On the genesis of new ridges at prograding coasts.

Génesis de nuevas crestas dunares en costas progradantes.

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Abstract: Prograding coasts usually feature the occurrence of multiple beach and/or foredune ridges whose record has been widely recognized to provide relevant information about changing meteocean conditions, sediment supply or sea-level oscillations. Yet, their formation, process of individualization and the mechanisms that determine their final configuration remain vague and under discussion. Progradation rate is the most commonly accepted factor regulating the final configuration and number of ridges while other factors as wind strength has been traditionally disregarded in this process. Here, we investigate the formation of multiple ridges across a prograding profile with relation to variable progradation rates and wind strength. For that, we use a process-based approach that integrates marine and aeolian processes by coupling XBeach and Duna models. Twenty-year simulations show successful generation of new ridges, whose number and shape appears modulated by the magnitude of the progradation rate and to a lesser degree by wind strength. Yet, simulations also suggest that marine processes are key on the process of dune ridge individualization, allowing or preventing the formation of a stable backshore or platform.

Key words: foredunes, beach ridges, dune vegetation, wind, waves.

Resumen: *Las costas progradantes generalmente presentan múltiples crestas de playa o dunares cuyo registro ha sido ampliamente reconocido por proporcionar información relevante sobre las condiciones ambientales en el pasado, el suministro de sedimentos o las oscilaciones del nivel del mar. Sin embargo, el conocimiento acerca de su formación, individualización y los mecanismos que determinan su configuración final permanecen vagos y bajo discusión. La tasa de progradación es el factor más comúnmente aceptado como principal regulador de la configuración final y el número de crestas. Otros factores como la fuerza del viento, se han tradicionalmente ignorado en este proceso. Aquí, investigamos la formación de múltiples crestas a través de un perfil progradante en relación con las tasas de progradación variable y la fuerza del viento. Para eso, utilizamos un enfoque basado en procesos donde procesos marinos y eólicos son integrados mediante el acoplamiento de los modelos XBeach y Duna. Las simulaciones de veinte años muestran la generación exitosa de nuevas crestas, cuyo número y forma aparecen modulados por la magnitud de la tasa de progradación y, en menor grado, por la fuerza del viento. Sin embargo, las simulaciones también sugieren que los procesos marinos son clave en el proceso de individualización de nuevas dunas, permitiendo o impidiendo la formación de una zona supramareal estable.*

Palabras clave*:* *dunas frontales, crestas de playa, vegetación dunar, viento, oleaje.*

INTRODUCTION

Prograding coasts are usually characterized by the presence of multiple beach and/or foredune ridges, whose record has been recognized to potentially provide relevant information about changing meteocean conditions, sediment supply or sea-level oscillations (Dougherty, 2018). The latter implies that these conditions control the final configuration of coastal plains and, thus, should determine the number, distribution and size of the observed features. However, caution must be taken when interpreting the record, as the actual mechanisms of ridge individualization and growth and their relation to the preceding driving conditions are not fully understood (Moore et al., 2016).

The generation of new ridges has been associated with the formation of new berms seawards from previously developed ridges, following an erosive event, whose crests are usually modified by aeolian processes after berms are colonised by plants (Bird, 1960; Davies, 1957; Dougherty, 2018). Alternative hypotheses reject the assumption that berms constitute the core of the ridges, due to their instability (Hesp, 1984; McKenzie, 1958) and suggest that ridges originate from the progressive morphological development from a ramp to a terrace and to a ridge foredune, as the beach is colonized by plant rhizomes and aeolian sand deposition takes place. In this line, Hesp (1984) found that the distance between the vegetation limit and the berm crest, as observed in one of the monitored sites, might remain constant. Yet, Psuty (1965) proposed the formation of ridges as a result of the combination of continued beach accretion under milder wave conditions and the vertical accretion of beach berms by the action of storm waves. According to the author, the continued beach accretion, eventually, separates the growing beach berm from the active beach profile, thus becoming a site of a succeeding ridge. Finally, hypothesis based on a process-based coastal dune model and assuming shape-fixed dune parameters, proposes internal feedback mechanisms as responsible for the occurrence and elevation of multiple foredunes (Moore et al., 2016). This suggests that the shape of new foredunes depends on the ratio between shoreline progradation rate and the rate at which dunes grow vertically, while the distance between ridges changes proportionally to the progradation rate. Therefore, this hypothesis assumes, on one hand, that the occurrence and size of ridges might not depend on external factors other than the sediment supply rate and, on the other, that dune ridges are generated and formed independently from the marine processes affecting the cross-shore profile.

