A Conceptual Model for Dune Morphodynamics of the Corralejo Dune System, Fuerteventura, Spain.

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ABSTRACT

The Corralejo dune system in Fuerteventura in the Canary Islands (Spain) is an aeolian landscape whose genesis and evolution has commonly been associated with a traditional input-output model by which sediments entered from northern beaches and accumulation occurred in the southernmost (land-locked) sections of the dune field. Satellite images as well as aerial photographic evidence over the last 60 years, however, shows that the evolution of the dunes may reflect a more complex scenario in which under current settings and orientation of the coast, a sediment leakage back into the southern coastal environment is occurring. Under these circumstances, longshore currents can then transport this sediment back along the coast toward its initial landfall location, thus re-joining a sediment-recycling pathway. Human occupation of such a system can sometimes interrupt this pathway, seriously impinging its functionality. Better understanding of its morphodynamics at this scale will help negate these impacts.

In this paper, we present a conceptual model for the functioning of the beach and dune systems of Corralejo, purporting that southbound winds and wave fields induce large-scale refraction patterns that in turn generate an intense increase in wave-induced radiation stress at the south tip of the dune field. The work highlights the need to further our knowledge of dune field dynamics in arid coastal settings, integrating aeolian and wave processes in order to promote appropriate science-led decision making for both environmental management and spatial planning.

ADDITIONAL INDEX WORDS: Dune Morphodynamics, Corralejo, Littoral Cells.

INTRODUCTION

Our understanding of coastal dune dynamics in arid areas remains relatively limited compared to those studied in tropical or temperate regions. Increased aridity in many areas worldwide however, gives added impetus to furthering our knowledge of the functionality of these systems.

Traditionally, an arid island system containing mobile dunes travelling in a mono-direction is viewed as a simple output of sediment. The throughput of sand through such systems is driven by local climate and sediment availability. Connecting this type of terrestrial system to the marine environment has proved elusive given the complexities of linking the two together. Since the terrestrial sediment supply is marine supplied in many cases we must therefore incorporate the two for full comprehension of the sedimentary system.

The polygenic sedimentary system of Fuerteventura, Canary Islands in Spain has been active over a number of periods during the Quaternary, as shown by the analysis from eolianite deposits (Criado et al., 2004; Criado et al., 2011). Aeolian sediments are mainly deposited on volcanic rocks, formed during the reactivation stage of this volcanic island and characterised by strombolian eruptions younger than 1.7 M yr. To the west and south, these volcanic rocks form the border, while to the north and east, the dune system is limited by the coastline. This is evidenced by the presence of alternating small coves and long sandy beaches, interrupted at times by Quaternary basalt flows forming low rocky coasts and occasionally, metric sized cliffs.

According to Fernández-Cabrera et al. (2011), the theoretical model that explains how the morpho-sedimentary system works implies that sediments are transported by waves from the north and northeastern shelf, forming a N-S littoral drift, given the inferred longshore direction moving sediments under the dominant trade winds. However, seasonal winds from the southwest could help slow the dominant southern dune migration.
The Corralejo dune system is a North-South aligned aeolian landscape closely associated with a nearshore system. Previous work has described the site in detail but has not taken full cognisance of the relationships between the terrestrial dune and nearshore environments. This has resulted in morphodynamic descriptions that cannot fully elucidate the long-term dynamics of the system. Satellite and aerial photographic evidence over the last 60 years shows that the evolution of the dunes may reflect a more complex scenario in which a sediment leakage back into the submerged coastal environment is somehow occurring, completing a recirculation cell that may represent a feedback in the system.

Under these circumstances, longshore currents can transport sediment back along the coast toward its initial landfall location, thus re-joining a sediment-recycling pathway. Human occupation of such a sedimentary recycling system can interrupt this pathway. Using available evidence from remote sensing and nearshore wave modelling analysis, we present a conceptual model for the functioning of the beach and dune systems of Corralejo.

