3D airflow modelling and dune migration patterns in an arid coastal dune field

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ABSTRACT


Mobility patterns within dune fields are driven by wind action, antecedent form and local conditions, which determine their temporal and spatial morphodynamics. This mobility can have considerable impact on human activity and infrastructure, as well as forming an important element of the sedimentary system. Understanding how dune fields migrate over time should form an essential part of future management. Although particularly important in arid and semi-arid locations due to their enhanced sand transport dynamics, research on these systems has received surprisingly limited attention, with studies largely focused on temperate and tropical examples.

Here, we utilise 3D airflow modelling, in-situ wind measurements and high resolution topographical measurement of surface features at an arid coastal dune field site in Gran Canaria, Spain. Using the Computational Dynamics (CFD) software OpenFOAM, airflow is simulated over a section of dunes along a northeast-southwest orientation, representing predominant local wind direction. A 3D surface was generated using a 1m resolution LiDAR survey (conducted 2006) to provide an accurate surface topography for CFD model runs. Output from the model provided information on surface airflow, allowing forcing winds to be located on top of the 3D surface. Using a 2008 LiDAR survey we compare the response of the dune field to that forcing and dune migration patterns. Modelled surface wind speed clearly corresponds to the resulting migration patterns of dune migration. Results show, for the first time at this resolution, that migration patterns and modelled wind flow provides useful information for arid dune studies in coastal regions.

ADDITIONAL INDEX WORDS: arid coastal dunes, computational fluid dynamics, dune migration, Aeolian.

INTRODUCTION

Mobile dune systems can contain and relocate vast quantities of sand through high level atmospheric (dust) processes and/or by near surface sediment transport. The dynamics of these terrestrial systems is of interest to both engineers and scientists for a variety of reasons, extending from structural engineering design to process geomorphology. Desertification now affects around one quarter of the Earth’s terrestrial land mass on which lives around one fifth of the world’s population (UNCCD, 1994). In this context, any degradation of vegetation and reduction in precipitation levels will lead to greater mobility of granular material if present in such environments. The importance of understanding how landforms might move is therefore crucial in managing human habitation in these areas. Moreover, the growing influence of humans has also altered aeolian sediment transport and the geomorphological evolution of many dune fields (Nordstrom et al., 2007; Jackson and Nordstrom, 2011). Preservation and effective management of these systems requires in-depth understanding of their dynamics and evolution, especially within highly mobile systems located in areas under development pressures (Mitsova et al., 2005).

The primary driving component of a sand dune system is the localised wind regime acting on its surface. Numerous other environmental parameters however, also control their response and therefore dictate migration or movement patterns. These include sediment supply, vegetation, moisture and antecedent conditions or form.

To date the investigation of dune field response to localised forcing variables has been examined through restricted point measurements of wind flow and crest position, combined with aerial imagery to infer longer term crest migration of the dunes. Detailed characterisation of wind flow over significant spatial extents has proved impractical and as a result large-scale migration patterns have only been observed as a general response rather than examining the localised forcing-response mechanism at play.

This shortfall in methodology necessitates the use of airflow modelling to extend the spatial coverage and resolution that can never be matched by using an instrumented approach (Jackson et al., 2011;2013; Smyth et al., 2011, 2012).

This study analyses the response of the dune movement to the wind force with direction comparisons to airflow simulations and dune migration patterns in an arid and highly dynamic coastal dune field in Maspalomas, Gran Canaria, Spain.

STUDY SITE

The study site is located in the central section of the east part of Maspalomas dune field, situated in the south of Gran Canaria island (Canary Islands, Spain) (Figure 1). The area has an arid

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climate with annual precipitation of less than 100 mm producing limited vegetation cover dominated by a small bush species (*Traganum moquinii*) that colonises the back shore in small thickets. In general, sand transport is free to operate and form embryo dunes at the back beach zone and beyond. Sand sheets and parabolic dunes then develop to eventually form *free barchanoid* forms that finally evolve into distinct barchanoid ridges, before returning to the sea again on the southwestern coastline.

Although the western and southwestern winds are more frequent (see inset of Fig.1), the eastern and northeastern winds determine the localised migration behaviour of the dunes due to their higher magnitude during the autumn-winter period (November-March). Recent research has identified a sedimentary deficit in this area (Hernández Cordero et al., 2006; Hernández et al., 2007). Other influences from tourism resorts (e.g. Playa del Inglés) and other human activities on the beach may also have had an influence in changing sediment supply at the site.

**METHODS**

Using a combination of 3D surface topography generated through LiDAR surveys, local meteorological wind data and 3D airflow modeling, we investigated the primary forcing component of the system (wind) against response (dune migration) at the Maspalomas dune field. The two LiDAR surveys conducted 17 months apart at the same acquisition resolution (1m x 1m spot spacing), provided spatial information to quantify migration vectors at selected locations. 3D wind flow simulations (CFD) conducted over the initial 2006 surface provided near surface wind vectors (magnitude and direction). These were then compared against localised dune migration patterns.

