PIV measurements of flow around interacting barchan dunes in a refractive index matched flume

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ABSTRACT: Barchan dunes are three-dimensional, crescent shaped bedforms found in both Aeolian and subaqueous environments, including deserts, river beds, continental shelves, and even the craters of Mars. The evolution of and dynamics associated with these mobile bedforms involve a strong degree of coupling between sediment transport, morphological change, and flow, the last of which represents the weakest link in our current understanding of barchan morphodynamics. Their three-dimensional geometry presents experimental challenges for measuring the full flow field, particularly around the horns and in the leeside of the dunes. In this study we present measurements of the turbulent flow surrounding fixed barchan dune models in various configurations using particle image velocimetry in a refractive index matching flume environment. The refractive index matching approach enables near-surface measurements, as well as access to the whole flow field by rendering the solid models invisible. While experiments using solid models are unable to directly measure sediment transport, they allow us to focus solely on the flow physics and full resolution of the turbulent flow field in ways that are otherwise not possible in mobile bed experiments. The results presented here include a statistical analysis, focusing on the spatial structure of coherent motions in the flow through the use of two-point correlations, as well as an analysis of 3D vortical structures in the flow captured using time-resolved cross-plane measurements.

1 INTRODUCTION

Barchan dunes typically occur in fields with significant heterogeneity in dune size and migration rate (Lancaster, 2009). In this situation, the interaction between barchans of different sizes produces complex processes such as collisions, 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 (e.g. Palmer et al., 2012; Bristow et al., 2018). “Minimal” models without an adequate simulation of the wake flow structure induced by dunes (Parteli et al., 2014) struggle to accurately predict the morphodynamics of barchans when they come in close proximity, including dune--dune collisions. This model deficiency is readily observed in the Figure 1 which compares the model results (a-e) (Parteli et al., 2014) of a smaller barchan approaching a larger one (barchan migration rate is inversely proportional to size) with a similar scenario observed in laboratory experiments (f-j) (Hersen and Douady, 2005). Figure 1 highlights the contrasting dynamics, with erosion of the downstream dune occurring prior to contact, indicating that key flow physics associated with such interactions is being missed by these models, and thus further experimental work is needed to elucidate the role of unsteady turbulence in barchan morphodynamics.

In the present work, we study the flow field both in the wake of an isolated barchan and in the interdune space of interacting barchans using a combination of low and high frame-rate measurements with both two-component planar PIV and three-component stereo-PIV. The low frame-rate

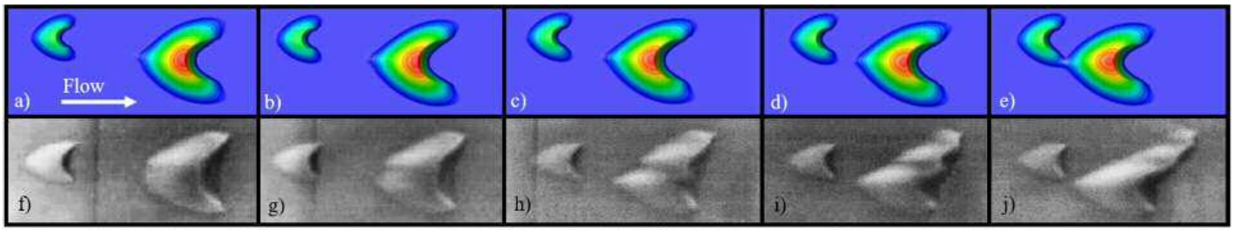

Figure 1. Comparison of (a-e) morphodynamic model and (f-j) mobile-bed flume experiments (Hersen and Douady, 2005), highlighting model deficiencies for a barchan collision. Code courtesy Dr. H. Herrmann (Parteli et al., 2014) (modified by us for this scenario).

measurements are made in all three planes independently (*x–y*, *x–z*, *y–z*), while high frame-rate measurements were limited to the cross-plane (*y–z*), allowing us to reconstruct the 3D flow field using Taylor's hypothesis. Several different configurations of models are investigated, including a baseline isolated case and a series of dune–dune collision configurations where the upstream and downstream barchans are laterally offset from each other.

Access to the flow field around these geometrically complex dunes is achieved using a refractive index matching (RIM) approach. Transparent models of barchan dunes, whose shape was based upon previous work (Palmer et al., 2012), were fabricated by 3D printing positive models, which were used to create negative silicone molds, which in turn were used to cast transparent acrylic models. The models were fixed in a RIM flow tunnel that employs an aqueous solution of sodium iodide (~63% by weight) as the working fluid, and rendered invisible, thus facilitating unimpeded data collection around the entire bedform configuration. The RIM approach also minimizes reflections of the laser sheet off the model and floor surfaces, allowing for higher accuracy measurements in these critical regions.

