 2006; Nnafie et al., 2014):

$$\Delta z_{rms}(t) = \sqrt{\frac{1}{A}\oiint_A [z_t(x,y,t) - z_0(x,y)]^2 dxdy} \tag{2}$$

where A is the total planar area of the embayment, and $z_0(x,y)$ and $z_t(x,y,t)$ are the bed surface elevations at time 0 and t respectively. The morphodynamic evolution can also be considered as a self-organized process tending to minimize the energy dissipation caused by, for example, the bed resistance and sediment transport (Rodríguez-Iturbe et al., 1992). The mean energy dissipation is calculated following the expression proposed by Van der Wegen et al. (2008):

$$E_d = \frac{1}{A}\oiint_A \left[\left|\rho_w g n^2 \frac{U^3}{\sqrt[3]{H}}\right| + \left|\frac{0.05}{\Delta D_{50}} \rho_w \sqrt{g} n^3 \frac{U^5}{\sqrt{H}}\right|\right] dxdy \tag{3}$$

The time series of the quantified bed evolution Δz_{rms} and the total energy dissipation E_d over the 2000-year simulation period are shown in Figure 4. The energy dissipation is relatively high at the beginning of the simulation, which implies that the initial bed morphology is far away from the equilibrium configuration (Van der Wegen & Roelvink, 2008; Zhou et al., 2014b, 2014c). Correspondingly, the system experiences pronounced evolution with Δz_{rms} increasing and E_d decreasing rapidly in the first 200 years. As the radial channel-ridge patterns are formed between year 100 and 500 (Figure 3a and 3b), the variations of Δz_{rms} and E_d are both reduced, indicating that the interaction between the tidal flow and the bed topography progressively becomes milder. Around the year 1500, the variation of Δz_{rms} is minimal and the energy dissipation E_d maintains at a low level. Therefore, it can be inferred that the system asymptotically converges to morphodynamic equilibrium.

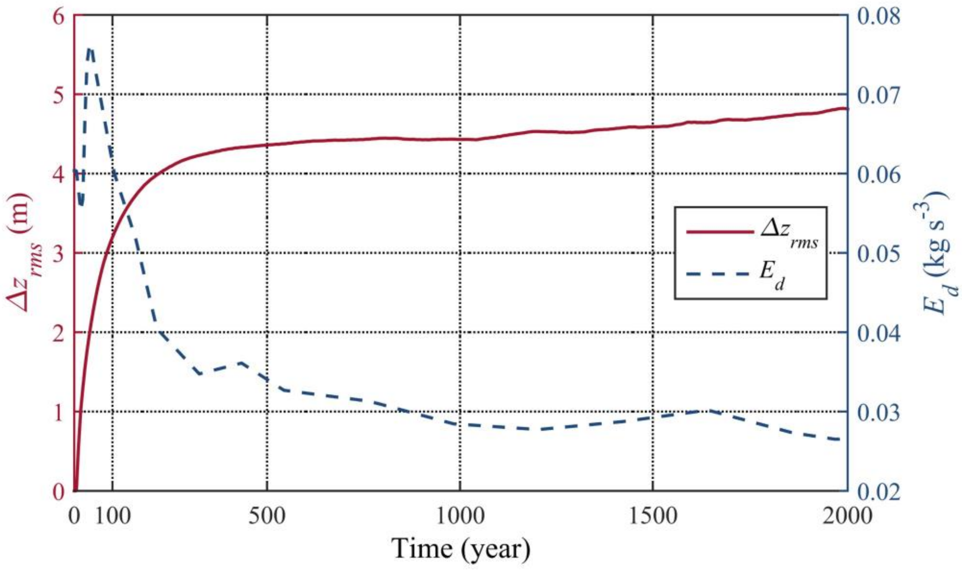

Figure 4. Time series of the overall variation of the Δz_{rms} and the energy dissipation per unit area E_d averaged over a tidal cycle.

4.2 The equilibrium configuration

Figure 5a shows the co-tidal chart of the M_2 constituent in run REF calculated using the initial bathymetry. The model successfully reproduces the typical tidal wave systems, which are characterized by an amphidromic point located in the north and the convergence of the tidal waves to the central area (e.g., Zhang et al., 1999). The tidal ellipses show a fan-shaped pattern with their major axes mainly oriented towards the center of the embayment. Moreover, the bidirectional and rotational tidal currents respectively occupy the north and south of the embayment (Figure 5b), which is also consistent with the tidal current fields over the RSRs (e.g., Xu et al., 2016). On the other hand, small differences are also observed that the modelled southern ellipses show less elliptical than the real case. This can be attributed to the restriction of the land boundary, which extends farther seaward than the real coast. The resultant 2000-year sand ridges show a similarly radiated spatial pattern and planimetric scale as the real RSRs (comparing Figure 3d with Figure 3e). The sand ridges located in the north are elongated, while those in the south are relatively short, which correspond to the distribution of the tidal ellipses (Figure 5b and 5e). The sand ridges are bending anti-clockwise, which is related to the rotations of the tidal ellipses in the centrifugal direction (Figure 5b). The tidal regime at year 2000 are overall in line with those at year 0 (Figure 5d), while the tidal currents tend to be bidirectional in the channels even in the south of the RSRs (Figure 5e).