STUDY AREA

The dune field in Fuerteventura, the Canary Islands (Spain) occupies an area of 18.35 km$^2$ of the northeastern corner in the island of Fuerteventura (Canary Islands, Spain) (Figure 1). It is one of the few active dune systems in the archipelago, and the only one on the island of Fuerteventura where the dunes have developed significantly (Hernández-Calvento et al., 2009, Alonso et al., 2011).

Climatic conditions are arid with an average annual rainfall of around 85 mm, with precipitation concentrated in winter months (October – February). The dominant wind regime has strong components from the North (25%) and North West (16%). Dune vegetation is dominated by bushes, which favours the formation of hummocky dunes. In areas of active aeolian processes, communities of *Euphorbia paralias*, *Ononis natrix* and *Launaea arborescens* can be found, however, inland in more stabilised areas where the sandy deposits are thinner, *Salsola vermiculata* predominates, while *Launaea arborescens* occupies the lower parts containing established ravines (Fernández-Cabrera et al., 2011).

Trade winds are dominant in the area, although slightly modified due to the presence of the nearby Lanzarote Island and Lobos Islet. Wind data from the Spanish Meteorological Agency recorded at the station located at Corralejo port shows that dominant directions are from North and North-NorthWest and represent the highest daily wind velocities (Figure 1b).

The sand composition in the system is mostly organic, containing nearly 90% carbonate bioclasts, while lithoclasts are around 10% (Criado et al., 2004; DGC, 2006, Gutierrez-Elorza et al., 2011). This indicates that the marine environment is the main source area of these sediments, and therefore the sand originates from the coastal shelf in the north and northeast of the island. In terms of terrestrial dune deposits, there is a noticeable difference between the northern and southern parts of this system. The northern sector is dominated by sand sheets and semi-established sand dunes, while in the southern sectors, free dunes, such as barchans or barchanoid ridges of around 3 metres high are common. Wave conditions around the coast of Fuerteventura are characterised by wave records maintained by the Spanish Port Authority in collaboration with the State Meteorology Agency. Offshore waves (figure 1c) are dominated by swell from the North and Northeast (depending on seasons) with peak periods of 8 seconds over 30% of the year and significant wave heights of 1.5 to 2 meters (over 35% of year), as indicated over a 1995-2012 time series reported from Spanish Port Authority (2012).

Wave geometry is based on WANA and SIMAR 44 model outputs, which are calculated from wind data (from atmospheric
models) and the wave propagation model WAM. The island is subject to an oceanographic southerly flow associated with the Canary Current with high wave energy found largely along the northerly and eastern coastline.

**METHODS**

**Remote sensing**

Using historical and contemporary aerial imagery covering a period of 60 years, a chronology of changes has been examined. Orthophotography with four spectral bands (visible and near infrared) and LiDAR, were acquired by the University of Las Palmas de Gran Canaria (ULPGC).

Three aerial photographs (scale 1:7000) covering the northern sector of the study area date from 1969. These are used as reference points to examine human impacts on the system, and show changes in urban development over this time. Aerial photography from the 1980s was also used to provide pre-urbanisation information. The latter has been used to compare the situation at two scales: 1:25000 (the mid north of the system) and 1:7000 (the three northern most areas) corresponding to the period just before urban development in the 1980s, and using the digital image as the current reference. All photographs were rectified and four distinct zones established: i) mobile areas; ii) stabilised or semi stabilised areas; iii) urban areas and infrastructures and iv) others (agricultural or abandoned areas).

**Near shore wave modeling**

A numerical third generation wave propagation model was used to simulate the modal nearshore wave fields at the site. Deep water waves were propagated into the shallow domain of the surf zone using SWAN (Simulating Waves Nearshore, Booij et al, 1996). A large-scale grid was produced interpolating data from the 2005 bathymetric chart and parametric wave data input was utilised from the WANA Puertos del Estado wave data network. Data to define wave input was taken for the deepwater boundary from WANA and SIMAR 44 parametric data (same geographical location).