2 RESULTS

Low frame-rate measurements from all three planes (*x–y*, *x–z*, *y–z*) provide an understanding of the mean flow topology (not shown here). For an isolated barchan, flow separates over the crest, forming a recirculation region in the leeside between the horns, and shear layer which emanates downstream. As flow reattaches in the wake, a vortex structure similar to a horseshoe vortex system develops downstream of the horns, where two counter-rotating streamwise oriented regions of strong swirling strength dominate the flow particularly near the bed. When a smaller barchan is placed upstream, at a lateral offset, a flow that is similar to that in the wake of the isolated barchan is produced as the new inlet condition for the downstream barchan, with its wake veering around the downstream barchan's horn.

In Figure 2 we show an example of calculations of length scales in the flow for the y/H = 0.25 plane, from all four barchan configurations. These calculations are made by computing the spatially inhomogeneous two-point correlation function ρ_{uu} at each grid point. The contour line of ρ_{uu} = 0.5 is fitted to an ellipse, of which the lengths of the long and short axes, as well as the orientation relative to the *x*-axis, can be calculated. The length of the long axis of the ellipse is thus a proxy for the integral length scale in the flow at that grid point. Calculations made at each grid point allow for contour maps of length scales (as well as aspect ratios and orientation angles, not shown here) to be analysed for the entire field of view, in each measurement plane.

Several key features are made evident through these correlation length scale calculations. The wake of the isolated barchan has a very complex structure, with a streak of short length scales aligned with the centerline, and longer length scales prevailing downstream of each horn. In the wake of the upstream barchan, starting with the first collision stage, the length scales are significantly reducing in the interdune region due to the imposition of the shear layer from flow separation over the upstream barchan. This structure prevails far downstream, with a short length scale "streak" continuing downstream of the downstream barchan's elongated horn. While this brief abstract is unable to fully explore the results from this statistical analysis of the scales in the flow, these calculations provide a wealth of information about the structure of large scale coherent motions in the flow.

Application of Taylor's frozen field hypothesis to high frame-rate measurements allows for 3D reconstruction of the flow field. In Figure 3 we show an example of this from the wake of the isolated barchan, where isosurfaces of swirling strength, $\lambda_{ci} \approx 0.2\ \lambda_{ci,max}$ are shown and the structures are colored by distance from the wall, *y/H*. While rapid dissipation of turbulence in the wake requires careful treatment of this application of Taylor's hypothesis, such reconstructions are at least valid within an integral length scale, which from the previous results in shown to be on the order of several barchan heights. Within this single flow reconstruction we can observe periodically shed structures, as well as elongated vortices near the bed and larger spanwise oriented arches near the crest height.

3. CONCLUSIONS

These results demonstrate the utility of the refractive index matching approach for the measurement of flow around complex geometries such as the barchan dune. The ability to capture the entire flow field, particularly close to the model surfaces, such as in the allows analysis of first order flow features, such as the veering of the wake of the upstream barchan, as well as higher order turbulent statistics of dominant length scales in the flow. The application of high frame-rate cross-plane stereo-PIV enables the fully 3D flow field to be revealed and analysis of the instantaneous structures shed from the shear layer of the barchan dune. Together, such results shed light on the fundamental flow structures associated with the complex morphology of a barchan which are likely to be responsible for determining the erosion of downstream bedforms in close proximity.