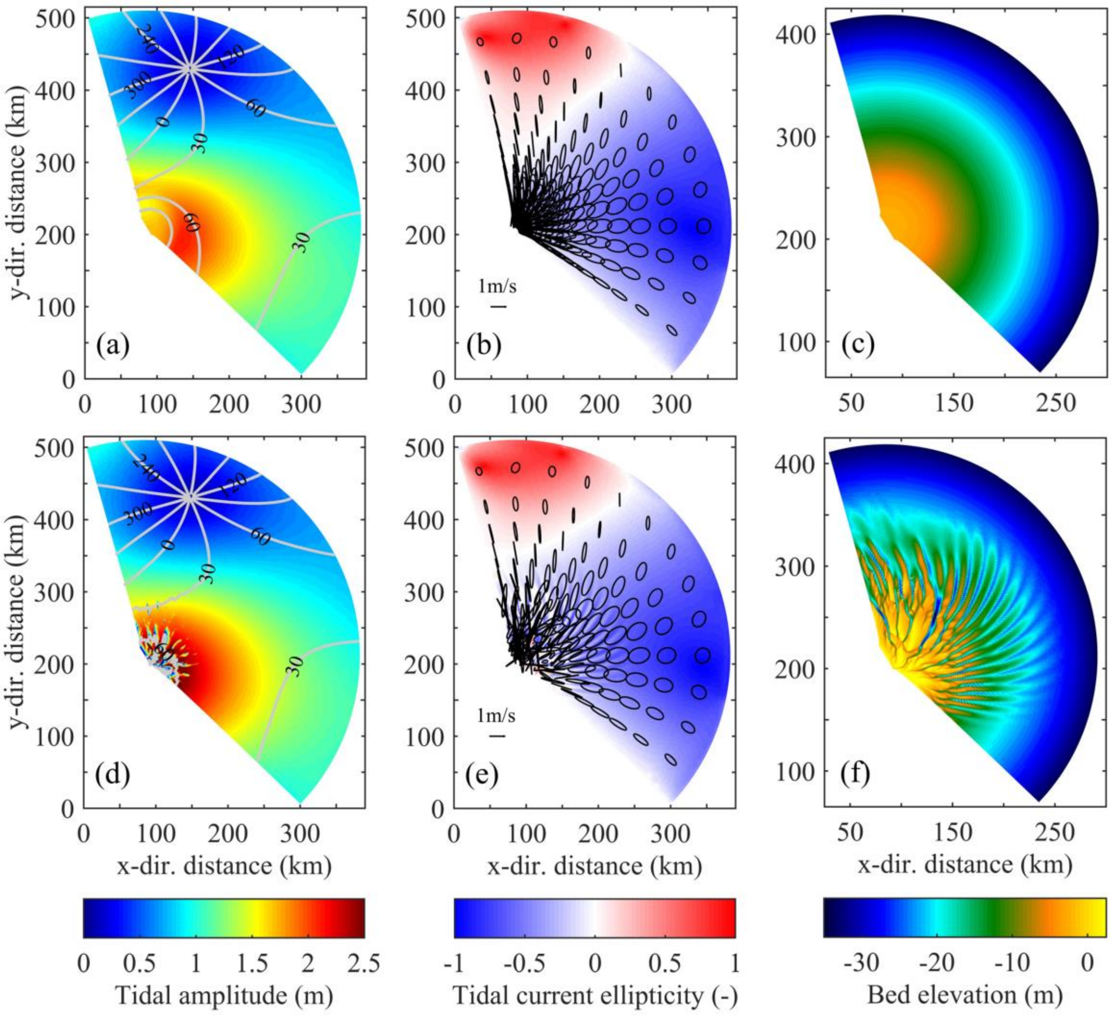

Figure 5. (a) Co-tidal charts and (b) the tidal current ellipses of the M_2 tidal constituent and (c) the morphology at year 0 simulated in run REF. Panels (d-f) show their 2000-year counterparts.

Huthnance (1982a) suggested that an approximately 28° angle between the orientations of bidirectional tidal current and linear sand ridge crest is necessary to form linear sand ridges. A series of elongated sand ridges with clear crest lines spreading outside the huge sand bodies are analyzed (Figure 6a). A least squares method is applied to fit the best ellipses to the tidal vector trajectories and their long axes are used as the main directions of the tidal currents (Figure 6b and 6c). The local orientations between the tidal current (denoted as “θ_{f}”) and the sand ridge crest (denoted as “θ_{c}”) are compared in Figure 6d (10 points are sampled on each crest). The sand ridge crests mainly fall into two groups characterized by $\theta_{\mathrm{f}} \approx \theta_{\mathrm{c}} - 28°$ (red triangles) and $\theta_{\mathrm{f}} \approx \theta_{\mathrm{c}}$ (black circles) respectively. The spatial distribution of these two types of sand ridge crests is shown in Figure 6a. Both relationships are also observed in numerical studies which focus on the tidal current in the RSRs (e.g., Xu et al., 2016). The sand ridge crests following $\theta_{\mathrm{f}} \approx \theta_{\mathrm{c}} - 28°$ mainly locate in the north and the south end of the embayment (see the black lines in Figure 6a), where bidirectional tidal currents prevail. The other ones indicating $\theta_{\mathrm{f}} \approx \theta_{\mathrm{c}}$ are situated in the mid-south part (see the red lines in Figure 6a), which are dominated by rotational tidal currents. Figure 6e shows the distribution of the sampling points in an angle-ellipticity plane, in which the color code indicates the number of points within an elementary area (i.e., density). The angle $\theta_{\mathrm{c}} - \theta_{\mathrm{f}}$ overall shows a decrease tendency with the increase of the ellipticity. Moreover, the sampling points concentrate in two regions: (1) $20 < \theta_{\mathrm{c}} - \theta_{\mathrm{f}} < 30$ and $0 < E < 0.3$ (E denotes the ellipticity), which indicates bidirectional tidal currents; and (2) $-10 < \theta_{\mathrm{c}} - \theta_{\mathrm{f}} < 10$ and $0.6 < E < 0.7$, which represents rotational tidal currents. Notice that the orientations of the sand ridge crests are in fact difficult to be exactly identified, since the morphology is complicated and the top of the sand ridges is flat. This may result in the relatively scattered distribution of sampling points in Figure 6d and 6e.

