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Three-dimensional airflow and sediment transport patterns over barchan dunes

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ABSTRACT

Airflow dynamics and potential sediment transport were measured and modelled across various barchan dune topographies and incident wind conditions. Modification of near surface flow was recorded simultaneously in three dimensions (3D) using dense arrays of high-resolution 3D ultrasonic anemometers. In situ measurements provided rigorous validation and calibration for computational fluid dynamics (CFD) modelling. Measured and modelled results show good agreement between flow velocity, directionality, and turbulence intensity. Modelling of characteristic airflow conditions and surface shear stress beyond the instrument locations, elucidated airflow dynamics across the entire landform surface at an unprecedented level of detail. Emergent turbulent airflow patterns were identified in the form of two counter-rotating vortices that converge at the dune centreline downwind of the dune crest. Integrating a sediment transport function with CFD surface airflow allows for the spatial mapping of flux patterns across the entirety of the dune and interdune surface. On the stoss slope and laterally along the outer barchan arms, there is strong potential sediment flux in response to increased streamwise stress. In lee-side locations, sediment transport remains at 'above threshold' conditions and is redirected in response to complex turbulent vortices identified in the overlying wake zone. The precision of the models allows for the identification of complex flow perturbations and associated surface stresses that prove difficult to measure in the field. CFD in combination with a sediment transport function is demonstrated to be a useful tool in investigating morphodynamics of mobile dune systems.

1. Introduction

Recent field studies of aeolian processes have relied on limited spatial and temporal in situ measurements that are highly site- and time-specific (Hugenholtz et al., 2012). This narrow focus has, in part, contributed to the development of an 'equilibrium' paradigm in which researchers relate limited empirical inputs to outputs (e.g. wind velocity effect on sediment flux), often at the single landform scale (Livingstone et al., 2007; Udo et al., 2008; Bauer et al., 2013). Some field experiments have identified complex, topographically-induced flow structures including flow stagnation downwind of the dune toe, compressed and accelerated flow on the stoss slope, detachment and flow expansion at the crest, recirculation or deflection in the lee, and downwind flow recovery (Frank and Kocurek, 1996b; Wiggs et al., 1996; Walker, 1999; Baddock et al., 2007, 2011; Weaver and Wiggs, 2011; Jackson et al., 2011). These studies have shown that the influence of turbulence stresses and convex curvature can maintain sediment transport at the dune toe despite reduction in overall velocity (Wiggs et al., 1996; Walker and Nickling, 2002; Baddock et al., 2011; Weaver and Wiggs, 2011). Due to streamline compression, airflow accelerates up the stoss slope and the onset of stabilizing convex curvature causes streamwise stress to become dominant at the surface leading to high levels of sediment transport (Wiggs et al., 1996; Walker and Nickling, 2002).

As airflow detaches at the crest, flow expansion occurs and a highly turbulent wake zone develops above the point of reattachment, usually at a length of x/h ~4–10 (Frank and Kocurek, 1996b; Walker and Nickling, 2002; Walker and Nickling, 2003; Parsons et al., 2004b; Schatz and Herrmann, 2006; Baddock et al., 2007, 2011; Delgado-Fernandez et al., 2011, 2013; Araújo et al., 2013). Upwind of the point of reattachment, within the recirculation cell, the importance of sediment transport in this region has been largely neglected due to reduction of velocity and highly intermittent turbulent fluctuations in these regions (Walker and Nickling, 2002). Sediment transport in these regions has often been overlooked; however, a few recent studies have identified the competence of sediment transport and the geomorphic implications of lee-side flow conditions (Walker, 1999; Lynch et al., 2008, 2009; Delgado-Fernandez et al., 2013). Downwind of reattachment, flow begins to recover in response to the dissipation of the turbulent wake layer and the redevelopment of the Internal Boundary Layer (IBL) (Walker and Nickling, 2002). This leads to

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increased erosive potential as airflow velocity begins to accelerate near the surface allowing for increased sediment flux (Baddock et al., 2007). Although limited by scale, these studies have significantly advanced our knowledge of the processes of sediment transport and changes in dune morphology.

Ultrasonic anemometry (UA), has enabled better understanding of small-scale flow signatures, such as coherent flow structures, and provides fresh insights into the non-linear processes of sediment transport and dune maintenance (Lee and Baas, 2012; Bauer et al., 2013). With this ability to monitor airflow in 3D there has been a shift in focus towards the study of complex turbulent flow variables (e.g. turbulent kinetic energy and Reynolds stress) (Baddock et al., 2011; Weaver and Wiggs, 2011; Delgado-Fernandez et al., 2011; Wiggs and Weaver, 2012; Chapman et al., 2012, 2013; Smyth et al., 2013). While challenges remain during both field set-up and post-processing, UA is providing a new understanding on turbulent flow signatures and subsequent sediment transport (van Boxel et al., 2004; Walker, 2005; Baddock et al., 2011; Weaver and Wiggs, 2011; Lee and Baas, 2012). Studies on topographically modified airflow perturbations and sediment transport conditions in arid environments (Baddock et al., 2011; Weaver and Wiggs, 2011; Wiggs and Weaver, 2012) have examined the role of time-averaged airflow and turbulent fluctuations on aeolian dynamics. However, studies that rely solely on in situ airflow measurements are not readily applicable to other environments. Livingstone et al. (2007) identified the need for future studies to utilize computational models to deductively identify important flow dynamics that are not easily measured in the field in order to guide future experimental designs.