Wave parameters for deep-water were taken from node WANA1027016/SIMAR441027016 calculated at 3 hour intervals (from wind) at location 3.25° W; 29.00° N, to the east of the island of Lanzarote and east of Fuerteventura. The initial model set-up included a wave direction from the NNE, significant wave heights of 1.5 metres and a mean peak period of 8.0 seconds. An 8.0 ms⁻¹ wind field was applied for the entire computational wave field in the prevailing direction (NNE at sea). The wave model was run in stationary mode to provide output over the entire field on a regular grid of 250 by 250 points (50 m resolution). This is estimated to provide sufficient information for the surf zone in the area of interest. Specific output was produced including wave direction, wave orbital velocities and wave-induced stress. The longshore component of the wave force was also produced to examine potential littoral cell development in both N and S directions.

Tabulated output data from SWAN is presented in table 1 to illustrate the directional component of wave-induced stress at key locations that may indicate northbound sediment transport.

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth (m)</th>
<th>Wave Energy Dir (Deg*)</th>
<th>TP (sec)</th>
<th>Wave Stress to North (N m⁻²)</th>
<th>Orbital Vel. (m sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.25</td>
<td>222.55</td>
<td>8.03</td>
<td>0.57</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>6.07</td>
<td>219.42</td>
<td>8.04</td>
<td>0.92</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>7.82</td>
<td>218.70</td>
<td>7.97</td>
<td>0.90</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>8.01</td>
<td>215.07</td>
<td>8.03</td>
<td>0.95</td>
<td>0.36</td>
</tr>
<tr>
<td>5</td>
<td>9.34</td>
<td>227.37</td>
<td>8.05</td>
<td>0.95</td>
<td>0.49</td>
</tr>
<tr>
<td>6</td>
<td>11.16</td>
<td>216.62</td>
<td>8.03</td>
<td>0.93</td>
<td>0.29</td>
</tr>
</tbody>
</table>

*direction where waves travel to (0 is positive X axis; i.e waves travel to East and 180 would imply travel to West)

Wave propagation simulations carried out in the conditions described above (methods) provided a wide range of output parameters to characterise the eastern nearshore zone of the Corralejo dune field. The main parameters used for the development of the conceptual model include the wave orbital velocities, wave height and the longshore directional component of wave induced stress. In terms of orbital velocities the intense
refraction observed in the simulation results provides wave induced speeds above 0.6 ms\(^{-1}\) in the nearshore. These velocities occur at depths within wave base (5.3 m) but hotspots appear to concentrate in the southern edge of the dune field with values above 1 ms\(^{-1}\) in localised areas (see figure 3B). These spots coincide with evidence of sediment input from the actual dune field spilling onto the shoreface.

**RESULTS**

Dune crests are shown to progress in a general south to southeast direction. Evidence of this advance is coupled with the potential starvation of sediment input due to urban development in the northern section of the system (town of Corralejo), which would imply that mobile dune fronts are carrying the sediments southwards. Analyses of images from 1969 and 1982 indicate the presence of distinctive bands of mobile sands extending from the north coast of the dune field to south. The remaining areas are characterised by the presence of sands largely stabilised by the presence of shrubs. However, south of this area, mobile sand zones are prevalent in places. Finally, in the southern reaches of the dune field, it is possible to identify dune crests that rotate to a shoreward direction.

From the point of view of the sedimentary dynamics, the main changes between 1982 and 2009 are a noted increase in the stability of the sands, especially in inland areas, and the reduction of the extent of mobile sand. However, the main change is at the extensive development of the urbanisation to the detriment of other coverage, such as agriculture (table 2).

