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Downwind effects on an arid dunefield from an evolving urbanised area

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ABSTRACT

The impacts of urbanised zones on aeolian dynamics are little understood, particularly within arid areas. This study examines the large-scale influence of a growing tourist resort in Gran Canaria Island, Spain, on the sedimentary dynamics of an arid dunefield. Direct downwind effects from the urban area on the dune field surface are modelled for pre-growth and post-growth phases of the urban development. The geomorphological changes observed in the area stretching from the shoreline to the inland transgressive dune field were documented through aerial photographic and LiDAR evidence. Impacts of the urban growth on airflow, as well as those induced by tourists in the upper beach zone (de-vegetation), are examined through analysis of topographic changes. These impacts on the system are shown to have been synergistic in driving the development of a composite dune ridge, formed by the coalescence of smaller dunes into a distinctive aeolian accumulation ridge.

1. Introduction

The conservation status of sandy coasts is varied, but in general, there is a direct relationship between human impacts and the degree of vulnerability and alteration it undergoes (Brown and McLachlan, 2002; Martínez et al., 2006). Tourism is a major factor in any adverse impacts on these systems and, paradoxically, the changes it causes can affect its own development (Gössling, 2002). In general, we can classify these impacts into three main groupings: the occupation of space by buildings and infrastructures, the development of recreational activities, and the implementation of management measures (van der Meulen and Salman, 1996; Alonso et al., 2002; Tzatzanis et al., 2003; Łabuz, 2004; Roig i Munar et al., 2006; Grunewald, 2006; Nordstrom et al., 2007).

Relatively few studies have addressed dunefield changes induced by human activities, although in the last decade much more work has emerged on this topic (e.g. El Banna and Frihy, 2009; Kiss et al., 2009; Bochev-van der Burgh et al., 2011; Jackson and Nordstrom, 2011). The main consequential impacts in these systems appear to be from changes in land use (Kutiel et al., 2004; Levin and Ben-Dor, 2004; Buynevich et al., 2007, 2010) and recreational activities (Andersen, 1995; Sherman and Nordstrom, 1994; Kutiel, 2001; Lemauviel and Rozé, 2003; Talora et al., 2007; Cabrera-Vega et al., 2013a). Research has therefore focused on analysing the impacts generated by related developments associated from these, to include beach infrastructure and management activities (Bauer, 2009; Jackson and Nordstrom, 2011).

Specifically, the disruption of aeolian landscapes through the presence of human infrastructure is related to the alteration of aeolian system dynamics and the subsequent transport and sedimentation patterns (Tsoar and Blumberg, 2002; Wiedemann and Pickart, 2004; Hilton et al., 2006). Jackson and Nordstrom (2011) highlight a number of key human activities that can induce these modifications: (1) building structures, (2) extracting resources (sand mining, deforestation, grazing), (3) walking or driving on dune systems, (4) modifying surface to accommodate recreation, (5) redistributing sediments to remove storm deposits and (6) planting vegetation to increase levels of protection. This results in three main consequences: (i) the inhibition of dune formation, (ii) the creation of new landforms, different than those generated from natural conditions, and (iii) the alteration of the characteristics and dynamics of the pre-existing dunes (Nordstrom, 1994, 2000; Nordstrom et al., 2002).

Most coastal dune impact studies have been carried out on temperate systems and have focused largely on their foredunes zone as well as their general system dynamics. Arid coastal dune systems

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on the other hand have received much less attention, particularly in terms of resulting geomorphological consequences as a result of human activities (Cabrera-Vega et al., 2013a). It is anticipated, however, that impacted systems will become more apparent in the future, if tourism pressure is maintained and/or proliferates in arid and tourist-popular areas. A recent study by Cabrera-Vega et al. (2013a) examined how human activities affected aeolian landforms in three dune systems of the Canary Islands, Spain from the 1960s to the present. In this study, the authors identified a landform known as an "accumulation ridge", located at a location south of El Inglés Beach, in the dunefield of Maspalomas, Gran Canaria Island (Fig. 1). They proposed that the genesis of this landform was through a combination of two mechanisms: (i) the development of a tourist resort, and (ii) the impact users (tourists) on the actual beach-dune system.

Here, we examine this human-induced aeolian landform further, highlighting its origin and development. We investigate changes in the nature and location of aeolian landforms pre-(1961) and in post-tourist phases.

2. Study area

The Maspalomas dune system is located in the southern section of the island of Gran Canaria (Canary Islands, Spain; Figs. 1 and 2). It is an arid, transgressive dunefield, where sediments entering the system from the eastern coast (El Inglés Beach) are transported by trade winds to the SW, forming mainly barchan dunes and barchanoid ridges up to 12 m high. In their final terrestrial phase, the dune forms return back into the sea along the southern coast at Maspalomas Beach (Hernández Calvento, 2006; Jackson et al., 2013b).

Since the 1960s, one of the largest seaside resorts in Spain was developed around this dune system (Domínguez-Mujica et al., 2011). Part of the new urban area was established on a Pleistocene sedimentary terrace (more than 20 m high), jutting wedge-like into the dune system in its eastern sector. The topographic base of the dunefield (between 2 and 6 m AMSL) determines its influence on aeolian dynamics. Up until this construction, sand deposits accessed the terrace top in the form of climbing dunes, crossed the terrace as barchans and continued their path along the leeward side of the terrace (Hernández Calvento, 2006; Fig. 1).