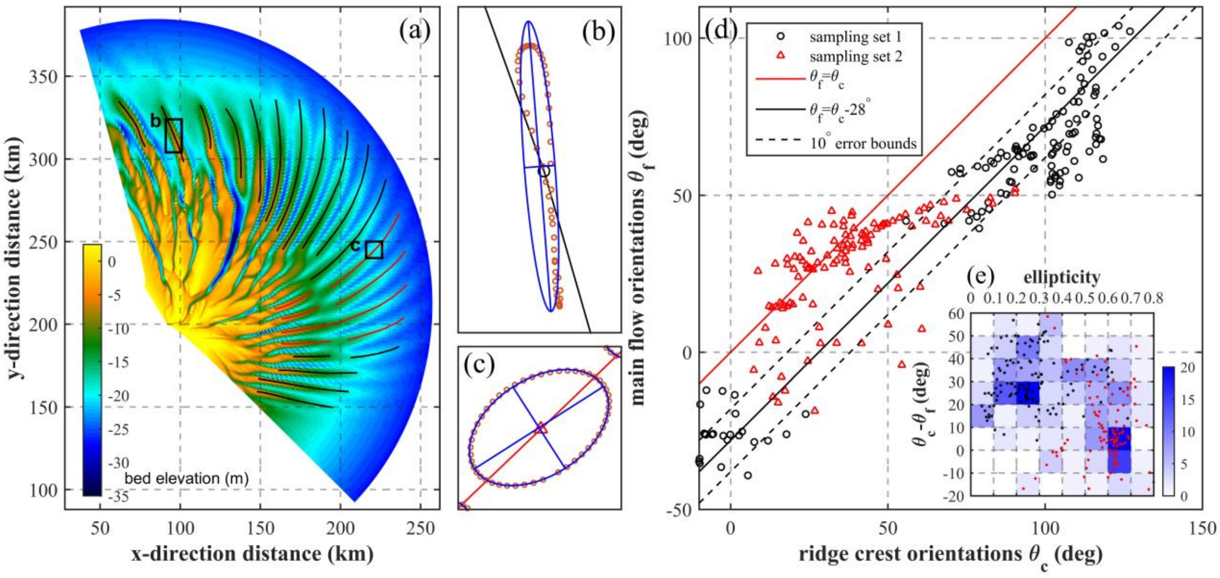

Figure 6. Comparison between orientations of the sand ridges and the main directions of the tidal currents simulated in run REF. Panel (a) indicates the locations of the sampled sand ridge crests, on each 10 points are sampled. Panels (b-c) illustrate the main directions of the tidal currents (red circles) based on the best fitting oval. The main directions of the tidal currents are approximated by the long axes of the ovals. Panel (d) compares the orientations of the sand ridges θ_c and the main directions of the tidal currents θ_{f}. The crests as well as the associated sampling points, which show consistency with $\theta_{\mathrm{f}} = \theta_c - 28°$ (as suggested by Huthnance, 1982a), are marked in black. The rest ones are marked in red, which indicate $\theta_{\mathrm{f}} = \theta_c$. The black dashed lines represent the 10° error bounds. Panel (e) shows the distribution of all sampling

points in an angle-ellipticity plane. The color code shows the number of points within the range (i.e., density).

To further evaluate the performance of the numerical model, the numbers of sand ridges simulated in run REF are compared with the real RSRs. The sand ridges are counted along 15 radial sections centered on the apex with radiuses increasing from 10 to 150 km (Figure 7). The total number of the sand ridges is overestimated by the numerical model, especially in the seaward sections (radius larger than 110 km), where the total number does not decrease as significantly as the real RSRs. It can be hypothesized that the sediment availability is excessive in the model and that sand ridges can extend longer than the real ones. However, the overall variation tendency is consistent with the real RSRs such that the total number initially increases and then decreases, peaking at approximately 70 km (Figure 7e).