<table>
<thead>
<tr>
<th>Classes (%)</th>
<th>1982</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile areas</td>
<td>29.81</td>
<td>19.31</td>
</tr>
<tr>
<td>Stabilized or semi stabilized areas</td>
<td>41.27</td>
<td>44.27</td>
</tr>
<tr>
<td>Urban areas and infrastructures</td>
<td>9.48</td>
<td>31.76</td>
</tr>
<tr>
<td>Other</td>
<td>19.44</td>
<td>4.66</td>
</tr>
</tbody>
</table>

Wave induced stress has a significant directional component which is most frequently showing a south-southwest component, as is to be expected given the initial NNE wave approach). However, northbound trends can be seen even under NNE propagating wave fields. This takes place in the same locations where hotspots for orbital velocities where accounted for, thus suggesting the wave activity has a great potential after intense refraction to carry sediments north. Values for stress of 1 Nm\(^{-1}\) can be found on the gridded results (see table 1 for sample force values in the nearshore) in those locations which coincide again where sediment input from dune fields enters the sea. Significant wave heights after initial conditions of 1.8 m in deepwater, show a spatial pattern indicating that the island of Lobo induces significant localised refraction patterns. This helps generate key energy shadows to the lee of the island and forces energy advection all along the eastern shores where dune fields predominate (Figure 3A). In the zones where wave orbital velocities show hotspots, wave heights are increased possibly from shoaling and refraction over the steep nearshore.

**DISCUSSION AND CONCLUSIONS**

Although the aerial photographic analyses document the recent evolution of the dune system, which has been linked solely to urban development of the northern most coastlines, many references indicate that the urbanisation process developed at the north of the dune field has forced a decline in the input of the sediment to the dune field. Dune crests at various dates (DGC, 2006) showed that mobile dunes progress southwards at an accelerated pace (Figure 2), introducing terminal dynamics in it’s evolution. This assumption is supported in the Master Plan for Use and Management (Plan Rector de Uso y Gestión) of the Natural Park Dunes of Corralejo (GOBCAN, 2006). Dirección General de Costas (2006) and Alonso et al. (2011) emphasise a key issue is the lack of sand in the submerged shelf located at the north of the dune field, perhaps due to the extraction of aggregates which may have had more negative effects on the sedimentary dynamic than the urbanisation process itself.

**Proposed Conceptual Model**

The southerly movement of sediment through dune migration is indicative of the strong sand-transporting wind regime operating from the North and North-NorthWest sectors in land. These winds dominate the terrestrial component of the system pushing sand from the north shoreline to eventually emerge at the southern shoreline around the southernmost edge of the Corralejo dune field (indicated as a box in the figures). Sand dunes appear to have been severely slowed or halted in the northern sectors of the site, due largely to urban development arresting natural dune movement southward. In the mid- to southern sectors of the dune corridor defined in Fig.1, however, dune migration is still very much active where no urbanisation has taken place. In the southern tip of this zone, dunes cascade over and into the rocky coastline to rejoin the marine environment.
The southerly input of sand to the nearshore zone represents a dune depositional area where wave processes, generated by significant refraction patterns emerging from the offshore island of Lobos, can move sediment into the nearshore zone. The conceptual model presented here purports that offshore waves generated under NNE conditions show significant wave-induced stresses on the seabed and are directional component suggesting a northbound littoral drift. This is induced by the intense refraction and diffraction introduced by the refracted wave fields off the island of Lobos and local bathymetry. Orbital velocities from wave simulations indicate above threshold velocities for medium sized sand, such as those documented in the area (average of 0.225 mm). Finer sediment inputted from the aeolian system also adds to the fine fraction found in the nearshore, facilitating enhanced wave-induced transport in the surf zone. We conceptualise that a nearshore transport belt, generated by the combination of local wind generated waves (from NNW) and NNE swell, exists along the eastern shore to help transport sand up toward Corralejo. Refracted waves from the northeast then begin to dominate again.
on the northern shores at Corralejo to return the sediment back onto the beach again. Wave lain sediment then eventually returns to the back beach and dune system to begin a recycle through the system again (see Figure 2 B).

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LITERATURE CITED