Previous studies of landscape changes in the area have identified substantial alterations in this aeolian system, particularly over the past 40 years (Hernández Calvento, 2006; Hernández Calvento et al., 2007). There are two main causes of these changes: (1) a naturally progressive sediment deficit, and (2) the development of tourism. Sediment deficit has manifested itself through the progressive decrease in the height of the dunes since the 1960s and the development of several deflation plains (Hernández Calvento, 2006; Hernández Calvento et al., 2007; Hesp, 2013). In terms of impacts from tourism, its clearest consequence has been the stabilisation of the inner section closest to the urban fringe after the development of the tourist resort on the sedimentary terrace (Hernández Calvento, 2006; Hernández Cordero et al., 2006; Pérez-Chacón et al., 2007). More recently, the reduction in the coverage of the pioneering shrub species *Traganum moquinii* has been observed on the backshore of El Inglés Beach (Hernández-Cordero et al., 2012). This fact is important in our understanding some of the processes described in this paper. *T. moquinii* is a shrub that

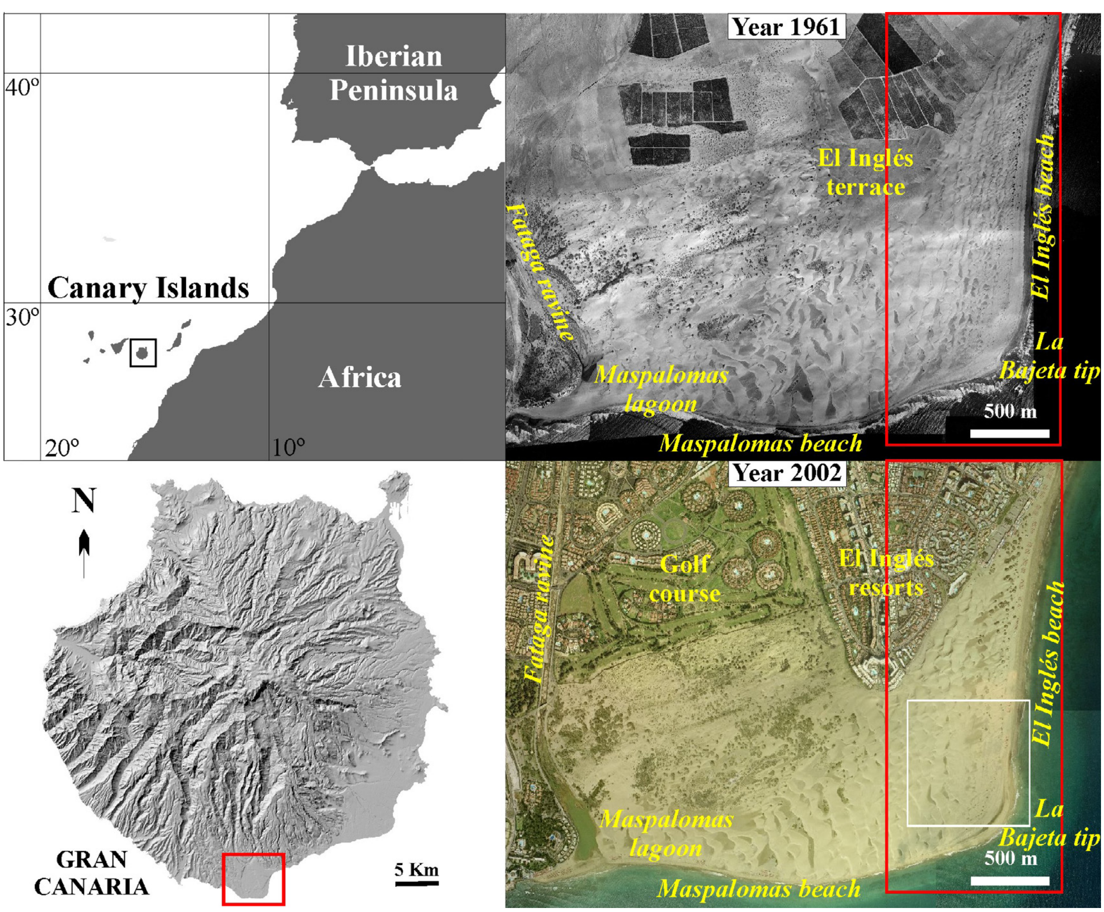

Fig. 1. Location of the study area and general view in 1961 and 2002. The white box shows the wind flow computational model area defined in Fig. 4.