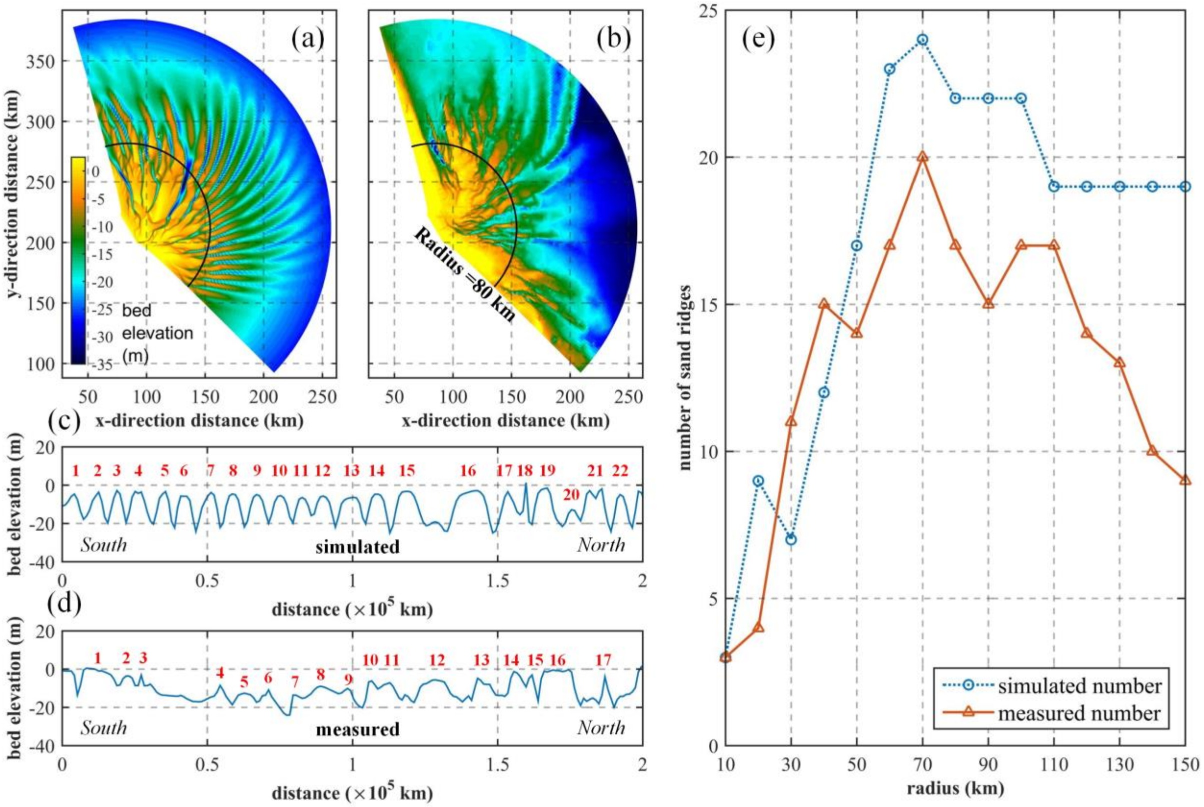

Figure 7. Comparison in the sand ridge numbers between run REF and the real RSRs. (a) The 2000-year bathymetry simulated in run REF. (b) The measured bathymetry of the RSRs. (c-d) The bed elevations and the correspondent sand ridge numbers at the cross-section with the radius of 80 km (see the black arc line in panel (a-b)). (e) The sand ridge numbers at 15 cross-sections with the radius varying from 10 km to 150 km.

4.3 Sensitivity analysis of key parameters

In addition to the reference simulation examining the correspondence between the tidal regime and the radial morphology of the RSRs, four sets of numerical experiments are performed to analyze the effects of the tidal boundary conditions (runs T1-T3), the Coriolis Force (runs C1-

C3), the bed resistance (runs R1-R3) and the sediment availability (runs S1-S3) on the tidal regime and the morphology of the RSRs.

The tidal phase is modified linearly varying from 0° to 270° along the seaward boundary in run T1. The amphidromic point moves close to the central area, so that the tidal amplitude is reduced (Figure 8b). Correspondingly, the sand ridges are not well developed and the overall scale of the morphological pattern is reduced (Figure 8f). In run T2 with constant amplitude along the seaward boundary and the same phase lag as run REF, similar phenomena are observed: the tidal wave is less concentrated and the overall sand ridges are not well developed (Figure 8c and 8g). The tidal wave directly converges to the center of the embayment in run T3, since both the tidal amplitude and phase are uniform along the boundary (Figure 8d). This leads to the largest tidal amplitudes and the most pronouncedly developed sand ridges among all the scenarios (Figure 8d and 8h). However, these sand ridges are overall radially distributed, while the asymmetric pattern in reality is not reproduced (Figure 8h).

The amphidromic point shifts landward as the latitude decreases (i.e., the Coriolis Force decreases, Figure 8i). When the latitude is set 10°N or smaller (i.e., runs C2 and C3, Figure 8j and 8k), the amphidromic point vanishes, such that the tidal wave almost directly propagates across the embayment from south to north rather than converges to the central area. However, without the constraint of the amphidromic point, runs C2 and C3 are of larger tidal amplitude in the central area than run REF. Therefore, huge sand bodies instead of elongated sand ridges are formed in the north of the embayment, which are seemingly more similar as the real morphology of the RSRs (Figure 8m and 8n). It is worth noting that this can be an artefact due to model simplifications. Since the main directions of tidal currents do not orient to the center of the embayment, the sand bodies do not show radial pattern (Figure 8n).

An increase in bottom friction leads to decreases in the magnitudes of tidal amplitudes and tidal current velocities, and hence, a decrease in the sediment transport by tidal flow. Correspondingly, runs R2 and R3, which adopt relatively large friction coefficients, indicate smaller sizes of tidal sand ridges than those of run REF (Figure 9g and 9h). Moreover, varying the friction coefficient changes the location of the amphidromic point (Figure 9a-9d), such that the overall tidal wave system and its associated tidal current fields are affected. This further lead to several different characteristics of the sand ridges from run REF, such as the orientation and the bending (Figure 9e-9h). Notice that the Manning coefficient used in run R3 (0.025 $s/m^{1/3}$) is a common value adopted in coastal areas (e.g., Soulsby, 1997). However, much less and smaller sand ridges are reproduced. This leads to a hypothesis that the reduction of the hydraulic drag due to high sediment concentration is relevant for the formation of the RSRs (e.g., the drag reduction suggested by e.g., Winterwerp & Wang, 2013; Winterwerp et al., 2013).

Runs S1 and S2 indicate that both the sizes and the number of the simulated sand ridges decrease as the initial water depth increases (Figure 9l and 9m). This is consistent with the theory proposed by Off (1963) that the development of sand ridges favors abundant sediment availability. Run S3 also show smaller and less sand ridges than run REF (Figure 9n), even though their initial sediment availabilities are the same. Notice that the only difference between these two runs is that the initial bed slope of run S3 is smaller than run REF.