The aforementioned suggests a certain degree of uncertainty, as the actual mechanisms responsible for the individualization and final configuration of beach and foredune ridges remain vague. This limits any interpretations from these types of geological archives and suggests limitations in understanding and predicting long-term coastal evolution. Here, we investigate the mechanisms of formation and development of multiple beach and dune ridges and the impact that changes in shoreline progradation rate and wind intensity may have on the configuration of ridges. To this aim, we use a process-based model approach, especially devoted to simulating the long-term evolution of sandy coasts. The approach integrates marine (storm and moderate conditions) and aeolian processes by coupling XBeach (Roelvink et al., 2009) and Duna models (Roelvink and Costas, 2019).

THE APPROACH

Modeling nearshore and aeolian processes

A hybrid model, XBeach-Duna (Roelvink and Costas, 2019), was used to simulate long-term (years to decades) coastal evolution of prograding, sandy coasts and to explore the mechanisms of ridge individualization and subsequent growth. The modeling approach couples beach and dune morphodynamics and can simulate the impacts of variable (intensity and direction) winds and waves over the coastal profile. The model accounts for the presence and growth of dune vegetation and its influence on aeolian dynamics and sand transport, including the most relevant factors limiting aeolian sediment transport, such as bed slope, moisture and grain-size variability. Regarding marine processes, the approach allows to simulate one of three options in XBeach (Roelvink et al., 2009, 2018) for wave incidence (i.e. stationary wave mode, surfbeat mode, or non-hydrostatic mode). This solution allows, for example, to simulate moderate wave conditions by applying the stationary wave mode, or to introduce the impact of storms through the surfbeat mode. In addition a longshore transport gradient, proportional to the longshore transport, is also included together with an approximation that nudges the beachface to a given 'bermslope'. Finally, the option of using the aeolian module, Duna, to simulate aeolian processes within the dune and the beach-dune transition for a fixed shoreline progradation rate is also possible.

Regarding the coupling of the two modules, forcing conditions are schematized into a series of marine (storm or moderate) and aeolian 'events', thus, specifying the order of conditions to be simulated and activating the corresponding (XBeach or Duna) model. The topography is updated after every event (time step).

Boundary and forcing conditions

In order to allow the formation of new ridges, we have forced the progradation of the system by introducing variable progradation rates. For that, we have selected a site where the present approach has been previously validated (Roelvink and Costas, 2019), focusing on a series of sensitivity analyses that evaluated the performance of the approach. The selected system is Faro Beach, located within the Ria Formosa barrier island system at the southern Portuguese coast (Ferreira et al., 2016). The cross-shore profile of the selected beach has been classified as reflective to intermediate, with the formation of nearshore bars that are rapidly welded to the emerged beach, as beach berms. The slope of the beach face is about 0.1 on average, varying from 0.06 to 0.15.