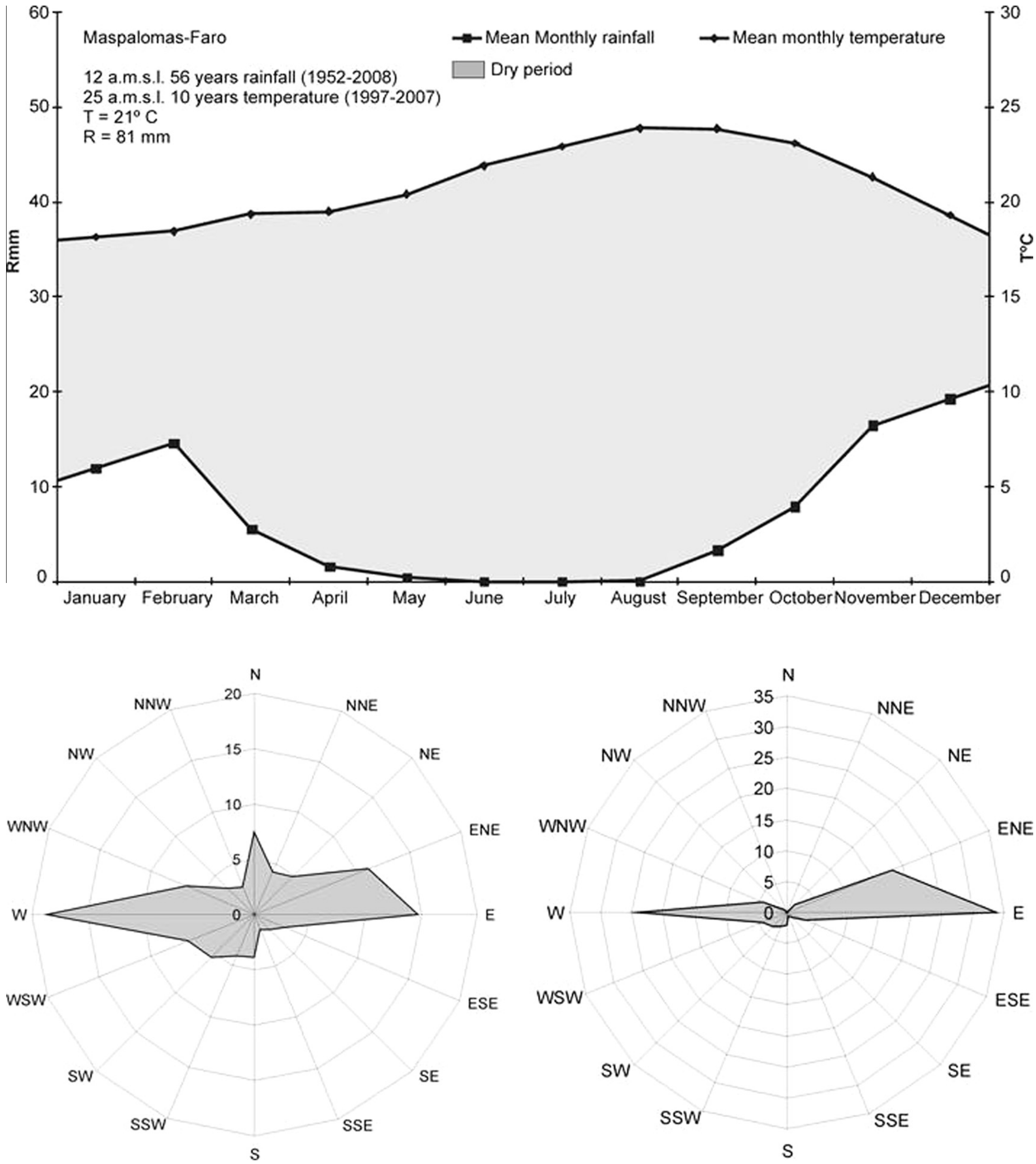

Fig. 2. Climatic characteristics of the Maspalomas dune field. The ombrothermic diagram (top) shows how the arid conditions are continuous throughout the year (modified from Hernández Cordero, 2012). The frequency of wind direction, in percentage (bottom), according to the available data (1997–present), shows a balance between two opposing directions (E–NE and W) (left image), but a clear dominance of the E and NE directions when effective winds (>5 m s^{-1}) are in operation (bottom right image) (modified from Máyer Suárez et al. (2012)).

grows on the sandy shores of West Africa, from southern Morocco to Mauritania, as well in the archipelagos of Canary Islands and Cape Verde. It usually grows in isolated clumps, and generally helps construct foredunes delineated by hummocky dunes. Thus, the presence of *T. moquinii* helps regulate the transport of sand into the system by retarding the progression of free dunes formed on the backshore. Its coverage and associated foredune accumulation, are a vital natural barrier that mitigates the effects of marine and wind erosion (Cabrera-Vega et al., 2013b). Consecutive measurements of the accumulation ridge position with respect to the backshore have shown an exponential migration rate (Hernández Calvento et al., 2007). Cabrera-Vega et al. (2013a) suggest that the origin and behaviour of this ridge could be the result of the combination of impacts from tourism and natural aeolian processes. This hypothesis has helped steer the methodology of the present study.

The area of interest is the fringe of El Ingles, measuring 2.5 km in length (north to south) and ranging in width between 100 and 500 m. The N and NW zone is somewhat limited in terms of dynamics due to beach and touristic infrastructure and equipment (kiosks, portable bathrooms, hammocks). In the west, it is restricted by its own dune field and by the sea to the south.

