Planar and Volumetric Quantification of Flow Associated with Interacting Barchan Dunes

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Abstract An experimental investigation of flow around interacting barchan dunes is presented herein. Barchan dunes are three-dimensional topographic features that are produced by geophysical flows in both aeolian and subaqueous environments. Barchans have been discovered on the surface of several planets, typically in regions with low variability in flow direction and limited sediment supply. They appear in fields in which dune-dune interaction mechanisms control dune evolutionary processes that involve collision, merging and splitting, producing highly dynamic topographic systems. While the morphology of barchan dunes has been widely studied, the morphodynamic interaction mechanisms controlling their formative processes remain poorly understood. In this paper, we report both high-resolution planar and volumetric PIV measurements focusing on a number of simplified tandem configurations in which the interaction between barchan dunes modifies the flow as compared to the flow around an isolated dune. The case of a symmetrical isolated barchan dune is reported for comparison. The investigation is based upon use of a refractive index matching (RIM) approach. Physical models of barchan dunes were fabricated by casting a urethane material into a mold that was 3D printed. The models were fixed in a RIM flow tunnel and rendered invisible, thus facilitating unimpeded data collection around the whole bedform. Planar measurements at high spatial and temporal resolution were conducted in the x-z plane at several elevations in order to reveal the three-dimensionality of the flow. In addition, volumetric measurements were performed to reveal the three-dimensional coherent structures shedding from the barchan crests and observe their evolution as they convect and impinge onto the downstream barchans. Our results have significant morphodynamic implications. The offset cases we considered show that the flow symmetry is highly sensitive to dune alignment and this can provide insight to understand the imperfect symmetry of barchans in natural environments. The $RSS$ and $TKE$ maps generated by our measurements demonstrate that the dynamics of the shear layer separating at the crest may drive the transport of sediment from the upstream dune and also erosion processes on the downstream dune.

1. Introduction

Barchan dunes are naturally occurring three-dimensional topographic features that have been observed on Earth’s surface as well as on other planets. On Earth, they occur both in aeolian environments characterized by sandy deserts (e.g. White Sands National Park in New Mexico) as well as in subaqueous environments (i.e. river beds, continental shelf; Charru and Franklin, 2012). The recent discovery of barchan dune fields on Mars (Fig. 1a) has attracted renewed attention among the geomorphological community. Understanding the morphodynamic mechanisms controlling the formative processes of these bedforms has the potential to provide critical insight on the environment in which they formed. Barchan dunes form in regions with weak variability in flow direction and limited sediment supply (Bagnold, 1941, Lancaster, 2009). In such environmental conditions, the flow mobilizes the sediments and produces bedforms with a crescent shaped planform that are termed barchans. The morphology of these bedforms has been investigated by several authors (see review in Lancaster, 2009). Typically, barchan dunes possess a gentle stoss side slope, rounded crest and steep leeside, with their horns being directed downwind in a quasi-symmetrical configuration. Barchan dunes are found with a wide range of heights, widths, lengths and aspect ratio. Natural occurring bedforms are dynamic systems whose evolution
involves changes in their size and shape. Additionally, as a result of sediment erosion on the stoss side and deposition in the leeside, these dunes migrate in the direction of the prevailing flow. Typically, barchan dunes form in fields that possess a broad distribution in dune size (Fig. 1a). For a given bedform, the migration rate can change within a certain range and is a function of the dune size and flow intensity. Each bedform is characterized by a mean migration rate that is inversely proportional to the bedform size (Fig. 1b, Andreotti et al., 2002). Different migration rates among dunes result in variable bedform spacing, with smaller dunes migrating at faster rates and approaching larger dunes that possess slower migration rates. Eventually, bedform–bedform interactions occur (e.g. collision, merging, splitting; see Endo et al., 2004). These morphodynamic processes are controlled by complex feedback mechanisms mutually linking three key elements: fluid flow, sediment transport and bed morphology.

The aim of the present work is to contribute to the understanding of the fluid-flow mechanisms responsible for the formation, migration and interaction of barchan dunes. To this end, we study the three-dimensional flow generated by the interactions between fixed barchan-dune models arranged in pairs via experiments in an optically-accessible flow environment using both planar and volumetric particle-image velocimetry (PIV) methods. Figure 2 shows a schematic of the topographic cases considered in this paper. In addition to the isolated barchan dune case (Fig 2a) that was used as a benchmark, the flow past three different tandem arrangements was studied: in-line collision, offset collision and offset ejection.