A time series of wind and wave conditions was defined by repeating the schematized conditions obtained by two years of observation (November 2009 to November 2011) over a total of twenty years. Wind data was available from the meteorological station at Faro Airport, located 2 km inland from the beach, in an area unobstructed from topographic barriers. Wave data was obtained from a detailed hindcast in the SIMAR database, provided by Puertos del Estado-AEMET, Spain (ref SIMAR-5017021, longitude: 8.08°W, latitude: 37.00°N). The winter of 2009-10 (first year) was especially stormy, with wind speeds up to 19 m/s and several events with significant wave height over 4 m and peak wave periods of 15-20 s. In order to simulate the 2-year period within reasonable runtime, schematized wind and wave climate were used (Roelvink and Costas, 2019). Sensitivity runs showed acceptable values for the morphological acceleration factor to be 5 for the surfbeat-mode storm simulations and 25 for the moderate conditions run in stationary mode. Wave heights lower than 2 m were considered to be 'moderate' while waves higher than 2 m were classified as 'storms' for this purpose. Only wind speeds exceeding the threshold for sand motion were considered in the record. Wave conditions cover 92% of the time-series (8% storms and 85% moderate) and wind speeds exceeding the critical value (aeolian transport events) occur only during 8% of the time.

Simulations

A series of simulations were carried out to test the generation and growth of beach ridges under the effect of variable sediment supply, using different longshore gradients and thus shoreline progradation rates (i.e. 10, 12, 15.5, 19 and 23 m/yr, Table 1), as well as the effect of wind strength, assuming an increase of 20% in magnitude (Table 1). In order to test if shoreline progradation is sufficient to generate ridges on its own, we tested three progradation rates (47, 72 and 97 m/yr) disregarding marine processes, using the stand-alone version of Duna (i.e. not coupled to XBeach).

	W = 1	**W = 1.2**
Longshore (LS) gradient	2 (10)	2 (10)
	3.5 (12)	3.5 (12)
	5 (15.5)	5 (15.5)
	6.5 (19)	6.5 (19)
	8 (23)	8 (23)

TABLA I. *Table 1. Considered values of wind speed multiplier (W) and the longshore gradient (LS; in 10-4 m-1) in coupled XBeach-Duna simulations. Values in parentheses are the related shoreline progradation rates (in m/yr).*

RESULTS

In general, simulations carried out for the particular case of Faro Beach show that the profile is mainly dominated by marine processes. Storm conditions appear to shape the upper profile by building beach berms upwards, while moderate conditions dominate the lower foreshore and inner nearshore. In fact, the seaward growth of the beach occurs mainly during winter and spring, while the width of the emerged beach decreases during summer, likely because of the advance of the dune vegetation cover. In the same line, it is worth noticing that most of aeolian transport events occur during winter. The transition between the beach and the dune appears as a diffuse zone, where marine and aeolian processes alternate, depending on the magnitude of the runup. When wave runup is high, it reaches the upper profile, contributing to the vertical accretion of beach berms and eventually overtopping incipient dunes.

The results show high variability with changes in sediment supply and wind strength. For low shoreline progradation rates (LS=2; Table 1), a new and unique foredune ridge is developed with a total of about 1.5 m of aeolian accumulation and a relatively wavy shape featured by small bumps after the merging of successive and overlapping foredunes (Fig. 1, left). As the shoreline progradation rate increases, the number of small ridges increases while their elevation decreases (Fig. 1).

Regarding the process of ridge isolation or formation of new ridges, simulations suggest that new ridges are only generated if wave impact allows the development of a stable backshore; a high and wide berm that becomes stable, rarely affected by runup and wave erosion, and where plants can eventually grow, fix the sediment and trap new aeolian sand blown inland. This suggests that topographical irregularities, associated with the growth of new berms, may play a key part in the individualization of new ridges, which appear favoured when wave conditions are dominated by less frequent storms. Conversely, the stormier conditions (1st schematized year) promote the vertical and inland accumulation of remobilized sand by marine processes to the upper beach or incipient dune surface.