3. Methodology

Initially we characterised the historical evolution of aeolian landforms at southern end of El Inglés Beach between two different periods: before the development of tourism (1961) and in more times (2002–2006). The general wind flow modifications induced by the tourist resort located on the terrace were also examined. Finally, a characterisation of the accumulation ridge was also

Table 1
Z_0 roughness values used for the various surfaces in the study area.

Land cover	z_0 (m)
Water	0.0002
Sand	0.00024
No urbanised terrace	0.03
Urbanised terrace	0.8

conducted using aerial images of the site. Orthophotographs from 1961, 2002, 2003 and 2006 were used to compare historical and recent landforms. A 2006 LiDAR survey of the site (1 m spatial resolution) allowed the creation of a digital elevation model (DEM). Finally, other orthophotos (from the Canary Islands official Spatial Data Infrastructure) were used to examine landscape evolution based on the distance of the last ridge to the backshore.

3.1. Aeolian landform changes

This study is based on the characterisation of landscape changes between 1961 and 2006, based on geo-referenced aerial photographic interpretation. Maps were constructed by screen digitising identifiable landforms and other land cover using the 1961 and 2006 ortho-photographs. Three main geomorphological units were identified: (1) foredune; (2) low transgressive dunes, and (3) high transgressive dunes. Within the foredune, we also identified three morphodynamic units, from east to west: (1) beach; (2) embryonic dunes (consisting of free small transverse dunes less than 1 m in height), and (3) the foredune itself, delineated mainly by hummocks and parabolic dunes. The foredune was generated by the depositional trapping qualities of the plant *T. moquinii*. The lower transgressive dune unit consists of barchans and barchanoid dunes with a maximum height of 3 m, in addition to deflation surfaces. Finally, the high transgressive dunes unit is formed by barchanoid ridges, with maximum height of 14 m, interspersed with dune slacks. The main accumulation ridge is clearly identified in the 2006 map, as well as on 2002 and 2003 orthophotos. The surface occupied by each landform is summarised in Table 2.

3.2. Analysis of wind flow modifications by the tourist resort

To assess the impact of urbanisation on wind flow and on local aeolian sediment dynamics, a simplified numerical wind model, based on a logarithmic wind velocity profile, was developed. It simulates the wind flow over the topography to determine the velocity field and wind directions at and beyond the urban zone. This model has been applied to the current configuration of the dune system and to the 1961 configuration with the sedimentary terrace without buildings. The comparison of both configurations allows for the assessment of changes in the wind field due to the presence of the urban infrastructure. This allows examination of any influences on the airflow and subsequent changes in the dynamics and morphology of the sand dune system.

The study area was delineated as a grid measuring 5000 m × 5000 m, and a cell size of 50 m. The vertical dimension of the airflow modeling was 50 m, based on a level at which the

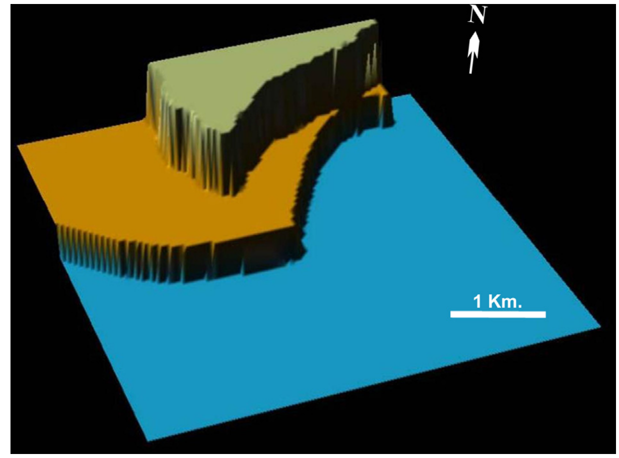

Fig. 3. Simplified topography of the study area for the wind flow model, showing the three areas distinguished: in blue, the sea (0 MSL); in brown, the dune field (7 m); and in grey the sedimentary terrace (20 m and 40 m in 1962 and 2006 configurations, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

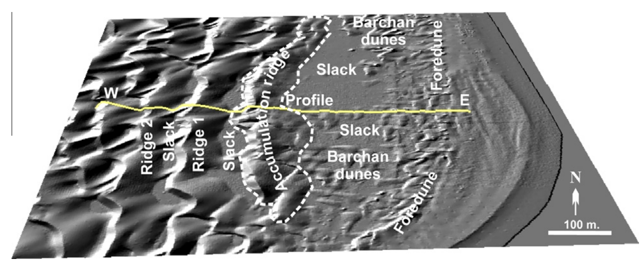

Fig. 4. Topographic profile (yellow line) located on a three-dimensional view of the study area. The irregular shape of the last ridge (delimited by the white line) over previous ones can be seen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wind profile is assumed to be unaltered (free stream) by the effect of the changes in surface geometry. The results are expressed as mean changes in the air column.

The model was supplied with the following data: (1) wind (air flow); (2) topography, and (3) roughness. Input wind conditions were assumed to be a 1 m s^{-1} airflow (at 50 m elevation from the surface) entering from the ENE. A reference value for wind speed of 1 m s^{-1} is considered adequate because the goal is not the determination of the velocity field for different wind cases but rather the detection of differences in the morphological changes of the dune system. As the net advance of the dunes is in a WSW direction, this is the input direction used for the initial upwind boundary conditions (Máyer Suárez et al., 2012).