Computational Fluid Dynamics (CFD) modelling allows for a wider scale understanding of emergent airflow dynamics over dune environments (Jackson et al., 2011, 2013a; Smyth, 2016). Early studies by Parsons et al. (2004a,b), showed the ability of a numerical modelling approach to simulate turbulent flow conditions over idealised transverse dune topography within a two-dimensional domain. Subsequent studies have modelled airflow in 2D over transverse (Schatz and Herrmann, 2006; Araújo et al., 2013; Jiang et al., 2014), foredunes (Wakes et al., 2010; Hart et al., 2012), and engineered dunes (Smyth and Hesp, 2015). 2D models allow for the simplification of model inputs and provide researchers with the ability to identify airflow perturbations and sediment dynamics in relation to user modified dune geometries (Parsons et al., 2004b; Schatz and Herrmann, 2006; Araújo et al., 2013; Jiang et al., 2014; Smyth and Hesp, 2015). While this idealised approach has improved understanding of the sensitivity of IBL conditions in relation to dune morphology, it oversimplifies flow dynamics by neglecting the horizontal spanwise flow component (v) (Liu et al., 2011). Michelsen et al. (2015) qualitatively compared flow conditions between a 2D dune profile and 3D dune topography. Modelling results showed that by omitting v 2D models underestimate flow velocity over the stoss slope. This, in turn, would modify the secondary airflow patterns often identified in 2D CFD models, including the reattachment point and streamline angles (Araújo et al., 2013).

3D CFD studies have been conducted over barchan (Herrmann et al., 2005; Feng and Ning, 2010; Michelsen et al., 2015), nebkah (Feng and Ning, 2010), star (Liu et al., 2011), foredune (Jackson et al., 2011, 2013a; Hesp et al., 2015), blowout (Smyth et al., 2012, 2013), linear (Joubert et al., 2012), and barchan dune environments (Jackson et al., 2013b). These studies provide a greater understanding of representative flow perturbations; however, numerical simulations require field measurements for model calibration and validation (Livingstone et al., 2007). Of these CFD studies only a few have actually quantitatively validated modelling results with recorded airflow measurements using comprehensive arrays of 3D UA across actual dune topography (Jackson et al., 2011; Smyth et al., 2012, 2013; Hesp et al., 2015). Generally, these studies showed good agreement between measured and modelled results of mean velocity, directionality, and secondary flow conditions (e.g. lee side flow deflection and recirculation cells). While advances have been made in recent years in CFD modelling, more field studies are still required to examine the role of varying 3D dune morphology and associated airflow dynamics. This paper investigates flow-bedform interaction for a variety of incident wind conditions and natural barchan dune shapes. It also, for the first time in 3D, examines the potential sediment transport directly from the CFD surface shear stress outputs, to show transport patterns across both the dune and interdune surfaces.

This paper is based on high density field measurements of aeolian dynamics across single dune lengths. Measured (field experiments) and modelled (CFD) 3D airflow perturbations and sediment dynamics are presented for three distinct dune environments. Experiment 1 was conducted over two small closely-spaced barchan dunes with crest-normal flow conditions. Experiment 2 measured flow over a medium sized barchan dune that was selected to examine both the crest-normal flow conditions over the stoss slope and the horizontal heterogeneity of secondary airflow (e.g. vortices and reattachment points) in the lee. Experiment 3 measured reversed winds, originating from the stoss slope, over a small rounded barchan dune. High resolution field measurement of 3D airflow over the dune topographies was used to calibrate and validate CFD models. This coupled approach allows the analysis of complex 3D airflow beyond traditional field sampling and measuring techniques. The main objectives of this paper are to: (1) present and analyse measured flow perturbations based on variability in dune morphology and incident airflow conditions; (2) test the CFD model's ability to simulate complex airflow in 3D; (3) identify emergent flow patterns across barchan dunes of varying geometries; (4) assess the geomorphic implications for characteristic airflow patterns including surface shear stress; and (5) for the first time examine potential sediment flux patterns across these landforms in 3D.

2. Study site

Maspalomas (27°44′24.73″ N and 15°34′26.19″ W) is an arid dune system on the south coast of Gran Canaria, in the Canary Island Archipelago, Spain (Fig. 1a, c). Maspalomas is a ~3.6 km^2 dunefield consisting primarily of barchan and barchan dune ridges. The dunefield receives 76 mm of precipitation per year on average and has a mean grain size of 0.22 mm (Mayer et al., 2012; Alcantara-Carrio and Fontan, 2009). There is a bi-modal competent wind regime of easterly and westerly winds with the higher magnitude and frequency of north easterly trade winds leading to net SW migration of sediment (Fig. 1b). Sediment is input into the system from a source area on the narrow offshore shelf adjacent to Playa del Inglés. Sediment deposited on the beachface by wave processes in the eastern section of the dunefield soon develops into small and highly mobile incipient barchan dunes. These rapidly moving barchan dunes coalesce into large barchan dune ridges in the central section of the dune field where sediment supply is the highest (Jackson et al., 2013b). Further downwind at the terminus section, adjacent to Playa de Maspalomas, sediment supply begins to diminish as individual barchan dunes continue their migration downwind before re-depositing sediment back into the ocean. The northwest section of the dunefield has experienced large scale stabilization caused by the disruption of airflow patterns and sediment transport in response to intensive urbanisation across an elevated paleo-alluvial terrace (Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014). This has led to an increase of vegetation and lack of dune mobility in the urban shadow zone. Experiment locations 1–3 (Figs. 1a, 2a–c) were selected based on