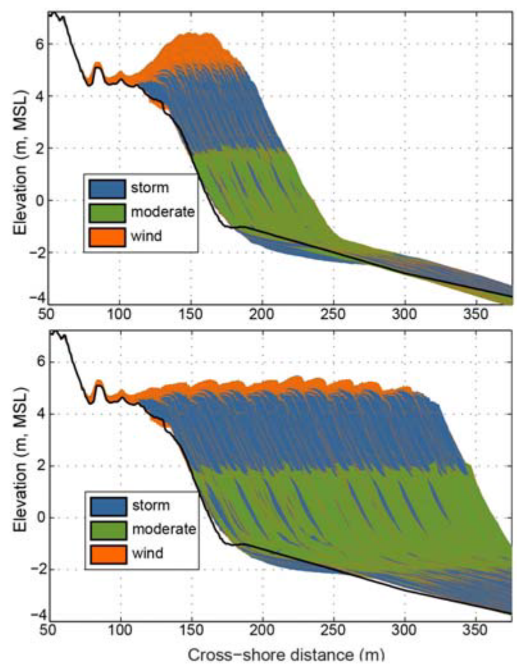

FIGURA 1. *Beach profile changes due to marine (storm-moderate) and aeolian (wind) processes during the simulation period, for runs with LS=2 (left) and LS=5 (right); W=1 in both runs.*

When the effect of wind strength is evaluated, the results show that stronger winds promote higher dunes, i.e. greater aeolian accumulation, accumulation that tends to happen inland from the incipient dune, which behaves as a weak barrier to the inland transference of aeolian sand by more stronger winds. Overall, the number of identified ridges increases linearly with LS gradient, with a new ridge formed, on average, per 4·10-5m-1 of LS gradient increase, while elevations decrease. The number of generated ridges slightly reduces if wind strength is intensified.

Finally, simulations using only the aeolian component (Duna) show that wind impact alone is unable to develop new ridges, regardless of sediment supply rates. The results show that, as sediment supply increases, the height of the dune decreases proportionally, but the result is a complex feature with multiple overlapping layers of aeolian sand.

DISCUSSION AND CONCLUSIONS

The numerical investigation presented shows that the modelling approach is capable of successfully generating distinct ridge patterns (shape and number) under variable shoreline progradation rate and wind intensity, in agreement with observations and hypotheses on the genesis and evolution of such landforms. Under conditions of low progradation rates, aeolian sedimentation tends to form a unique and complex feature that results from the coalescence of dune deposits through time. In addition, we have observed that wind strength controls the position of maximum aeolian accretion, moving it inland from the incipient dunes during strong wind events overcoming the deceleration effect caused by the vegetation.

Previous work, modelling dune ridge generation using geometrically fixed criteria, postulate that the only condition dictating the generation of new ridges is the magnitude of shoreline progradation relative to the lateral growth rate of the dune ridge (Moore et al., 2016). However, the results presented here suggest that the genesis of new ridges depends on the marine conditions shaping the transition between the beach and the dune within the cross-shore profile. In fact, the pattern of new ridge formation, depicted by our simulations, is in line with the sequence of new ridge formation detailed from field observations by Psuty (1966). According to the author, initial conditions are typically characterized by a pre-storm profile, whose foreshore is partially eroded under the impact of storm conditions. In addition, storms are responsible for transporting a small part of the remobilized sand inland and depositing it on top of the former berm. The sequence suggests that the eventual shift to milder conditions might contribute to recover the foreshore profile. However, this process may alternate with the impact of storms, which transfer sand upwards to the inland berm, inducing its widening and vertical aggradation. Under progradation conditions, this berm can move inland, beyond the reach of subsequent storms and eventually get isolated from the active beach profile. The sequence described by Psuty (1966) is successfully reproduced by our simulations that, in addition, document the subsequent colonization of the inactive berm or backshore by plants that may start trapping aeolian sand. Yet, if progradation is not fast enough, or if storms are strong enough to induce high wave runup, this incipient feature can be buried by marine transported sand, contributing to the vertical growth of the initial stages of a foredune ridge.

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