Regarding the topography, three areas have been distinguished: sea, dunes field, and sedimentary terrace. A maximum height was assigned to each of these zones (Fig. 3). The mean sea level (MSL) has been considered as the base surface, with the dune field set to 7 m above MSL and the terrace assigned at 20 m height based on the 1960s topography and 40 m height when urbanised,

Table 2
Surfaces (in ha) covered by each landform and changes (in%) between 1961 and 2006.

Year	Foredune	High transgressive dunes	Accumulation ridge	Low transgressive dunes	Slacks	Urban area	Gardens
1961 (ha)	13.2	71.2	0	6.7	3.5	0	0
2006 (ha)	10.1	40.5	5.6	15.9	10.9	10.8	0.4
Changes (%)	−23.5	−43.1	+5.6	+137.3	+211.4	+10.8	+0.4

considering that the tallest buildings built on the terrace are 6–7 floors in height.

A surface roughness value (z_0) was assigned to each of these areas, considering the Chézy friction coefficient determined from background roughness and drag coefficient. Roughness values obtained from the European Wind Atlas (WAsP) are shown in Table 1.

3.3. Ridge characterisation

The characterisation of the ridge was examined using three methods. First, a topographic profile was extracted from the DEM (Fig. 4), to visually analyse ridge characteristics, comparing its appearance with neighbouring ridges. The migration rate of these three ridges was also calculated using the method proposed by Gay (1999) and applied by Tsoar and Blumberg (2002) and Ojeda et al. (2005). To accomplish this, each location was digitised from 2003 (November) and 2006 (October) orthophotos and equidistant vectors were drawn between consecutive dates, with path lengths calculated for each period. Finally, changes in the distance of the last ridge to the backshore was calculated with respect to Hernández Calvento et al., 2007, using the slacks (Ranwell, 1959; Hesp and Thom, 1990) located in front of the ridge as references, and identifiable specimens of *T. moquinii* in the backshore.

4. Results and discussion

4.1. Landform evolution

The landforms of Maspalomas dune system have changed substantially over the past 50 years (Fig. 5). In the early 1960s, the fringe of El Ingles sediment input zone had a fairly simple geomorphologic scheme: a hummocky foredune was formed in the backshore, stretching from north to south, generated by the interaction of the *T. moquinii* shrubs with aeolian deposition. Parabolic dunes were established between these hummocky end members. Immediately behind them, where the vegetated areas decreased, high transgressive dunes (barchanoid ridges) with well-defined slacks and, to a lesser extent, low transgressive (barchan) dunes were developed.