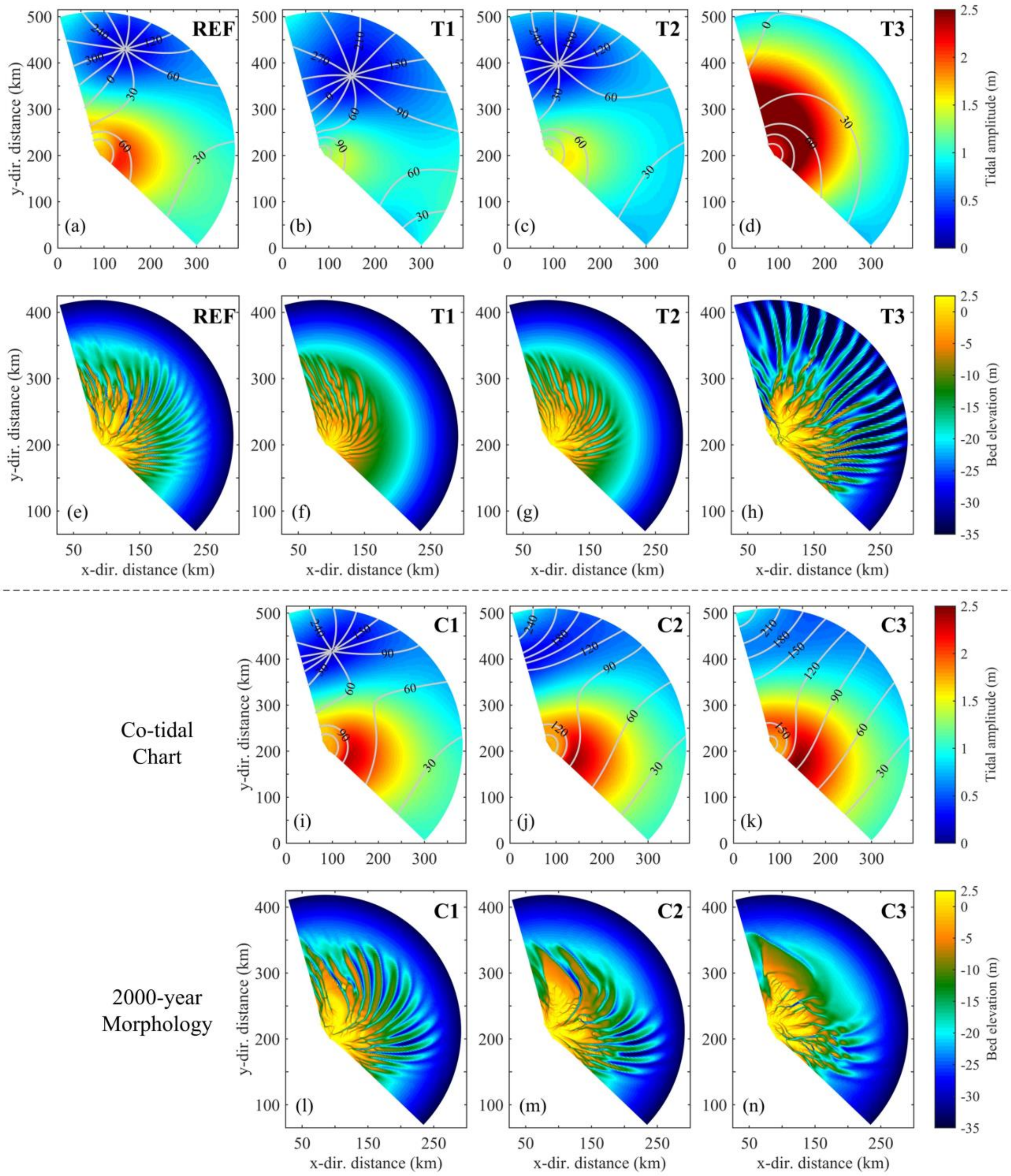

Figure 8. Comparison between run REF and runs T1-T3 and C1-C3 (Latitude = 20, 10, and 0 °N) on the co-tidal charts of the M_2 tidal constituent and the resultant morphologies at year 2000. The reader is referred to Table 1 for detailed model setup.

