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Review papers

Effects of sea level rise on the formation and drowning of shoreface-connected sand ridges, a model study

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ABSTRACT

Shoreface-connected sand ridges occur on many storm-dominated inner shelves. These rhythmic features have an along-shelf spacing of 2–10 km, a height of 1–12 m, they evolve on timescales of centuries and they migrate several meters per year. An idealized model is used to study the impact of sea level rise on the characteristics of the sand ridges during their initial and long-term evolution. Different scenarios (rates of sea level rise, geometry of inner shelf) are examined. Results show that with increasing sea level the height of sand ridges increases and their migration decreases until they eventually drown. This latter occurs when the near-bed wave orbital velocity drops below the critical velocity for erosion of sediment. In contrast, in the absence of sea level rise, the model simulates shoreface-connected sand ridges with constant heights and migration rates. Model results furthermore indicate that sand ridges do not form if the rate of sea level rise is too high, or if the initial depth of the inner shelf is too small. A larger transverse bottom slope enhances growth and height of sand ridges and they drown quicker. When shoreface retreat due to sea level rise is considered, new ridges form in the landward part of the inner shelf, while ridges on the antecedent part of the shelf become less active and ultimately drown. Only if sea level rise is accounted for, merging of ridges is reduced such that multiple ridges occur in the end state, thereby yielding a better agreement with observations. The physical mechanisms responsible for these findings are also explained.

Contents

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1. Introduction

On many sandy coastal shelves complex interactions occur between sea waves, currents and the bottom, resulting in a large variety of bedforms with a rhythmic structure. These bedforms have horizontal length scales ranging from a few decimeters (ripples) to several kilometers (sand ridges) (cf. Lobo et al., 2000). The present study focuses on shoreface-connected sand ridges (sfcr), which are observed on many storm-dominated inner shelves in depths of 10–20 m. These ridges are 2–10 km spaced apart and they are obliquely oriented with respect to the coastline. Their height is between 1 and 12 m, they evolve on a timescale of centuries and they migrate several meters per year along the coast. Examples of these ridges are observed on the Atlantic shelf of North America (Duane et al., 1972; Swift et al., 1978), Argentina and Brazil (Figueiredo Jr. et al., 1982; Parker et al., 1982) and the North Sea (Swift et al., 1978; Antia, 1996; van de Meene and van Rijn, 2000). Fig. 1 shows sfcr located on the Long Island continental shelf. Few observational data on the evolution of these bedforms is available. Observations by Swift et al. (1978) and Parker et al. (1982) indicate that sfcr evolve only during intense storms, during which the joint action of high waves and strong wind-driven currents causes significant erosion and transport of sediment. These storms occur several times a year, with durations ranging from hours to days.

Gaining fundamental knowledge about the processes that control the morphodynamics of sfcr is important because they influence (through refraction) wave patterns between the inner shelf and the shoreline (Hayes and Nairn, 2004). Any morphodynamic change in these bedforms will affect these wave patterns with potentially large consequences for the nearshore zone and beach. Moreover, recent studies suggested that these ridges may be an important source of sand for the nearshore zone, maintaining beach stability (Hapke et al., 2010; Schwab et al., 2000, 2013). Furthermore, movements of sfcr might damage pipelines and cables and might cause infilling of navigation channels, thereby hampering ship traffic.

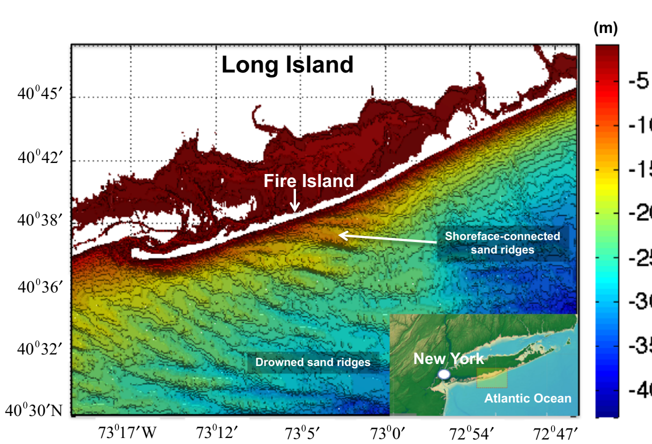

Fig. 1. Bathymetric map of the Long Island continental shelf. Active shoreface-connected sand ridges are located offshore of Fire Island in water depths of less than ~20 m and 'drowned' sand ridges occur beyond ~20 m water depth. Map based on data from NOAA (2013).

Several theories have been proposed for the formation and long-term evolution of sfcr (Dyer and Huntley, 1999; Hayes and Nairn, 2004). Duane et al. (1972) and Swift et al. (1973, 1978) concluded that these ridges were submarine features formed by storm-induced currents at the foot of the shoreface. As the latter underwent erosional shoreface retreat in response to sea level rise, the ridges were lowered on the shelf floor to form a field of isolated bedforms. McBride and Moslow (1991) presented a model whereby sand ridges evolve from ebb-tidal deltas as the latter became submerged due to the rising sea level and were reworked by waves and currents.

More recently, Trowbridge (1995), who analyzed a simple process-based model that governs hydrodynamics, sediment transport and bottom evolution on an inner shelf with a transverse bottom slope, demonstrated that sfcr can spontaneously develop as free instabilities of the coupled water-bottom system (morphodynamic self-organization). He found that the underlying physical mechanism was the offshore deflection of the flow over the shoals and the related sediment convergence in the offshore direction due to the transverse bottom slope. However, this model was not able to predict the correct time scales related to growth and migration of these bedforms. Calvete et al. (2001) resolved this problem by including both bedload and suspended load sediment transport and by adding depth-dependent stirring of sediment by waves. Later studies by Calvete and de Swart (2003), Vis-Star et al. (2008) and Nnafie et al. (2011) describe also the long-term evolution of sfcr towards finite heights.

A drawback of these process-based models is that they assume a constant mean sea level, albeit that in several studies (Swift and Field, 1981; Stubblefield et al., 1984; McBride and Moslow, 1991; Goff et al., 1999; Schwab et al., 2013) it is argued that sea level rise during the Holocene plays an important role in the evolution of these ridges. This is because the evolution time scale of sfcr is of the same order of magnitude as that of changes in the sea level. Beyond a certain water depth (typically ~20 m), waves only stir sediment from the bottom during extreme storms events (e.g. hurricane Sandy). Consequently, ridges in such areas become less active (Goff et al., 1999). Examples of these ridges (also called shoreface-detached or drowned ridges) are observed far offshore on the continental shelf of Long Island (Fig. 1) and also off the coast of Korea (Park et al., 2006). The former ridges are believed to have formed in the early Holocene when the rate of the relative sea level rise was ~3–5 mm/year (Rampino and Sanders, 1980; Engelhart et al., 2011a) and local depths were much smaller than present-day depths.

The specific objectives of the present work are twofold. First, to examine the impact of sea level rise on the characteristics (growth rate, migration speed, height) of the shoreface-connected sand