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Dynamics of shoreface-connected and inactive sand ridges on a shelf, Part 2: The role of sea level rise and associated changes in shelf geometry

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ABSTRACT

Many inner continental shelves are characterized by the presence of large rhythmic bedforms, such as shoreface-connected ridges and the more offshore located sand ridges, which have heights of several meters and are spaced several kilometers apart. This study focuses on explaining the observed orientation difference between shoreface-connected sand ridges and the more offshore located ridges. For this, an existing idealized morphodynamic model is used, but modified such that sea level rise simultaneously induces a steepening of the inner shelf and a retreating shoreface. Different settings (rate of sea level rise; landward depth of the inner shelf) are systematically explored. For each setting, the gross characteristics of ridges (growth rate, height, migration, orientation) during their initial formation and long-term evolution are quantified. Model results show that a rising sea level and associated shoreface retreat and shelf steepening lead to new ridges in the shallow area of the inner shelf, which remain active in time (i.e. ongoing growth and downstream migration in time). Old ridges that were already formed in the antecedent area of the shelf and which in the course of time experience deeper water become less active with the rising sea level. In the case that migration of the offshore parts of the ridges vanishes, these parts change orientation to become more shore-parallel compared with the active onshore parts of these ridges. In the case of small landward depths of the inner shelf and a decreasing rate of sea level rise, the active onshore parts migrate too fast, thereby causing the drowned offshore parts to detach and to become inactive. The characteristics of modeled shore-oblique shoreface-connected and more parallel offshore located ridges agree with those of observed sand ridges.

1. Introduction

The rise of mean sea level (MSL) during the Holocene has had a profound impact on the evolution of continental shelves and shores of coastal seas. This is evident from studies cf (Rampino and Sanders, 1980; Swift and Field, 1981; Stubblefield et al., 1984; Hapke et al., 2010; Schwab et al., 2013) in which coastal evolution was reconstructed from field data.

As argued by e.g. Duane et al. (1972) and McBride and Moslow (1991), sea level rise has also had a major impact on the evolution of shoreface-connected sand ridges (hereafter abbreviated as sfcr). These large-scale rhythmic bedforms have heights of up to 12 m, they are spaced apart by 2–10 km, they have a shore-oblique orientation, they evolve on a timescale of centuries and they migrate several meters per year along the coast. Sfcr occur on continental shelves where storms generate wave- and wind-induced currents (Duane et al., 1972; Swift et al., 1978). The continental shelves of the Mid Atlantic Bight are examples where sfcr occur. Fig. 1 shows sfcr on one of these shelves, viz. the shelf of Long Island off the coast of Fire Island. Field data (Swift et al., 1978; Niedoroda et al., 1984) indicate that sfcr undergo an intermittent process of development, which is associated with storm wave activity and storm-driven currents.

Understanding the dynamics of sfcr is of high interest, because they modify wind-generated surface waves, thereby causing a complex wave pattern that influences coastal sediment transport and related morphological changes (Hayes and Nairn, 2004). Any morphodynamic change in these bedforms may have large impact on beach erosion patterns. Also, recent studies hypothesize that these ridges may be an important source of sediment to maintain beach stability (Hapke et al., 2010; Schwab et al., 2013). Moreover,

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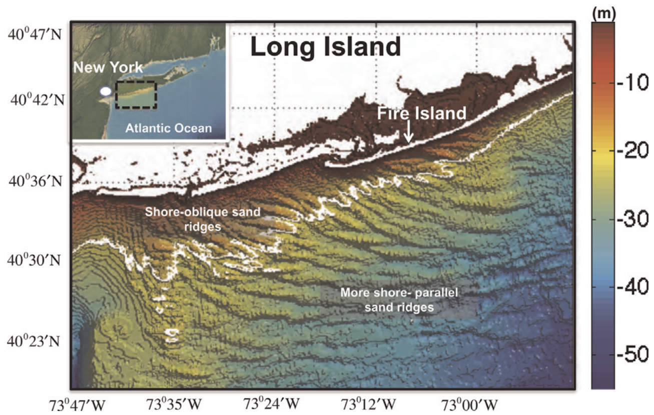

Fig. 1. Bathymetric map of the Long Island continental shelf. Inset on top left: large scale map. Active shore-oblique sand ridges (sfcr) are located in shallow waters offshore of Fire Island. Further seaward (indicated by the white 20 m-isobath), more shore-parallel sand ridges are observed. According to Goff et al. (1999), beyond a depth of ~ 20 m sand ridges become less active. Map based on data from NOAA (2013).

because of their proximity to the coast, the ridges are also considered as potential locations for future offshore wind mill park (Barrie and Conway, 2014).