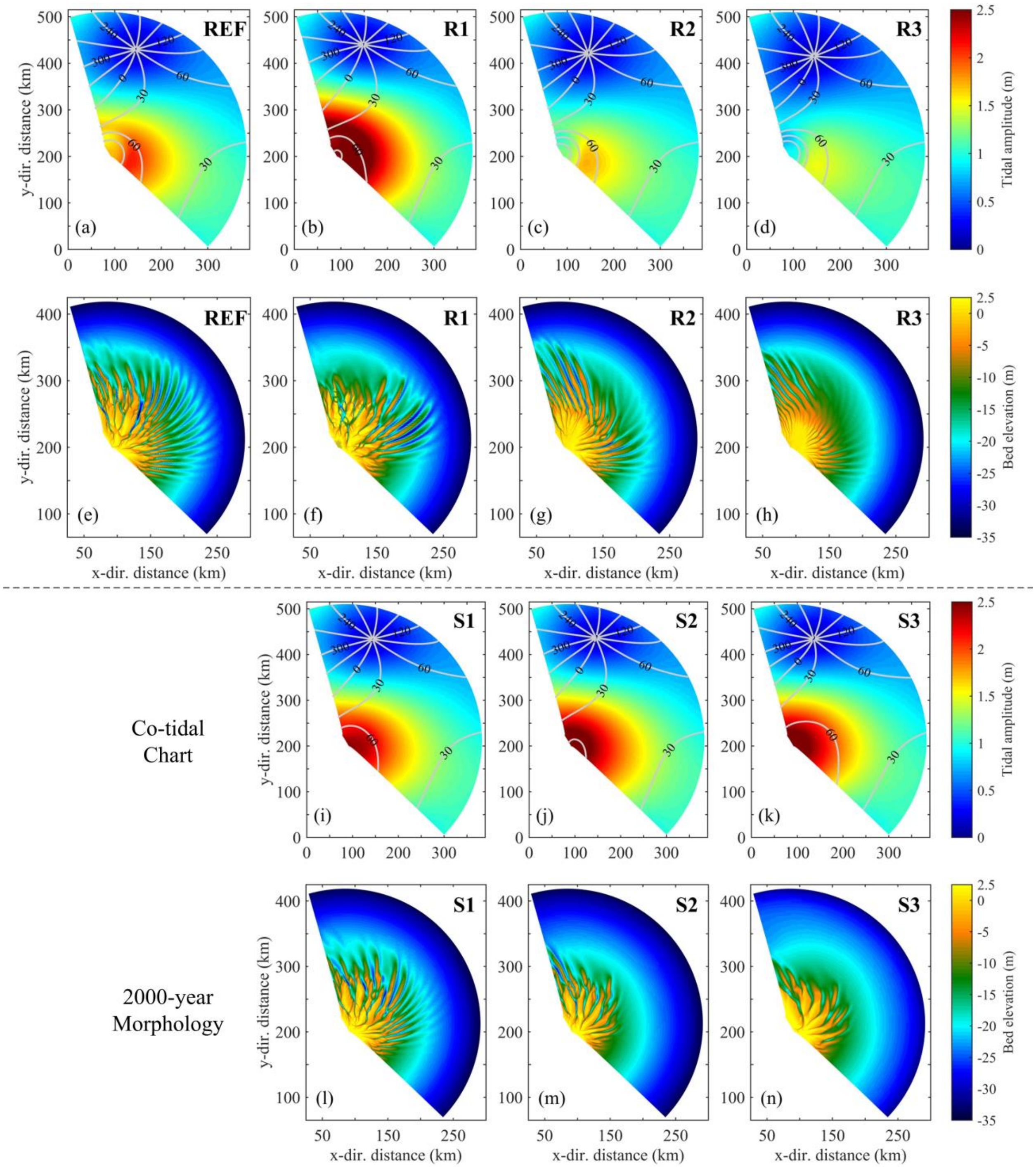

Figure 9. Comparison between run REF and runs R1-R3 (Manning coefficient = 0.01, 0.02 and 0.025 s/m$^{1/3}$) and S1-S3 (initial slope = 0.167, 0.153 and 0.13 ‰) on the co-tidal charts of the M$_2$ tidal constituent and the resultant morphologies at year 2000. The reader is referred to Table 1 for detailed model setup.

5 Discussion

5.1 Tidal regime, sediment availability and morphology

It has been suggested that the formation of the rotational tidal wave system in the north of the RSRs results from the constraint by the east coastline of China, such as the reflection of the tidal waves by Shandong Peninsula (Zhang et al., 1999). The constraint by the coastlines is not explicitly considered, but implicitly represented by the tidal boundary conditions in the present model (Figure 1b). As shown in runs T1 and T2, modifying the phases or the amplitudes along the seaward boundary shifts the position of the amphidromic point and further result in limited development of sand ridges. Moreover, the magnitude of the Coriolis Force, which is determined by the geographic latitude, also considerably affects the tidal wave systems and the formation of linear sand ridges (runs C1-C3, see Figure 8). Therefore, both the current tidal regime and the morphology of the RSRs depend on the east coastline of China as well as their specific geographic latitude.

Off (1963) suggested that the formation of sand ridges requires abundant sediment availability and strong current velocities. The effects of these two factors are represented in runs R1-R3 and S1-S3. The sediment transport capability of the tidal current is low in the runs with relatively large Manning coefficient (i.e., runs R2 and R3). Therefore, the resultant morphology indicates that both the development of sand ridges and the accretion of sediment in the central area are limited (Figure 9g and 9h). When simulating with low sediment availability (i.e., runs S1 and S2), large sand bodies are formed in the central area (Figure 9m and 9n), which is attributed to the convergence of the sediments driven by the tidal regime. However, the seaward extension of the sand ridges is limited. The comparison between runs S3 and REF further suggests that the sediments from outer sea is less efficient than those near the coast in forming of the RSRs. This result highlights the contribution of the littoral sediment transport to the development of the RSRs, such as the sediment supply from the Abandoned Yellow River Delta (as suggested by Wang et al., 2012b; Du, et al., 2018).

5.2 The asymmetric pattern of the RSRs

One of the typical characteristics of the RSRs is their asymmetric pattern showing larger northern sand ridges than the southern ones (Xu et al., 2016). Therefore, we are motivated to divide the computational domain into two halves from the middle radial line (see the black bold line in Figure 10a) and compare the planar areas of the sand ridges between the northern and southern parts (Figure 10b and 10c). We calculate the areas of the regions with water depth smaller than 5 m and 10 m respectively, for the consideration of the underwater sand ridges (see black and red contour lines in Figure 10a). The 10-m areas of run REF indicate a favorable distribution consistent with the real RSRs. Moreover, both the 5-m and the 10-m areas of run REF agree well with the real RSRs in magnitude. On the other hand, most sensitivity runs exhibit less consistency with the real RSRs, which highlights the rationality of the parameterizations selected in the run REF.

The major sediment source for the present-day RSRs came from the Abandoned Yellow River Delta in the north (Wang et al., 2012b; Du, et al., 2018). However, run REF starts from equally distributed sediment availability between the south and the north. As a result, the 5-m area of run REF appears to be smaller in the north than that in the south, which is inconsistent with the real RSRs. It thus can be inferred that the larger size of the northern sand ridges over the southern ones is partly attributed to the unequal sediment supply between the south and north. On the other hand, the consistency indicated by the distribution of the 10-m area of run REF confirms that the tidal regime over the RSRs does prefer a larger scale of the northern sand ridges than the southern ones.

When the rotational tidal wave vanishes and hence the entire embayment is dominated by the progressive tidal wave (run C3, Figure 8k), the advantage in size of the northern area over the southern one is amplified (Figures 8n, 10b and 10c). It can thus be inferred that the asymmetric pattern of the RSRs is promoted by the progressive tidal wave system in the south, while is restricted by the rotational one in the north. However, run C3 does not show elongated sand ridges as presented in the real RSRs. This implies that the RSRs cannot be formed without the convergence of the tidal waves to the central region.