**3D airflow modelling**

The open source computational fluid dynamics (CFD) software package OpenFOAM was used to calculate near surface wind flow throughout the study site. OpenFOAM’s native meshing utility, SnappyHexMesh, was used to create a 2,145,796 cell computational domain measuring 815 m x 510 m x 100 m in which the study site was contained. Cell sizes gradually increased toward the surface of the dune from a maximum of 10 m to 1.25 m close to the dune surface. Surface roughness was accounted for using a Ks value of 0.05, based on values calculated by Wakes et al., (2010) for a beach and parabolic dune deflation basin. The wind flow was solved using a Reynolds-Averaged Navier-Stokes (RANS) solver based upon the PIMPLE algorithm (Habchi et al., 2012). Turbulence was modelled using the Re-normalised Group (RNG) k-epsilon equation due to its ability to accurately simulate flow over complex foredune (Parsons et al., 2004; Wakes et al., 2010) and blowout topography (Smyth et al., 2012).

Airflow was simulated over a 649 m x 154 m area (95,397 m$^2$) of dune field, orientated along the predominant ‘transport capable’ winds from the ENE, stretching from the coast to inland (Fig. 2). Local wind direction and velocity data for the simulation was obtained from a 7.5 m high meteorological station (see Figure 1 for location). The wind period between November 2006 and February 2007 (recording interval 1 hour) was used as input for the simulated flow. This period was selected as it represents the most frequent wind direction (67.5º) at the site. The mean wind speed over this period was 5.82 ms$^{-1}$, representing wind magnitudes capable of transporting the sediment grain size of the dunes (mean diameter 0.22 mm) (Alcántara-Carrió, 1998).

**Dune migration**

The “crest to crest” method, one of the most widely used to quantify dune form movement (Hugenholtz et al., 2012), was utilised to calculate dune migration rates between 2006 and 2008. Using GIS tools, successive positions of the dune brink were mapped over a high resolution orthoimage of 2006 (0.1m pixel) and hillshade models (1m pixel) derived from two digital elevation models (DEMs) obtained from LiDAR surveys conducted in October 2006 and March 2008. A total of 21 different dunes shapes were considered, taking into account only those with brink positions clearly identifiable in both dates.
Enumerating from the backshore to the landward side and considering elevations in 2006 above mean sea level, these were: sand sheets and small barchans and barchanoid ridges (between 4.31 m and 6.88 m high), medium-size barchans and barchanoid ridges (between 4.49 m and 10.82 m) and large barchanoid ridges (between 10.96 m and 19.73 m high) (Figure 3).

Equidistant vectors (61 in total) were analysed between the dune brinks of both dates following the direction of the slip face advance (Ojeda et al., 2005). This way, the dune movement has been represented at different parts of each landform in order to partially compensate some limitations of the crest to crest method highlighted by other authors (Bailey and Bristow, 2004; Levin and Ben-Dor, 2004).

The annual advance rate (here termed $A_{av}$) was calculated by:

$$A_{av} = \left(\frac{l_{av}}{m}\right) \cdot 2$$

(1)

Where: $l_{av}$ is the length of the advance vectors, and $m$ is the number of months elapsed between the reference dates. Lastly, using the centroids of the advance vectors a raster surface has been created modeling migration rates on a continuous surface by means of the inverse distance weighted interpolation method.

Correlations were conducted to elucidate spatial differences in dune advance rates which could be indicative of migration patterns, according to the shore distance or dune elevations. The wind effect over the dune movement was also analysed and correlated to magnitude and direction of dune migration with the simulated airflow obtained from the CFD model.

### RESULTS

#### Computational Fluid Dynamics

Total wind speed was exported from the simulation at a resolution of 2 m x 2 m, 0.5 m above the dune surface. These results were interpolated using the kriging method to form a raster image and draped over aerial photography of the site (Figure 4). Figure 4 also shows wind speed and direction 0.5 m above the dune surface at the crest of 61 dunes where equidistant vectors were generated to measure dune migration rate and direction. A cross-section of the surface and throughout the study site identical to the one illustrated in Figure 1 was also made through the computational domain (Figure 5).

The wind speed data calculated 1 m above the surface in Figure 2 demonstrates that wind speed throughout the Maspalomas dune field is very heterogeneous. Zones of flow acceleration and retardation are apparent throughout the study area. Larger zones of retarded wind speed, however, are apparent in the west of the study area where the dune shape is much more linear than in the east of the study site and where dune height is also much higher. This variation in flow from east to west throughout the study site is further illustrated by the cross-section of simulated flow in Figure 5. In the east of the study site wind flow is accelerated and still attached over the small barchans whilst toward the west of the study site, wind flow becomes separated in lee of the barchanoid ridge crests forming zones of slow moving, re-circulating airflow.

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Wind speed and direction at the dune crest remains relatively unchanged throughout the study area as exemplified by the vectors shown in Figure 5. Wind direction throughout the study area remains orientated to the south-west irrespective of the transition from small barchans in the east to barchanoid ridges to the west whilst wind speed predominantly remains between 5.1 ms\(^{-1}\) and 6.3 ms\(^{-1}\) throughout.

