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Sensitivity of growth characteristics of tidal sand ridges and long bed waves to formulations of bed shear stress, sand transport and tidal forcing: A numerical model study

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ABSTRACT

Tidal sand ridges and long bed waves are large-scale bedforms that are observed on continental shelves. They differ in their wavelength and in their orientation with respect to the principal direction of tidal currents. Previous studies indicate that tidal sand ridges appear in areas where tidal currents are above 0.5 m s^{-1}, while long bed waves occur in regions where the maximum tidal current velocity is slightly above the critical velocity for sand erosion and the current is elliptical. An idealized nonlinear numerical model was developed to improve the understanding of the initial formation of these bedforms. The model governs the feedbacks between tidally forced depth-averaged currents and the sandy bed on the outer shelf. The effects of different formulations of bed shear stress and sand transport, tidal ellipticity and different tidal constituents on the characteristics of these bedforms (growth rate, wavelength, orientation of the preferred bedforms) during their initial formation were examined systematically.

The results show that the formulations for bed shear stress and slope-induced sand transport are not critical for the initial formation of these bedforms. For tidal sand ridges, under rectilinear tidal currents, increasing the critical bed shear stress for sand erosion decreases the growth rate and the wavelength of the preferred bedforms significantly, while the orientation angle slightly decreases. The dependence of the growth rate, wavelength and the orientation of the preferred bedforms on the tidal ellipticity is non-monotonic. A decrease in tidal frequency results in preferred bedforms with larger wavelength and smaller orientation angle, while their growth rate hardly changes. In the case of joint diurnal and semidiurnal tides, or spring-neap tides, the characteristics of the bedforms are determined by the dominant tidal constituent. For long bed waves, the number of anticyclonically/cyclonically oriented bedforms with respect to the principal current direction increases as the ellipticity of the cyclonic/anticyclonic tidal currents increases. Besides, under anticyclonic tidal currents, the growth rate of cyclonically oriented long bed waves increases as the tidal ellipticity increases. The model was also used to provide a possible explanation for the fact that the Dutch Banks have a larger wavelength than that of the Flemish Banks in the North Sea.

1. Introduction

Tidal sand ridges are observed on the continental shelves of many shallow seas with sandy beds where the tidal current is larger than about 0.5 m s^{-1} (Off, 1963; Liu et al., 1998; Dyer and Huntley, 1999 and references therein). Examples are the shelves of the North Sea (Fig. 1) and the East China Sea. These rhythmic seabed features have a typical wavelength (the distance from crest to crest) of order 10 km and a height of order 10 m. Their crests are oriented slightly cyclonically (5° to 30°) with respect to the principal direction of the tidal current, and they evolve on a time scale of centuries. Until recently, it was stated that other offshore rhythmic bottom patterns had considerably smaller length scales than those of tidal sand ridges (sand waves: wavelength of about 500 m; megaripples: wavelength of about 10 m), and that the crests of these smaller scale bedforms were orthogonal to the direction of the principal current (McCave, 1979). This perspective changed when Knaapen et al. (2001) identified a new type of large-scale bedforms on the outer shelf of the southern North Sea (Fig. 1). These so-called long bed waves have wavelengths in the range of 1–3 km. Later, van Dijk et al. (2011) reported the presence of another patch of long bed waves north of Texel and Vlieland on the Dutch continental shelf. Besides their smaller spacings, long

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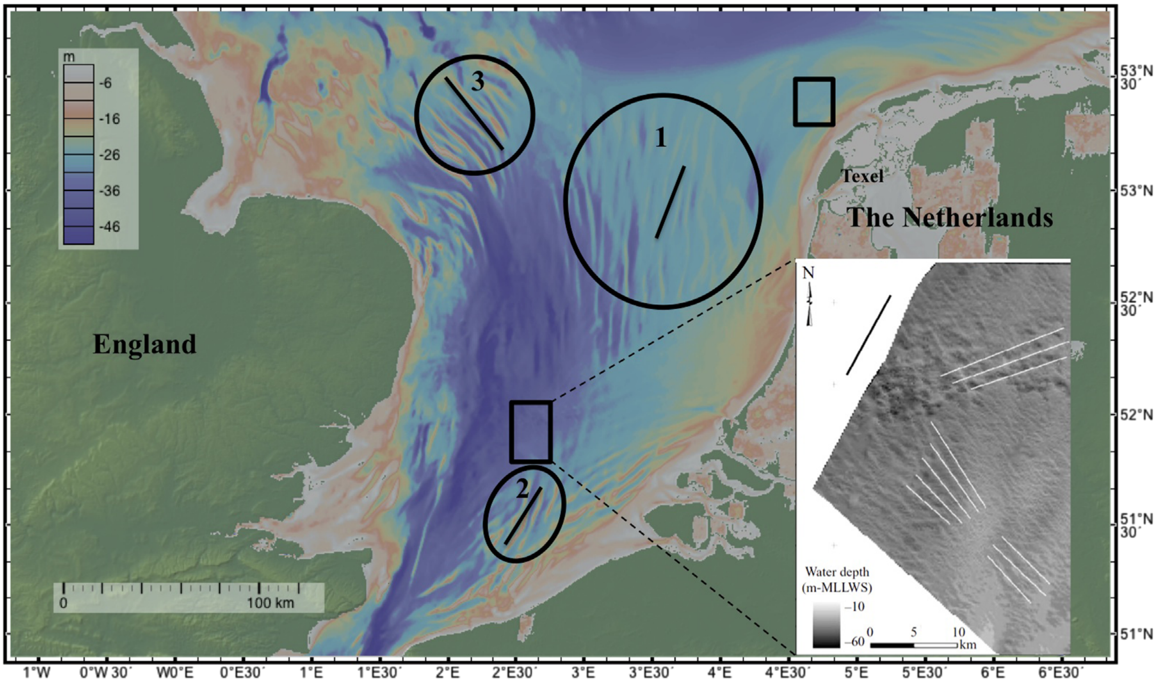