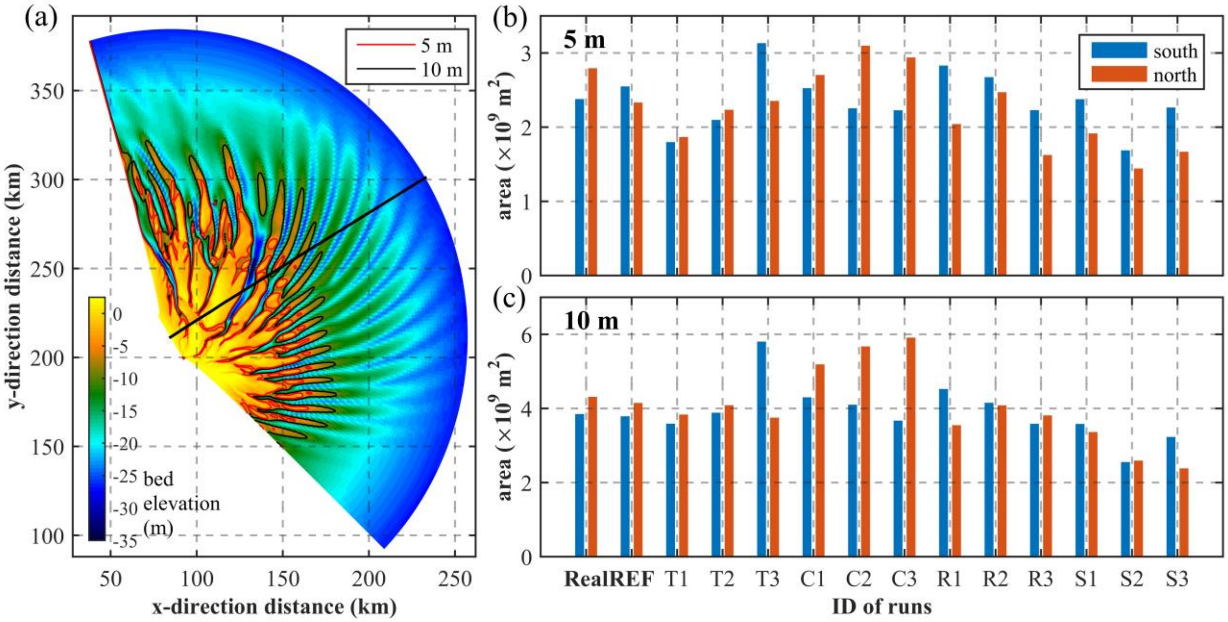

Figure 10. Comparison of the sand ridge areas between the real RSRs and the numerical runs. Panel (a) illustrates the method of calculating the areas of the southern and the northern sand ridges. The computational domain is divided into southern and northern halves from the middle radial line (see the black bold line). Panels (b) and (c) illustrate the planar areas enclosed by the 5-m and 10-m contour lines respectively.

5.3 Comparison with other sand ridges

Sand ridges over the world have a wide variety of forms due to the difference in hydrodynamic and sediment regimes (Dyer & Huntley, 1999; Off, 1963). However, the growth of sand ridges always requires mechanisms that drive the sediment flux to converge to the ridge crest and to diverge from the channels (e.g., Calvete et al., 2001; Huthnance, 1982a, 1982b). In this section, the mechanisms underlying the formation of the RSRs are compared with two typical categories of sand ridges, viz. the linear sand ridges (e.g., Hulscher et al., 1993) and the shoreface-connected sand ridges (e.g., Swift, 1975).

The linear sand ridges (also known as “linear sand banks”) generally occur in open shelf seas, where oscillatory tidal currents prevail. The offshore sand ridges lying on the seabed of the North Sea are representative linear sand ridges, of which the dimensions are typically tens of kilometers long, several kilometers broad and tens of meters high, and the directions slightly deviate from the principle axis of the tidal ellipses. It has been shown that linear sand ridges can be formed on a flat seabed under back-and-forth tidal movements and a faster-than-linear sediment transport rate related to the tidal current velocity (Hulscher, 1993; Huthnance, 1982a, 1982b). A possible mechanism leading to the positive feedback between the tidal currents and the erodible seabed has been given (Huthnance, 1982a): when the tidal current moves over a sand ridge, which cyclonically rotates with respect to the main current direction, an anticyclonic residual circulation can be formed around the sand ridge by both the Coriolis and frictional torques. Both torques vanish at the ridge crest, such that sediment can be accreted exactly on the ridge crest.

The shoreface-connect ridges are usually observed on storm-dominant inner shelves, where net longshore currents are strong. There are significant morphological differences between the storm-induced ridges (i.e., shoreface-connected ridges) and tide-induced ridges (i.e., tidal sand ridges). The spatial sizes of tide-induced ridges are evidently larger than those of the storm-induced ridges. On the other hand, the orientations of the tidal sand ridges are cyclonically rotated with respect to the major directions of the tidal currents, while the orientations of the shoreface-connected ridges are primarily related to the orientations of the coastlines. The formation of the shoreface-connected ridges has been attributed to the presences of the residual longshore currents and the transversal seabed slope in the inner shelf regions. Since the seabed is inclined, the Coriolis and frictional torques do not vanish as in the flat bed case. Therefore, the anticyclonic residual circulation is constrained to the coastlines (Calvete et al., 2001; Trowbridge, 1995).

The RSRs have been classified as tide-induced sand ridges formed during Holocene transgression (Wang et al., 1999; Yang, 1989). The stationary tidal wave system covering the South Yellow Sea, which has been suggested to be crucial for the formation of the RSRs, have been demonstrated to exist since the early Holocene (Wang et al., 2012b; Zhang et al., 1999). Although the ends of the RSRs connect to the Jiangsu Coast, which seems to be similar with the shoreface-connected ridges, the hydrodynamic regime and the spatial dimensions of the RSRs apparently differ from those of the shoreface-connected ridges (Wang et al., 2012b). Comparatively, acting as tidal sand ridges, the RSRs represent evidently tidal-sand-ridge characteristics. For example, the orientations of the sand ridges are anti-clockwise deviating from the major directions of the tidal currents (Figure 6) (Huthnance, 1982b), and the sizes of the seaward parts of the sand ridges are in accordance with tidal sand ridges (Wang et al., 1999).