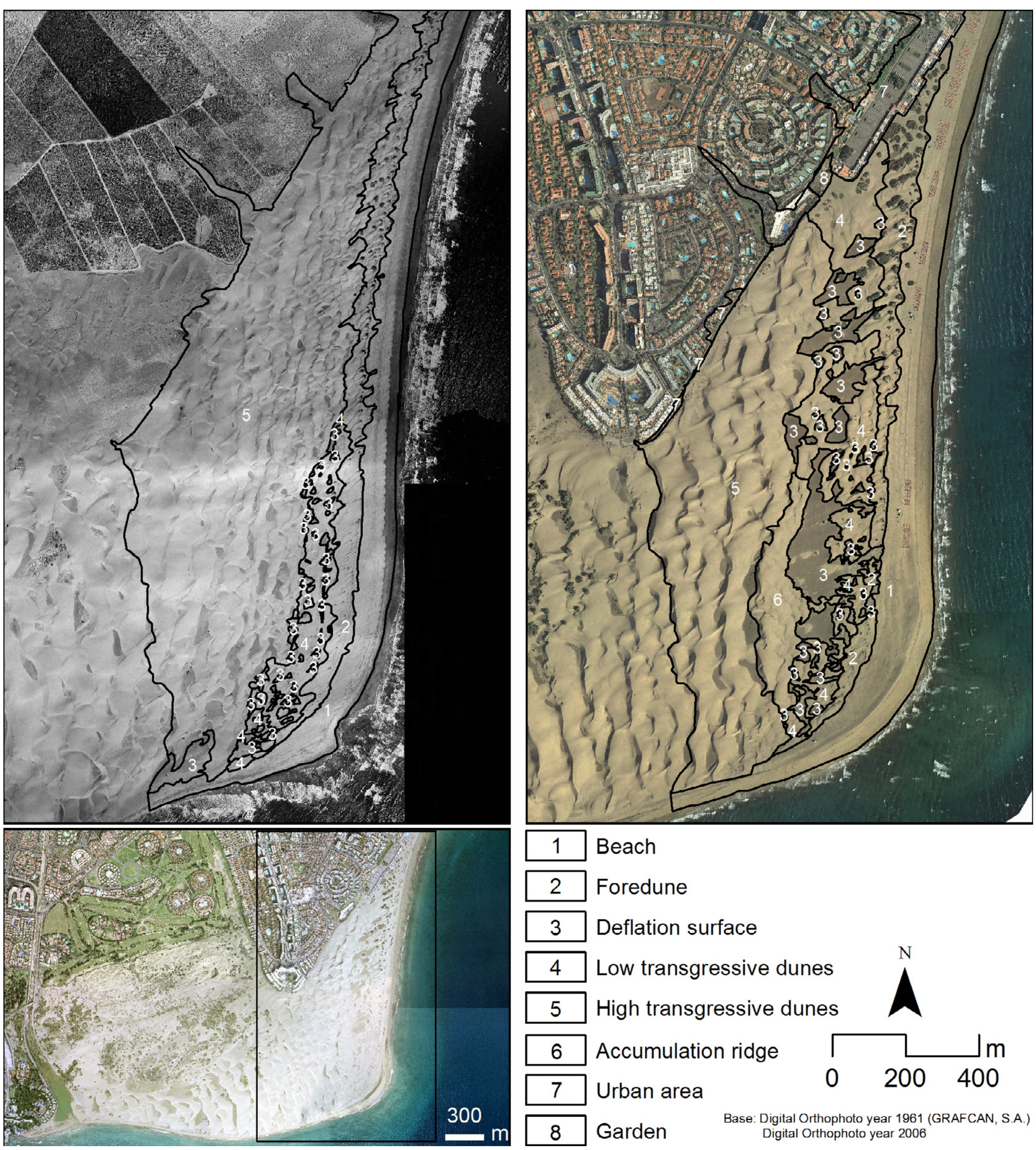

Fig. 5. Aeolian landforms map from aerial imagery in 1961 (top left) and 2006 (top right).

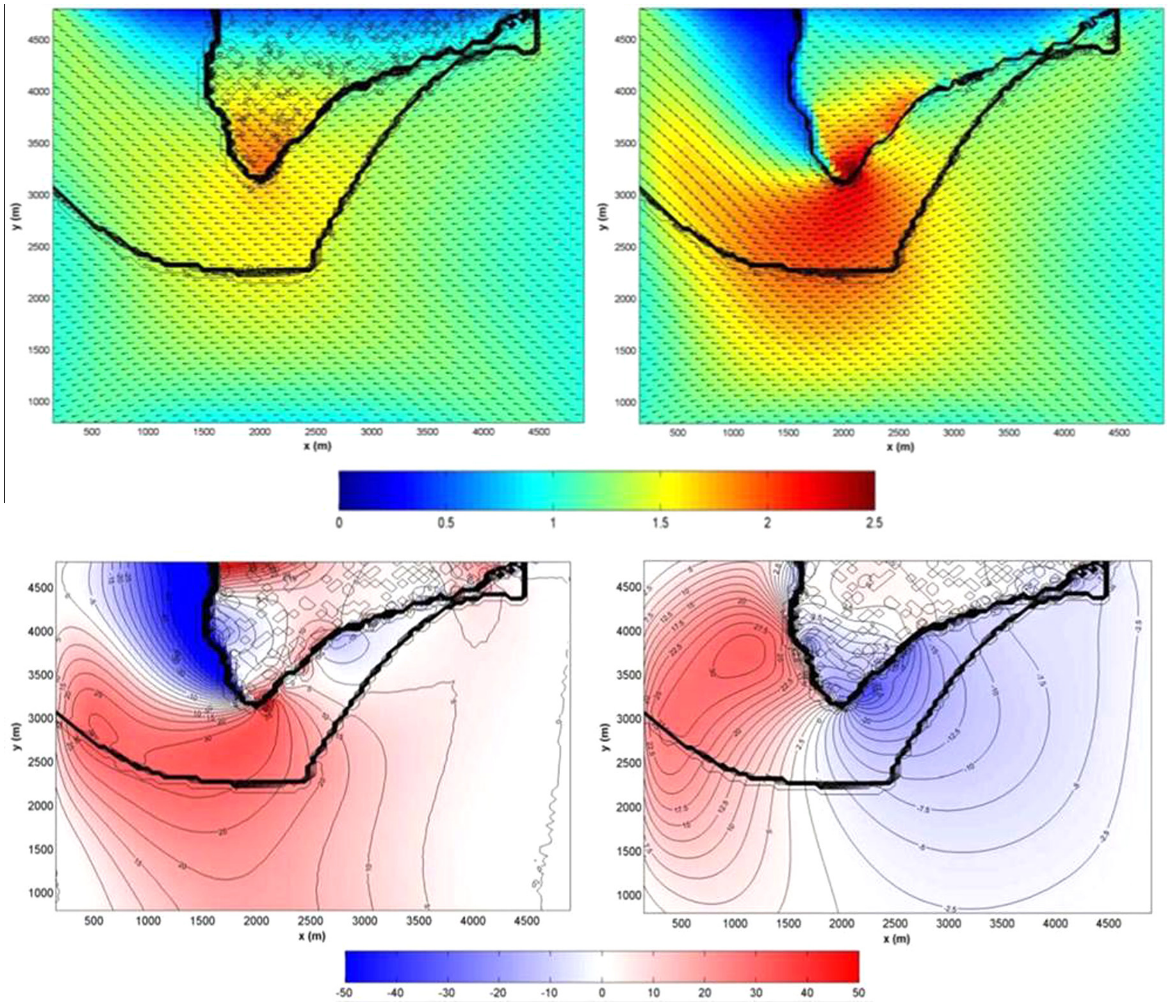

Fig. 6. Wind velocity model results (in m s^{-1}) across the area in a 1960's scenario (top left) and during recent urbanised configurations (top right). Percentage differences in velocity rates are shown (lower left) and in direction differences (lower right) between the two configurations.