Fig. 1. a) Barchan field on Mars illustrating interacting barchan dunes with different sizes and spacing but oriented in the same direction (Credits: HiRISE Camera on the Mars Reconnaissance Orbiter, NASA; b) Field measurements showing the relationship between dune height and migration rate (from Andreotti et al., 2002).

Fig. 2 Schematic diagram showing the four barchan dune configurations used herein.
2. Experimental method and physical models

All barchan dune measurements were conducted in a new Refractive-Index-Matched (RIM) flow facility developed in the Laboratory for Turbulence and Complex Flow (LTCF) at the University of Illinois at Urbana-Champaign (Blois et al., 2012, 2013). RIM techniques inherently refer to two-phase systems and involve immersing transparent solid materials in a fluid having identical refractive-index, RI, such that the solid objects are rendered invisible within the working fluid. RI matching eliminates refraction at the solid-fluid boundaries and allows unobstructed and unaberrated optical access near and through the solid phase. The solid and fluid phases are selected such that their RIs can be precisely matched by adjusting both the chemical composition of one or both of the two phases (typically the fluid) as well as the temperature of the system. This novel facility employs an aqueous solution (~63% by weight) of sodium iodide (NaI) as the working fluid (refractive index, \( n_f \approx 1.49 \)). This solution has a specific gravity of \( \sim 1.8 \) and its kinematic viscosity \( (\nu_{\text{NaI}} = 1.1 - 1.5 \times 10^{-6} \text{ m}^2\text{s}^{-1}) \) is only 10-15% greater than that of water.

The barchans dune models were fabricated by casting a clear urethane material \((n_s \approx 1.49)\) into specific molds (Fig. 3a). Figure 3b shows an example of a barchan model used herein. The morphology of each individual barchan model was based on previous work. In particular, we used the digital elevation model (DEM) that was developed by Palmer et al., (2012) through a statistical analysis of a large field dataset on barchan morphology. Nevertheless, we used a height-width ratio that was twice as large as that used by Palmer et al., (2012), and thus our results are not directly comparable with previous work. More specifically, we used two different barchan models. The dimensions of the larger barchan-model were: height \( h = 15 \) mm, width \( w = 70 \) mm, and length, \( l = 70 \) mm. This model was used for the isolated case (Fig. 2a). The volume of the smaller barchan was 1/8th that of the larger, isolated barchan. Like the model shown in Fig. 3, all the barchan models used herein were perfectly symmetrical.

The barchan models were fixed to the side wall of the test section and immersed into the working fluid. By fine-tuning the temperature of the working fluid, the refractive indices of the fluid and the solid model were matched precisely. This procedure rendered the models invisible, minimizing laser reflections and optical aberrations and therefore facilitating full optical access to the flow around such complex three-dimensional topography. Figure 4 shows a sequence of photographs in which one of the tandem barchan models (i.e. offset ejection), fixed in the test section, is imaged prior to immersion in the NaI solution (Fig. 4a), during partial immersion (Fig. 4b), and after full immersion (Fig. 4c) in the NaI solution, illustrating the fidelity of the refractive-index match achievable in this experimental set-up. The RIM methodological approach was essential to enable study of the three-dimensionality of flow around the barchan model.