**Dune migration patterns**

Mean advance rates of 13.69 m yr\(^{-1}\) are noted, equating to an average displacement of 19.40 m between 2006 and 2008. These rates are not spatially constant however, with a high oscillation occurring between the minimum (1.59 m yr\(^{-1}\)) and the maximum (34.55 m yr\(^{-1}\)). Correlation analysis shows that migration rates have a slightly higher agreement with shoreline distance \(R^2 0.51\) than with dune elevations \(R^2 0.47\) (Figure 6). Even though these correlations are not very high, a migration pattern can be identified showing the fastest movements (ranging from 22.07 m yr\(^{-1}\) and 34.55 m yr\(^{-1}\)) occurring along the first 316 m from the shoreline and corresponds to some of the smallest dunes at the study site. The best example is the case of the maximum rate obtained, which is produced in the lowest point measured (3.51 m) located 117 m from the shoreline. Toward the landward zone, the correspondence between migration rates, shoreline distance and elevation is also observed. From 316 m shoreline distance to inland, the dunes are higher, reaching average elevations of 15.9 m, and a significant decrease in migration rates occurs (between 1.59 and 14.89 m yr\(^{-1}\)) (Figure 6 and 7). This means that the maximum displacement produced close to the shoreline is more than twice (2.32) than that of the maximum movement occurring on the landward sections.

Considering advance directions, all the dunes analysed move toward West South West (between 231º and 255º). 246º is the most frequent advance direction (mode), representing 14.75% of all cases. This clearly indicates that dune migration follows the predominant wind direction of the transport capable winds from the East North East. Poor correlation \(R^2 0.02\) was found between theadvance rates and the direction of the dune movement. This is likely due to the fact that all dunes move in the same range of direction, independent of the magnitude of their advance.

**DISCUSSION**

Results show a distinct zonation in the migration of dune forms at Maspalomas. The faster, smaller barchanoids/sandsheet area close to the initial source area at the coast, demonstrate rapid migration rates. These smaller dune forms have less volume of sediment to displace and roll over much faster, thus promoting fast migration rates within the initial zones near the coast. As sediment accumulates inland into higher dune forms, the resulting larger barchanoid dunes slow down given the shear quantities of sand that require transportation.

The CFD wind flow simulation results support this pattern with fast moving air found in the initial coastal zone, driving sand transport significantly. As the CFD simulation traverses over the higher dunes inland, distinct parcels of slow, re-circulating (i.e. detached) air flows are found in the lees of the dunes. This helps slow the transport of sediment and therefore dune form migration.

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Figure 5. Top image: Cross-section of simulated flow across the 640 m profile delineated in Figure 1. Middle image: Recirculation zone in lee of a barchanoid ridge in the west of the study area. Bottom image: Attached flow in lee of a small barchan dune in the east of the study area. N.B. Scale bar covers vertical and horizontal scales for middle and bottom image.

Figure 6. Correlations between advance rates and shoreline distance (a) advance rates and elevations (b). Note slightly higher agreement between advance rates and shoreline distance.
Even though similar wind flow velocities are travelling across the larger dune forms and at times exceeding the upwind velocities, the larger dune form migration rate is a lot slower that the upwind smaller barchanoid forms. It should also be noted that the simulated flow directions across the entire site are coincident with the dune migration directions noted from the LiDAR survey analysis. This helps to validate the point that modelled wind and its resulting adjustment (any localised steering and deflection) from the underlying surface, are indeed representative of the actual flow that ultimately pushes the dune forms in that forcing direction.

Interestingly, there appears to be a threshold distance of around 300-320 m from the initial source area at the coast where the system gathers into larger barchanoid forms. This notably sharp transition may represent a zone of coalescence where the faster moving primary dunes come together to form a larger and higher dune field. This may be due to the system becoming over-saturated with sediment and the accumulated sand then subsequently affects the surface wind flow as well, perpetuating the accumulation. An analogy would be an ecological system attaining climax vegetation, so too might a dune system, whereby the dune size and extent cannot grow further.

CONCLUSIONS

This study highlights the rapid migration rates that can occur in an arid coastal dune field and the associated spatial heterogeneity of this migration behaviour. A distinct zonation of migration is evident within the system, whereby rapid dune crest movement occurs in the initial coastal source area and then a retardation of migration with distance inland. Wind flow modelling around the dune forms in each of these areas shows distinctive flow characteristics that support this behaviour. Fast, unattached surface flow is present in the source zone while the larger and slower barchanoid forms found further inland force wind to detach and re-circulate in their lee sides, slowing migration of the dune form. These results point to a dune form saturation point with distance inland, aided by the physical limitation of the actual dune size and the associated airflow around the landforms themselves.

The work represents the first attempt at directly comparing calculated rates of migration to results from a 3D computational fluid dynamics (CFD) airflow model in this type of environment. Results highlight the usefulness of the CFD technique, where the use of field instrumentation to quantify airflow is problematic. Results support the use of this technique in other coastal and desert dune studies to investigate the wind forcing responsible for driving the dynamics of dune migration in arid climates.

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LITERATURE CITED