Table 3
Average migration rates in recent years of the three last ridges (m yr^{-1}).

Landforms	Average	Maximum	Minimum
Accumulation ridge	6.8	16.3	0.4
Ridge 1	8.4	18.6	1.6
Ridge 2	7.8	15.2	1.1

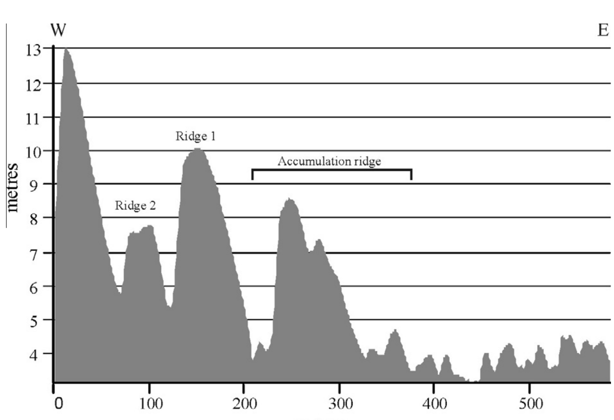

Fig. 7. Topographic profile, indicated in Fig. 4, across the coastal strip.

In 2006, this configuration shows substantial changes, extending to ∼50% of the studied area. First, the area of the foredune was reduced by 23.5% (Table 2). This transformation is due to the decrease in the number of specimens of *T. moquinii* by human activities (Hernández-Cordero et al., 2012). This produces the fragmentation of the foredune, and in 2006 large sections no longer have hummock dunes to intercept the aeolian transport. Today, three foredune units are differentiated.

Secondly, as of 1961, 43.1% of the area of the high transgressive dunes has been covered by smaller-scale free landforms consisting mainly of barchan dunes and sand sheets, particularly in the southern area (Fig. 5).

4.2. Wind flow alteration

Fig. 6 (upper left image) shows that in the early 1960s, the elevation of the sedimentary terrace produced some acceleration of wind flow over the dune field, reaching values of 1.6 m s^{-1}. On the leeward side of the terrace, a small shadow area can be identified. These data contrast with those of the current configuration (Fig. 6, upper right image), which shows the results for the current configuration with the terrace fully urbanised. In this case, the influence of buildings on the acceleration of wind over the dune field is very notable, reaching values of 2.5 m s^{-1} in the area close to the southern end of the terrace. A wide shadow zone at the lee of the terrace can be also observed.

The difference in wind speeds between the two configurations can be seen in Fig. 6 (lower left image). The major differences in speed increases occur in the area near the southern end of the terrace, where values increased between ~30 and 35%, decreasing with distance from this point. The major differences in terms of decreased speed occurred in the shadow zone generated in the lee of the terrace, with decreases of up to 50%.

The difference in wind direction is shown in Fig. 6 (lower right image). On the windward side of the terrace there is a distinct northerly shift in direction, tending to be parallel to the orientation of the first line of urbanisation. These changes make a difference of approximately 15–20° to the original system configuration. In the northern part of this area, there is also a small reduction in wind speed. In the area downwind of the terrace the greatest rotations of the wind direction to the south is produced, with differences of up to 30° relative to the 1960s flow configuration.

The southern sector of the fringe of El Ingles experiences an increase in wind speed of ~20%, which increases to 30% farther into the dune field.

4.3. Accumulation ridge characteristics

The accumulation ridge has a width of almost 70 m, a maximum height of 12 m and an average height of 7 m. Its general features are similar to those of the two preceding ridges, numbered as 1 and 2, depending on their proximity to the coast. However, average migration rates in recent years of preceding ridges are greater than the accumulation ridge (Table 3). This may be caused by the presence of the urbanised terrace within the wind flow as mentioned previously, because the more the ridges are located inside the dune field, the greater the acceleration of the wind flow.

Considering the topographic profile, a clear morphological difference between the accumulation ridge and the others is noted (Fig. 7): the accumulation ridge is formed by the super-positioning of several dunes, while the other ridges form single entities. Therefore, the accumulation ridge is a noted as a 'composite' dune.

The distance of the accumulation ridge with respect to the backshore continues its exponential increase as the ridge enters the dune field (Fig. 8), with respect to the previous observation (Hernández Calvento et al., 2007; Pérez-Chacón et al., 2007). This ties into the findings from the wind model results.