The test section of the tunnel, entirely constructed with clear acrylic, is 2.50 m long with a constant cross-section of 0.1125 × 0.1125 m. The slope of the test section is adjustable from 0 to +2% and the slope can be monitored using a liquid capacitive, gravity-based inclinometer. While the floor and lateral walls are fixed, the ceiling is removable to provide full access to the interior of the tunnel for maintenance operations and installation of flow models. The removable cover is sealed with an EPDM gasket and secured with stainless steel fasteners to handle a slight positive (5 psi) pressure. This capability allows generation of free-surface flows by filling the test section only partially with the working fluid and introducing nitrogen gas \((N_2)\) into the overlying space under a slight positive pressure. The use of \(N_2\) avoids the risk of discoloration of the salt solution (that occurs by \(I^-\)ions formed by simultaneous exposure to oxygen and visible light) during operation of the facility. The RIM flume was equipped with two identical, close-coupled, fiberglass-reinforced centrifugal pumps that deliver a combined discharge in the range 0.016 – 1 m³s⁻¹ when utilizing an aqueous solution of NaI (at 64% by weight) as the working fluid and operating at 0% slope. A transistor inverter variable-frequency controller regulates the frequency output to the pump to precisely control the flow rate through the system. The volumetric flow rate through the tunnel is monitored by an electromagnetic flowmeter mounted in the supply line of the system piping.
to energy transferred by the pumps to the working fluid, the temperature of the fluid would tend to progressively increase during the experiments. The temperature control system was thus critical, not only for fine-tuning the RI of the fluid, but also to maintain it over long periods of time, thus allowing long experiments to be conducted. Such a control system comprises a thermocouple, an electronically-controlled modulating valve and an in-line heat exchanger. A tube and shell heat exchanger was installed in the supply pipe. The working fluid is conveyed through a set of 36 titanium tubes (0.019 m diameter) held inside a PVC shell while the cooling fluid is circulated through the shell. The modulating valve regulates the flow rate of the cooling fluid, while a set-point controller monitors the temperature of the working fluid through input from a thermocouple probe installed in the upstream duct. Upon initiation of the temperature control system, the working-fluid temperature stabilizes to a constant set-point value. The temperature control process is fully automated and is able to maintain the temperature constant to within 0.05°C, which translates to a 0.001% change in the fluid RI.

The NaI solution is chemically unstable in the simultaneous presence of oxygen and light. This chemical instability results in two problems: high corrosion and, above all, optical degradation. The NaI was stabilized by removal of the dissolved oxygen using a dedicated deoxygenation processor. The deoxygenation procedure consisted of exposing the solution to cycles of deep vacuum (-29.9” Hg) followed by nitrogen pressurization (5-10 psi). By increasing the partial pressure of the nitrogen component, the partial pressure of the oxygen in turn decreases. In order to enhance this process, the solution was recirculated and sprayed from the top in order to increase the surface-volume ratio of the solution. Additional details on the facility are given in Blois et al., (2012).

The models were fixed to the side wall of the test section and arranged in a number of geometrical configurations. In this paper, we report results relative to the four configurations described in Fig. 2, which include one case of an isolated barchan and three cases of barchans in tandem. Contrary to the experiments conducted by Palmer et al., (2012) that considered exclusively aligned barchan models that would produce a symmetrical flow field, herein we considered an offset dune configuration. Additionally, only the case of interacting barchan dunes with different sizes was considered herein. The spacing, λ, between the barchan models was kept constant and equal to the length of the smaller dune.

Some of the simplifications we adopt in our physical models are: i) the bedforms are symmetrical and preserve their shape regardless of their position; ii) we study steady state conditions assuming that the time scales associated with bedform migration and morphological evolution are much larger than those associated with the dynamics of the flow; iii) sediment transport is absent in our experiments, and thus we cannot either measure the erosion or deposition rates or assess the feedback mechanisms between mobilized sediments and fluid flow; iv) the interaction is limited to the two bedforms, and thus cannot establish the interaction of more complex field configurations.

Figure 3. (a) Barchan mold. (b) Model cast in a clear urethane material with $n \approx 1.49$. 
the identification of the out of the model employed required angled orientation of the cameras would be beneficial as confirmed by previous work (Palmer et al., 2012) in which the opaque nature of the model employed required angled orientation of the cameras, thus introducing uncertainties in the identification of the out-of-plane motion.