Many studies focused on gaining fundamental insight into the formation and long-term evolution of sfcr (Dyer and Huntley, 1999; Hayes and Nairn, 2004). McClennen and McMaster (1971) proposed that they are relict features from before the Holocene transgression and became submerged during a period of sea level rise. Duane et al. (1972) and Swift et al. (1973, 1978) concluded that the sand ridges evolve from an initial sand source as the latter became submerged by the rising sea level and reworked by wave and currents. As the coast retreated in response to sea level rise, the ridges experienced larger water depth to become a field of isolated bedforms. McBride and Moslow (1991) postulated that one of the initial sand sources is a segment of an ebb-tidal delta abandoned by inlet migration. However, these models did not explain the shore-oblique orientation and the migration rates of sfcr.

The latter two aspects were explained by Trowbridge (1995), who analysed a simple process-based model and showed that bedforms resembling sfcr can form as a result of positive feedbacks between a storm-driven longshore flow and the sandy bed. The underlying mechanism is that a storm-driven flow moving over an upcurrent-rotated ridge (seaward end of the crest is shifted upstream with respect to its landward end) is deflected seaward, as a result of mass conservation. The offshore flow component and the related sand transport decrease with increasing distance to the coast, because of the larger depths, thereby resulting in deposition of sand. Thus, a crucial factor in this model is the occurrence of a transverse bottom slope. The offshore veering of the current over the ridges is supported by field data (Swift et al., 1978; Warner et al., 2014). A drawback of this model is that it was not able to simulate 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. More recent 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.

Although these models successfully describe many features of sfcr, they are not able to explain the fact that shoreface-connected sand ridges are in general more obliquely oriented with respect to the present shoreline, while the more offshore located sand ridges (sometimes also called shoreface-detached ridges, or 'drowned' ridges (Snedden et al., 2011) or moribund ridges (Goff and Duncan, 2012) are more parallel to the shoreline (Fig. 1).

Nnafie et al. (2014) used an idealized model to study the impact of sea level rise on the characteristics of sand ridges during their initial and long-term evolution. Different scenarios (rates of sea level rise, geometry of inner shelf) were examined. Their results showed that with increasing sea level the height of sand ridges increases and their migration decreases until they eventually drown. Furthermore, their model indicates that if shoreface retreat due to sea level rise is included, new ridges appear in the landward part of the inner shelf that remain active in time. Old ridges that were already formed in the antecedent part of the inner shelf, which gets located further offshore, become less active and drown in the course of time. However, the latter result was based on a rather simple scenario, in which geometrical parameters of the inner shelf (slope, width and water depth) have their present-day values, and the rate of sea level rise is 1 mm/yr. However, geological records (as e.g. presented in Cowell et al., 2003; van Heteren et al., 2011) reveal strong variations in width and steepness of the shelf and shoreface at time scales of millennia. These variations result from processes like flooding by sea level rise, sediment reworking by waves and tides and sand supply by rivers. Hutton et al. (2013) demonstrated that sea level rise, in combination with landward migration of the coastline, leads to shelf steepening due to a seaward increasing water loading on the shelf in the newly created accommodation space. Variations in width and slope of the shelf will have a strong impact on the evolution of sfcr, as Vis-Star et al. (2008) already demonstrated that steeper bottom slopes result in larger growth rates and smaller migration rates of ridges. Thus, when considering sea level rise, retreat and steepening of the inner shelf, new ridges that form on the landward side of the shelf will grow and migrate differently than ridges that formed on the antecedent part of the shelf.

Of primary interest in the present work is the fundamental understanding of the observed orientation difference between the shoreface-connected ridges and the more offshore located ridges. The key hypothesis in this study is that observed orientation difference between the shoreface-connected ridges and the more offshore located ridges is the consequence of their differential migration rates caused by the rising sea level and the retreating shoreface. To test this hypothesis, runs are conducted with the numerical morphodynamic model used by Nnafie et al. (2014) (called MORFO56), but modified by implementing an equilibrium beach profile that allows for a combined effect of shoreface retreat and shelf steepening due to sea level rise. The Long-Island inner shelf is taken as a study area where both shoreface-connected and the more offshore located sand ridges are observed (Fig. 1). With this model, first, the impact of a retreating shoreface and a changing inner shelf geometry (increasing width and slope) on the characteristics (growth rate, height, migration, orientation) of the sand ridges is investigated. Next, the sensitivity of model results to different rates of sea level rise and to different values of the landward water depth of the shelf is examined.

An overview of the model formulation, the setup of the model experiments and tools to analyze model output are given in Section 2. Results are presented in Section 3, followed by a discussion (Section 4) and the conclusions (Section 5).

2. Material and methods

2.1. Model formulation

The model governs feedbacks between waves, currents and bottom evolution on the inner and outer shelf. The inner shelf is the transition area between the relatively steeply sloping nearshore