Fig. 1. Bathymetry of the southern North Sea. The black circles indicate the areas where tidal sand ridges are located: (1) the Dutch Banks, (2) the Flemish Banks, and (3) the Norfolk Banks. Black lines inside the circles qualitatively indicate the principal direction of tidal currents based on Davies and Furnes (1980). The rectangular boxes show the areas where long bed waves are observed. In the map on the bottom right, the crests of long bed waves are marked by white lines, and the black line indicates the principal current direction (from TNO, on courtesy of T. van Dijk). The main map is obtained using GeoMapApp (Ryan et al., 2009).

bed waves differ from tidal sand ridges in their orientation, i.e., their crests are around 60° cyclonically or 30° anticyclonically rotated with respect to the principal current direction, as is shown in the bottom map of Fig. 1. The formation time scale of long bed waves, from the perspective of available field data, is unclear. The large-scale bedforms mentioned above provide not only habitats for marine organisms, but also potential resources of sand for beach nourishment. Knowledge of these seabed features and their dynamics is important for the stability of underwater structures and strategic planning of marine sand mining (van Lancker et al., 2010).

The formation of tidal sand ridges has been explained as a free instability of the system that describes the interaction between the sandy sea bed and the tidal currents (Huthnance, 1982; Hulscher et al., 1993). For this, linear stability analysis was conducted, with which the evolution of infinitesimal bottom perturbations on an otherwise flat bed, subject to tide-induced sand transport, was quantified. It turns out that linear stability analysis yields a wavelength and an orientation of the preferred bedform that are in fair agreement with those of many ridges observed in the field.

In the above cited studies and in later work on the initial formation of tidal sand ridges (Carbajal and Montaño, 2001; Roos et al., 2001; Walgreen et al., 2002), several simplifications in the bed shear stress, tidal forcing and the sand transport were used. First, a linearized bed shear stress was employed. The sensitivity of the growth characteristics of tidal sand ridges to the formulation of bed shear stress has not been systematically investigated yet. Second, the tidal forcing employed was simple, i.e., only one tidal constituent was used or only rectilinear tidal currents were considered. Roos et al. (2001) and Walgreen et al. (2002) imposed several, yet rectilinear, tidal constituents (residual current, semi-diurnal lunar tide M_2 and quarter-diurnal tide M_4) to study the effect of tidal asymmetry on the characteristics of tidal sand ridges. In reality, tidal currents are elliptical rather than rectilinear. Moreover, they are composed of several other principal tidal constituents, such as the diurnal tide K_1 and the semidiurnal solar tide S_2, which together with M_2 give rise to a mixed semidiurnal tide and a spring-neap tide, respectively. The effects of mixed tides and spring-neap tides on the formation of tidal sand ridges have not been studied yet. Third, the sand transport formulations used in these studies were highly simplified, i.e., both the threshold of sand erosion (Miller et al., 1977 and references therein) and anisotropic bottom slope-induced sand transport (Talmon et al., 1995) were neglected.

With regard to long bed waves, their initial formation has only been studied in Blondeaux et al. (2009), in which a depth-averaged hydrodynamic model was employed. Using linear stability analysis, they demonstrated that under the conditions that the tidal currents are elliptical and the maximum velocity is just above the threshold for sand erosion, long bed waves form alongside tidal sand ridges. In contrast, if the tides are rectilinear or the velocity is stronger, only tidal sand ridges are observed.

The considerations above motivate the two aims in this study. The first aim is to quantify the dependence of growth rate, wavelength and crest orientation of large-scale offshore tidal bottom patterns on formulations for (1) bed shear stress, (2) sand transport (critical shear stress on/off, an-/isotropic slope-induced transport), and (3) tidal forcing (ellipticity, diurnal/mixed tides, spring-neap tides). The second one is to gain more detailed insight into the formation of long bed waves, specifically, to assess the importance of nonlinear bed shear stress, critical bed shear stress, anisotropic sand transport, tidal ellipticity and current velocity on the formation of long bed waves.

To fulfill these aims, a numerical morphodynamic model was developed, which governs feedbacks between tidally forced depth-averaged currents and the sandy bed on an open domain that represents the outer shelf. There are several advantages to use a numerical model, as is done in the present study. First, unlike linear stability models which all employ the rigid-lid approximation, the time-dependent surface elevation is maintained in the present model. Second, linear stability models require explicit linearization of all equations and in particular for sand transport,