The volumetric PIV measurements were conducted using the V3V system (V3V-9800) from TSI (Lai et al., 2008; Sharp et al., 2009) illustrated in Fig. 5b. The system consisted of three high-speed (180 fps) 4-million pixel cameras (2048 × 2048) rigidly fixed on a triangular configuration through
a purpose-designed mount. The images are 8-bits, with a pixel size of 5.5 microns. 85 mm camera lenses were used with a fixed aperture of f16. To illuminate the tracer particles, a 200ml/pulse Nd:YAG dual cavity laser (Evergreen from Quantel) combined with two cylindrical lenses to illuminate the measurement volume, were used. The V3V cameras and laser pulses were triggered by a synchronizer with 1 ns resolution. The pulses from each laser were timed to straddle neighboring camera frames in order to produce images suitable for 3D particle tracking. The V3V measurements were performed by orienting the axis of the cameras in the wall-normal direction as shown in Fig. 5b. Measurements were conducted at three different streamwise locations for two different interacting dune configurations: the inline collision (Fig. 2b) and the offset collision (Fig. 2c). A total of 1000 image pairs were acquired for each configuration. InsightV3V 4G was used to process and reconstruct the image pairs into instantaneous velocity volumes. The measurement volume was 50 × 20 × 50 mm³ (x × y × z, respectively). The system is capable of resolving the flow with a spatial resolution of approximately 2 mm³.

Fig. 5. (a) Planar PIV experimental setup illustrating elongated streamwise field of view in the x–z (wall-parallel) plane achieved using two PIV cameras with slightly overlapping regions of interest. Bottom left shows a representative PIV particle image at y = 0.5h. (b) Volumetric PIV setup.

V3V Data Processing

Each V3V realization consists of six separate images, three images at time t₀ (one image from each of the three apertures) and three images at time t₀ + Δt (one image from each of the three apertures). The 3D particle interrogation scheme is based upon the work of Ohmi and Li (2000) and is implemented in three primary steps: 2D particle identification, 3D particle identification and 3D particle tracking. The three steps consist of: 1) determining the 2D particle locations in each image; 2) determining the 3D particle locations in space, and 3) tracking the particle displacements in the measurement volume. Detailed description of these steps are given as follows.

2D Particle Identification

The first interrogation step involves identifying the 2D particle locations in the individual images. This is achieved by setting two parameters. The first is a baseline intensity threshold. Any valid particle must have a peak intensity above this threshold. This quickly reduces the search area to include valid particles and eliminate background noise. The second parameter is a local ratio, in which the particle peak intensity must be larger than the local background by this ratio. Finally, a Gaussian intensity profile is fitted to the particle image, the peak of which represents the center of the particle.
3D Particle Identification

Images from each of the apertures are effectively combined in order to determine the 3D location of each particle. Each triplet represents a single particle in the flow. The centroid of the triplet represents the x and y location and the size of the triangle represents the z location. The correspondence of a 2D particle in one image to the same particle in the other two images is achieved through a volumetric spatial calibration. The spatial calibration is performed by traversing a single plane target through the measurement region in the z direction and capturing images at regular intervals. Dots on the calibration target are regularly spaced at 2.5 mm in the x and z directions, and the target is traversed in 2 mm increments in the depth or y-direction. The calibration dot locations from each image are analyzed in order to define a set of dewarping polynomials relating unique locations of intensity on the camera sensor with particle locations in real-world coordinates.

Figure 6a shows a schematic of the V3V aperture arrangement. The view is from the back of the camera looking toward the measurement volume (green cube in center). Only the camera lenses (blue cylinders) and a single particle (gray sphere in center) are shown for clarity. The blue, green, and red lines represent rays extending from the top, left, and right aperture lenses to the particle, respectively. White squares behind each lens display 2D representations of the view from that aperture. Consider the particle as seen by the top 2D image. The blue ray appears as a single dot; however, in the left and right images, the blue ray appears as a line. The algorithm searches along this defining ray in the left and right images for possible 2D particle matches. The search is performed in two steps, a coarse search, and then a fine search. The fine search requires the centroid of the particle position to match within 0.5 pixels in all three images. If a triplet is not found that falls within the 0.5 pixel criteria, the 2D particles are not used. This process is repeated for all particles in the field.