On the other hand, the RSRs, which are situated at a semi-open sea area, differ from those tidal sand ridges observed in open sea regions (e.g., the North Sea) remarkably in terms of their fan-shaped spatial patterns and the huge exposed sand bodies in the central region (Figure 1b, see also Wang et al., 2012b). Controlled by both the land boundaries of China and Korea Peninsula and the slope of the South Yellow Sea Shelf, the tidal waves converge to the central region of the RSRs, and further produce the distinct fan-shaped tidal current field covering this region (Qian et al., 2015). Correspondingly, as shown in Figure 3a, the sand ridges which are formed in the early stage of the simulation, are radially distributed with their spacing diminishing landward, rather than approximately parallel to each other (as e.g., North Sea). As the sediments continuously accumulate in the central region owing to the landward residual movements of the sediment (Xing et al., 2012), the channels between the sand ridges are filled up, and hence the landward parts of the sand ridges merge and finally expose above the water surface (Figure 3b-3d). Overall, the RSRs are tide-induced sand ridges, while the morphological details are determined by their specific geographical position and the typically fan-shaped and converging tidal current fields.

5.4 Model capability and further research

The idealized model used in this study is developed based on the current tidal regime over the RSRs. This can help us to understand the relationship between the present tidal regime and morphology of the RSRs. However, this model does not aim to solve the controversy related to the origin of the RSRs (Li et al., 2001; Wang et al., 1999, 2012b), because the historical transitions of the coastline (e.g., the Jiangsu coastline) and the sediment source (e.g., the migration of the Yellow River mouth) (Wang et al., 2012b) remain elusive. Moreover, the current boundary condition implies no external sediment supply. Therefore, the model cannot be used to explain whether the sediments are from the Yangtze River (Milliman et al., 1986; Wang et al., 2012b) or the Yellow River (Lee & Chough, 1989; Saito & Yang, 1994; Zhou et al., 2014a). In addition to the simplifications related to the idealized modelling configurations, several processes that may play a certain role in shaping the RSRs are neglected and deserve further research:

(1) Only non-cohesive sand with a single representative grain size of 125 μm is considered in the model, while the RSRs are characterized by the presence of mixed grain sizes from very fine sand to fine sand (Zhang, 2012). The modelled sand ridges are more irregular than the simulated ones, because of the homogeneous bed sediment configurations used in the present model. On the other hand, processes such as sediment sorting and sand-mud interactions should be addressed in future research, which can play an important role on the morphodynamics evolution of sand ridges (De Swart et al., 2008; Vis-Star et al., 2009).

(2) Winds and waves are not considered. Previous studies have shown that waves affect the morphology of sand ridges (Calvete et al., 2002), particularly during low tidal levels (Reynaud et al., 1999). Similarly, storm surges have been found to effectively modify the morphologies of the sand ridges in the short term (Calvete et al., 2001), while tidal currents act as a restoring force in the long term (Zhang et al., 1999).

(3) The effect of long-term sea-level rise and riverine sediment supply are not considered in this model, although it has been argued that they played an important role in the evolution of tidal sand ridges (Gao, 2013; Uehara et al., 2002; Uehara & Saito, 2003; Wang et al., 2012b). Sensitivity simulations of Nnafie et al. (2014) indicate that a rising sea-level results in an increasing height of sand ridges. At the same time, their simulated results suggest that sand ridges do not form if the rate of the sea-level rise is too high, or if the initial depth of the inner shelf is too small. On the other hand, major rivers can affect the long-term morphodynamic evolution of the RSRs by favoring sediment deposition and modifying the local morphology near the outlet (Zhou et al., 2014b), which should be properly considered in further research.

(4) Extensive human interferences (e.g., the large-scale land reclamations along the Jiangsu Coast) have not been taken into account. According to Song et al. (2013), Tao et al. (2011, 2018), Wang et al. (2012a) and Zhang and Chen (2011), large-scale human activities can modify the

tidal wave systems and sediment transport patterns, hence have effects on the morphological development of the RSRs. The fact that these details concerning the hydrodynamic forcing and sediment transport processes can be ignored for simulating the formation of the RSRs and for reproducing their major characteristics reveals that the presented modeling has captured the major controlling factors for the development of the RSRs.

The neglected factors and processes also imply that not all the details of the morphology of the RSRs can be reproduced by the model. Albeit the simplified nature, the model can capture the main features of the RSRs and provide insights into the mechanisms underlying the formation of the RSRs.

6 Conclusions

An open source numerical model (Delft3D) is employed to investigate the morphodynamics of the RSRs of the southern Yellow Sea off the Jiangsu Coast, China. The computational domain is schematically fan-shaped and all the runs start from a smooth sloped bathymetry. The following conclusions can be drawn from this study:

(1) Close-to-reality sand ridge patterns can be modelled with the configurations consistent with the current tidal regime of the RSRs. The numerical results directly demonstrate that the formation and the maintenance of the current morphology of the RSRs are governed by the specific tidal regime over the southern Yellow Sea.

(2) The current distributions of the rotational and progressive tidal wave systems over the RSRs are important and are determined by the east coastline of China (e.g., the reflection of Shandong Peninsula) and the geographic latitudes (i.e., the Coriolis Force) of the RSRs.

(3) Deviation in the location of the amphidromic point can reduce the convergence of the tidal waves to the central area of the RSRs, such that the development of the sand ridges is limited.

(4) Sediment can accrete to the central area under the control of the current tidal regime, which results in the formation of the large sand bodies of the RSRs. However, the seaward extension of elongated sand ridges is subject to the availability of sediment supply.

(5) The asymmetric spatial patterns of the RSRs characterized by larger northern sand ridges than the southern ones are promoted by the progressive tidal waves and restricted by the rotational tidal waves.

(6) Insufficient sediment supply is another reason that the southern sand ridges are smaller than the northern ones in the RSRs.

Acknowledgments

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