The formation and evolution of the accumulation ridge appears to be responding to the combination of three processes, two of which are directly related to urban tourism development:

1. A sedimentary budget deficit observed in this system and identified by Hernández Calvento et al. (2007) has forced a reduction in sand supply to the dune system. In this regard, the accumulation ridge is the last ridge formed in the system. Current barchans dune and sand sheets are formed on the backshore instead of forming any new ridges.
2. The weakening and fragmentation of the foredune, through the action of beach users (Hernández-Cordero et al., 2012), has modified the sedimentary transport. Small mobile landforms (barchans dunes and sand sheets) meet fewer obstacles during their advance into the dune field. Trampling pressure from beach tourists has induced some die-back further reducing coverage. This will likely result in the narrowing of the coastal dune and its fragmentation, being replaced in part by deflation surfaces (Hernández-Cordero et al., 2012).
3. Wind flow disturbance, caused by the urbanisation of the sedimentary terrace, has accelerated the rate of sediment transport in certain parts of the dune field.

Therefore, small dunes formed on the backshore, move up to the first ridge, forming a composite dune, termed here as an "accumulation ridge". The distance from this ridge to the beach increases exponentially, as demonstrated by Hernández Calvento et al. (2007), because the wind flow is substantially modified due to the presence of the terrace.

This implies an artificially-induced acceleration in the aeolian dynamics at this site, accelerating sand output from the system, which is greater than the supply (input), due largely to the urban development. Paradoxically, the tourism development itself has negative consequences on the tourism resource (dunes) already mentioned by other authors (Gössling, 2002).

Some have suggested that this type of dune landform behaviour is typical of arid coastal dune systems, displaying rapid geomorphic changes that are very apparent in aerial image analysis (Cabrera-Vega et al., 2013a,b). It is difficult to argue that the urban

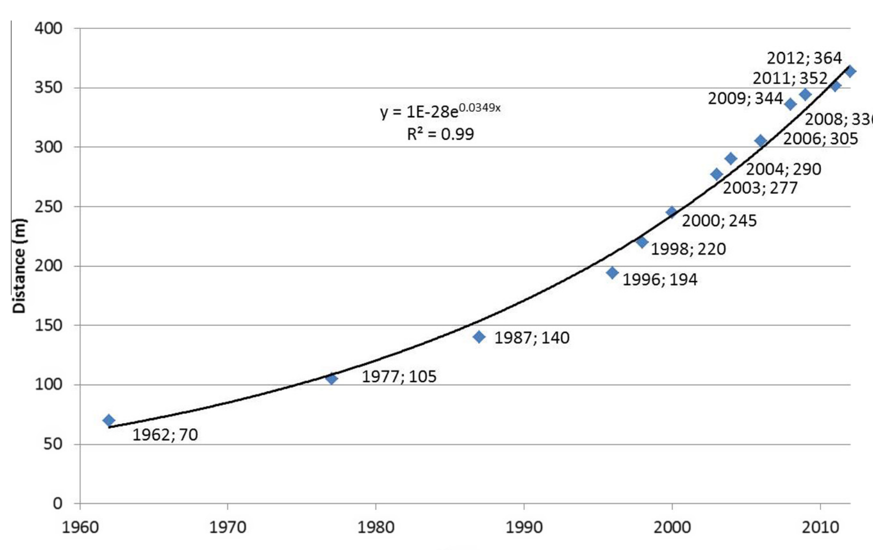

Fig. 8. Changes in the distance of the accumulation ridge with respect to the backshore position (1962–2012). Seven ortho-photographs taken between 2003 and 2012 have been used to actualise data from Hernández Calvento et al. (2007). The distance in each date was measured between specimens of *T. moquinii* that have been permanently located on the backshore since 1962, and the contact between the leeward of the dune and slack.

area has had no effect on the dune system here. Results clearly show significant alteration of the forcing wind condition on the site and these have obvious implications for the local dune dynamics. Future work on this phenomenon should involve use of more detailed 3-D airflow models such as computational fluid dynamics (Jackson et al., 2011, 2013a,b; Beyers et al., 2010; Smyth et al., 2011, 2012, 2013) and particularly on any coherent air flow structures (Lynch et al., 2010; Bauer et al., 2013; Walker and Shugar, 2013) that may be induced by adding human infrastructure into active aeolian dunefields.

5. Conclusions

Changes induced in part by urban-tourism development in an arid coastal dune system on Gran Canaria Island, Spain, have been analysed. The main conclusions are:

1. Significant changes on this arid dune system are due to two main drivers: a sedimentary deficit and the pressure of users. The result is the replacement large sand dunes by smaller aeolian landforms, and a weakening and fragmentation of the natural foredune.
2. Through wind modeling we have shown that the influence of an urbanised resort area has been significant with obvious impacts on the potential dune morphodynamics of the site. It has been observed that the wind has been accelerated as much as 35% in some parts of the system as a result of placing urban buildings in these types of environments. Along the southern part of the dune field, the magnitude of the wind speed was shown to have increased by 20–30% under the same impact.
3. The last ridge formed on the dune system is generated by the accumulation of smaller dunes that migrate at high rates and coalesce to form a single ridge.

The results allow us to conclude that the formation and dynamics of this accumulation ridge is the result of three concurrent processes: a sediment deficit, the action induced by users of the beach and dunes, and the large-scale construction of an urbanised resort. It is, therefore, a type of dune that has been generated by direct impacts of a tourism development inside a dynamic aeolian environment, the first time that this type of anthropogenically-generated landform has been described. Such impacts are more easily observed within arid coastal dune systems, because of their increased mobility allowing easier detection at decadal time scales.

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