3D Particle Tracking (Relaxation Method)

Once the volumetric particle locations are determined in frame A and frame B, the particles are divided into subgroups called clusters according to their spatial locations. Clusters here can be thought of as similar to interrogation regions in PIV. Clusters in B are larger in volume than corresponding clusters in A because particles may move out of the cluster area. Within a cluster, each pair of corresponding particles is assigned a number representing match probabilities. For example, \( P(m; n) \) is the match probability between particle \( m \) in frame A and particle \( n \) in frame B. Initially, each particle pair has the same probability, \( 1/N \), where \( N \) is the number of possible pairs between A and B for each cluster. The probability computation is based on the assumption that neighboring particles move similarly. These probabilities are then iteratively recomputed for all particles in the cluster, until they converge. For particle \( m \) in frame A, the maximum match probability \( P(m; n) \) is found among \( P(m; 1), P(m; 2) \). If this maximum probability is greater than a given threshold, then \( (m; n) \) is considered a matched pair. As shown in Fig. 6b, the probability is high (case shown on the left) when, if the displacement from particle \( m \) to particle \( n \) is applied to the other particles in the cluster, a matching particle is nearby. The probability is low (case shown on the right) when the displacement of other particles in the cluster results in no nearby particle matches.

After the 3D particle tracking step, the vectors lie on a randomly spaced grid, according to particle locations. In order to compute quantities such as vorticity, it is useful to have vectors on a rectangular grid. This was done through regular Gaussian-weighted interpolation.
4. Results and discussion

Instantaneous time-resolved 2D velocity vector fields were obtained for each of the four barchan configurations (isolated barchan dune, in-line collision, offset collision and offset ejection) at four different elevations (0.25h, 0.5h, 0.75h, 1h). Figure 7 illustrates an example of the distribution of streamwise instantaneous velocity for the specific case of an isolated barchan dune in the x-z plane. Note that measurements in this plane would be impossible in either a wind or water tunnel owing to laser blockage and/or aberration upon interaction with the barchan models. In contrast, because the RI of the fluid and the solid models is matched precisely in the present experiments, no loss of laser energy nor laser deflection is noted as it traverses through the solid models, while optical aberrations are also minimized. The results show that the flow accelerates on the stoss side where it may induce erosion over a mobile sediment bed due to high bed shear stresses. The flow then separates at the ridge, producing a three-dimensional shear layer that is suggested to present an arc shape. The flow region behind the leeside and underneath the shear layer is characterized by low momentum flow. In the case of mobile sediments, this low-momentum region (LMR) is associated with deposition of a fraction of the sediments that were entrained by the flow upstream and transported as bedload. The remaining fraction is transported along the horns of the barchans and is then entrained within the shear layer and transported downstream. The shear layer embodies a significant fraction of the Reynolds shear stress (RSS) and thus plays a central role, not only in transport but also in the erosion processes induced downstream of bedforms. The results reported in Fig. 7 show the high degree of flow three-dimensionality induced by these bedforms. In fact, each elevation presents a different flow structure with the LMR that shrinks as the measurement plane moves from the floor to the dune crest and with the two sides of the shear layer that move closer.

In order to reveal the differences between the flow produced at the same elevation by different barchan geometrical configurations, the ensemble-averaged flow field was computed for each case. The mean streamwise velocity field in the x-z plane at y = 0.25h for each of the four barchan-dune configurations is shown in Fig. 8. These results confirm that the mean flow for the isolated case (Fig. 8a) is perfectly symmetrical as expected. Nevertheless, Fig. 8b reveals that in the case of another symmetrical configuration, the in-line collision, the presence of the small barchan upstream introduces some asymmetry. This can be noticed both between the two barchans and in the leeside of the downstream barchan. This disturbance from perfect symmetry, probably due to a non-perfect alignment of the two barchans, suggests that the flow is highly sensitive to any source of asymmetry. In fact, even a slight misalignment of two symmetrical bedforms may break the symmetry. These results illustrate that the asymmetry is exacerbated by offsetting the smaller barchan dune for both collision and ejection configurations (Figs 8c and 8d respectively). The offset significantly alters the flow around the larger barchan when compared to flow over the isolated
barchan dune, breaking the symmetry both upstream and downstream. Specifically, for the offset configurations considered herein, the characteristics of the recirculation region of the large barchan dune are rendered asymmetric in the spanwise direction due to a flow channeling between the two barchan dunes, with a noted enhancement in this recirculation near the horn of the larger barchan closest to the smaller dune. These results have important morphodynamic implications, as they suggest that even a small offset disturbance, such as in Fig. 8b, may significantly alter the dynamics of sediment movement in terms of erosion/deposition balances and sediment fluxes, leading to progressively less symmetrical configurations.

Figure 7: Velocity maps of instantaneous streamwise component for the isolated barchan configuration showing the flow structures at four different elevations. 0.25h, 0.50h, 0.75h, 1.0h.

In order to inform morphodynamic models able to estimate erosion/deposition rates, we constructed turbulent fluctuation maps around the barchans in terms of turbulent kinetic energy (TKE) and Reynolds shear stress ($\langle u'w' \rangle$; RSS). Specifically, Figure 9 presents the turbulent kinetic energy (TKE) computed from the resolved in-plane turbulent fluctuations while Fig. 10 presents the in-plane Reynolds shear stress ($\langle u'w' \rangle$; RSS). These single-point turbulence statistics confirm similar asymmetry owing to the presence of the smaller dune in all the three interacting cases examined herein (Figs 9b, 9c and 9d and Figs 10b, 10c and 10d). As expected, the isolated barchan model induces a symmetric flow structure in both of these quantities (Figs 9a and 10a). Similar to the case of the mean streamwise velocity component, the presence of a smaller colliding dune (Figs 9b and 10b), may introduce asymmetry in the distribution of turbulent fluctuations both in-between the dunes and downstream of the larger dune. This effect, probably due to a non-perfect alignment between the dunes, is revealed more clearly by the TKE distribution by comparing the two symmetrical cases (Figs 9a and 9b). The offset of the smaller dune, either upstream (offset collision) or downstream (offset ejection) of the larger barchan, enhances the symmetry in the configurations (Figs 9/10c and 9/10d, respectively). In the case of TKE, a noted reduction is observed downstream of the horn of the larger barchan closest to the smaller dune in both of these configurations, along with a clear increase downstream of the other horn of the larger barchan (both relative to the TKE values of the isolated dune, Figs 9c and 9d). This reduction in TKE is spatially
coincident to the enhanced recirculation noted near the horn of the larger barchan closest to the smaller dune (Figs 8c and 8d). The offset collision and ejection configurations also induce asymmetry in the in-plane RSS (Figs 10c and 10d, respectively), though an enhancement is noted downstream of the horn of the larger barchan closest to the smaller dune when the latter is upstream of the larger dune (collision, Fig. 10c), while a reduction is noted when the smaller barchan is downstream of the larger dune (ejection, Fig. 10c). The turbulent structures responsible for these patterns transport a significant fraction of the RSS and likely play a critical role in dune evolution by driving sediment transport processes as recently identified in complementary large-eddy simulations (Omidyeganeh et al., 2013).

Figure 8. Mean streamwise velocity fields for the four different barchan-dune configurations in the x–z plane at y = 0.25h. Streamlines are overlaid to highlight the mean-flow structure.

Figure 9. Turbulent kinetic energy, TKE, computed from the in-plane velocities for the four different barchan-dune configurations in the x–z plane at y = 0.25h.
Figure 10. In-plane Reynolds shear stress, $<u',v'>$ fields for the four different barchan-dune configurations in the $x$–$z$ plane at $y = 0.25h$.

Figure 11 presents representative successive velocity fields from the volumetric PIV measurements with the V3V system for flow between the smaller and larger dunes arranged in the in-line collision scenario. The iso-contours of swirling strength shown reveal the presence of complex three-dimensional coherent structures (horseshoe-like) that shed from the smaller dune, advect downstream and eventually impinge on the larger, downstream barchan dune. During their motion, these structures stretch and their heads move upward. These observations are consistent with results recently obtained in complementary large-eddy simulations (Omidyeganeh et al., 2013) that have important morphodynamic implications. These flow structures transport a significant fraction of the Reynolds shear stress and are thus likely involved in dune evolution by driving bedload and suspended sediment transport dynamics, hence controlling erosion/deposition processes. In particular, the vortex shedding process is associated with intense peaks of low pressure, which plays a role in sediment entrainment. Figure 12 presents instantaneous snapshots of the flow at two locations downstream of the larger barchan dune, highlighting the spanwise rollers that are shed from its crest that eventually evolve into horseshoe-like structures as they advect downstream.

Fig. 11 Instantaneous flow structures in successive velocity volumes captured by the V3V system.
5. Summary

This paper presents results from an experimental investigation of flow around interacting barchan dunes and provides insight to understand a number of morphodynamic issues associated with their evolution. Barchan dunes are three-dimensional topographic features generated by geophysical flows in the presence of mobile sediments and are important for a number of engineering and geophysical reasons. Barchans typically occur in fields with significant heterogeneity in dune size and migration rate. In this situation, the interaction between barchans of different sizes is highly recurrent and produces complex processes such as collision, amalgamation and breeding. While the morphology of barchan dunes has been widely studied, the interaction between turbulent flows and barchans is limited to a few recent studies (Charru and Franklin, 2012, Palmer et al., 2012). The number of direct measurements is even lower when it comes to the interaction mechanisms occurring between close barchans within a dune field due to the complexity of the geometry of these bedforms. As a result, the sedimentary processes involved in the collision and breeding of such dunes remains poorly understood. In this paper, we approach the study by using idealized physical models that allow, for the first, time accurate interrogation of the flow with both high-resolution planar and volumetric PIV measurements. We focus on a number of simplified geometrical configurations of barchan dunes in tandem and reveal the modifications induced to the flow as compared to the case of flow around isolated dunes. We started our analysis from the benchmark case of a symmetrical isolated barchan dune, and then discussed three tandem configurations: in-line collision, offset collision and offset ejection.

The investigation is based upon use of an approach employing refractive index matching. Physical models of barchan dunes whose shape was based upon previous work (Palmer et al., 2012) were fabricated casting urethane material into 3D printed molds. The models were fixed in a RIM flow tunnel and rendered invisible, thus facilitating unimpeded data collection around the whole bedform. Planar measurements at high spatial and temporal resolution were conducted in the x-z plane at several elevations from the wall in order to reveal the three-dimensionality of the flow. In addition, volumetric measurements were performed to reveal the three-dimensional structures generated by the barchans and to observe their evolution as they convect and impinge onto the downstream barchans. The measurements conducted in this work would be impossible in either a wind or water tunnel owing to laser blockage and/or aberration upon interaction with the barchan models. In contrast, because the RI of the fluid and the solid models is matched precisely in the present experiments, no loss of laser energy nor laser deflection is noted as it traverses through the solid models, while optical aberrations are also minimized.
The analysis of the case of an isolated barchan shows that the flow separates at the crest of the barchans, producing a three-dimensional shear layer that is suggested to present a symmetrical (in the spanwise direction) arc-like shape. The flow region behind the leeside is characterized by low momentum. Here, in a mobile bed, a fraction of the sediment that was entrained upstream would be deposited resulting in bedform migration. Our results reveal the structure of the shear layer which has important morphodynamic implications. The shear layer embodies a significant fraction of the Reynolds shear stress (RSS) and thus plays a central role in the erosion processes induced by the dune to downstream bedforms.

While the flow symmetry for an isolated barchans was confirmed, our results indicate that the presence of an upstream disturbance may break the symmetry of the whole flow around the downstream barchan unless the two dunes are perfectly symmetrical and perfectly aligned. The in-line case we considered shows that the symmetry of the mean flow is highly sensitive to dune alignment, and this can provide insight to understand the imperfect symmetry of barchans in natural environments.

The offset cases enhance the asymmetry. This is particularly apparent in the single point statistics (TKE and RSS). The streamlines show an enhanced recirculation near the horn of the larger barchan that is closer to the smaller barchan in both the offset cases. A reduction in TKE, spatially coincident with the enhanced recirculation, is noted at the same location. RSS show a contrasting behavior with enhancement for the case of offset collision and reduction in the case of offset ejection.

Finally, the three-dimensional flow visualizations obtained extracting the iso-contour of the swirling strength from the V3V dataset reveal the presence of horseshoe-like vortical structures shed from the barchan crest. In the in-line case considered herein, these vortices convect and impinge onto the larger barchan dune downstream. Their behavior is consistent with recently published LES simulations using similar geometries.

Although our experiments refer to fixed bedforms and no mobile sediments are considered, our results have strong morphodynamic implications suggesting that the dynamics of the shear layer separating at the crest may drive not only the transport of sediment from the upstream dune but also erosion processes on the downstream dune. These results can be used to inform and validate numerical models that can be used to generate predictions on more complex configurations. Future refractive-index matching experiments using mobile sediment may allow us the intriguing opportunity to investigate these turbulent flow – mobile bed interactions.

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