4. ACKNOWLEDGEMENTS

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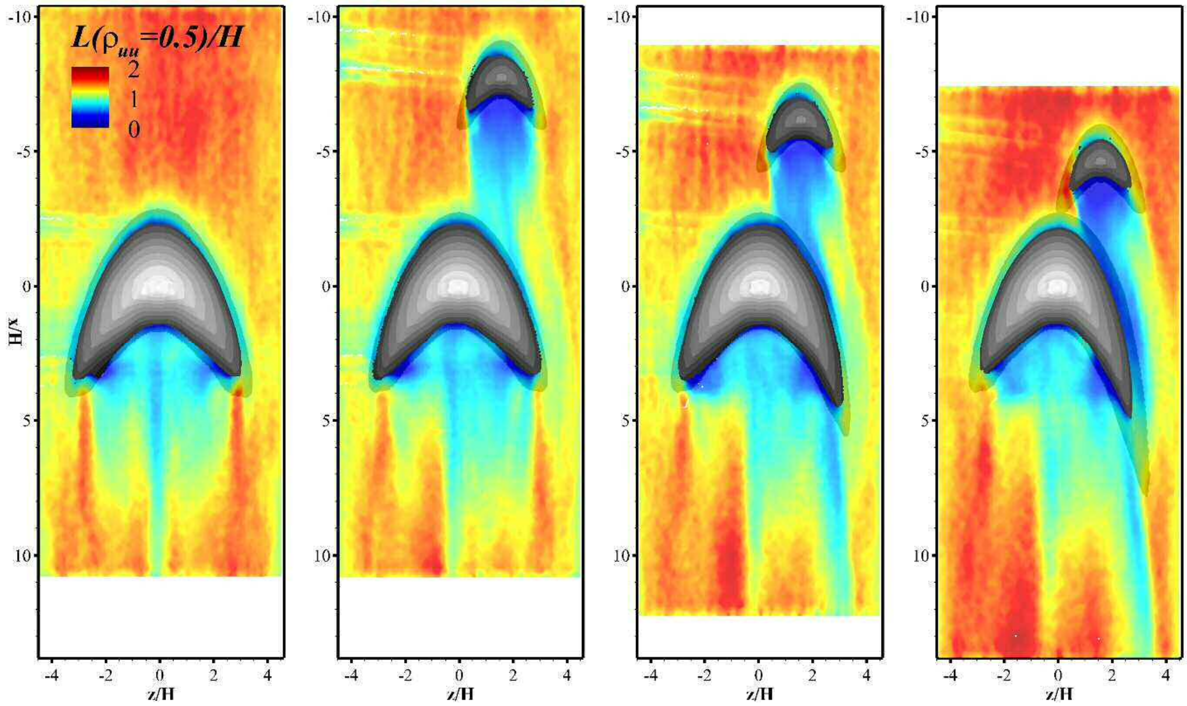

Figure 2. Spatial distribution of length scales, L, in (a) the isolated case, and (b-d) the collision cases, calculated in the wall-parallel plane y/H = 0.25.

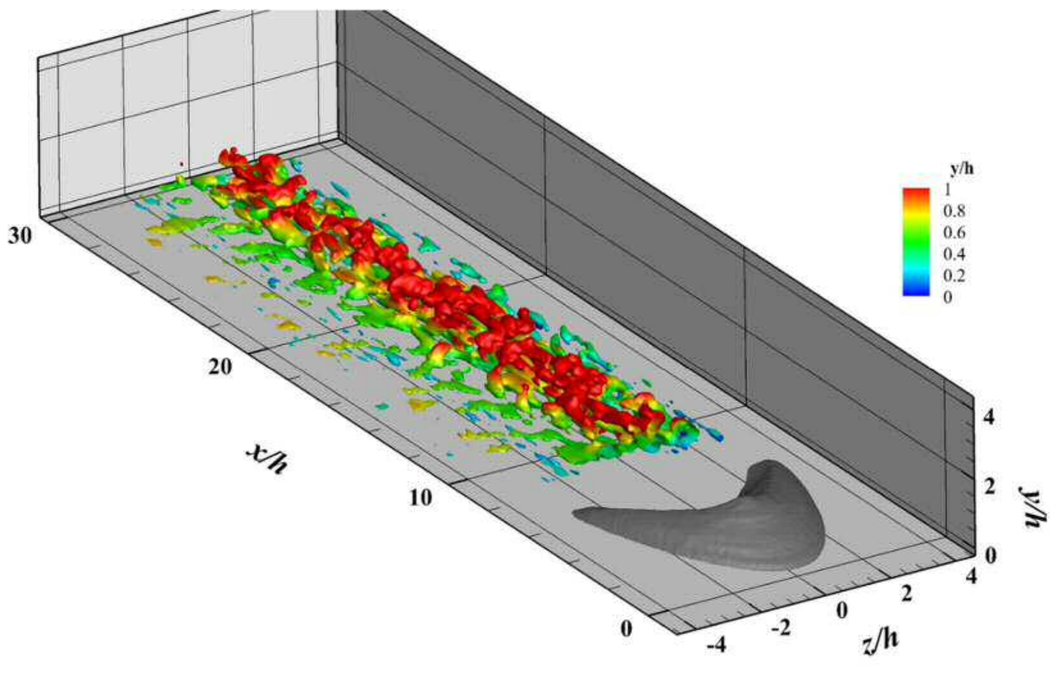

Figure 3. Isocontours of 3D swirling strength, $\lambda_{ci} \approx 0.2\ \lambda_{ci,max}$, colored by distance from the wall, in the wake of an isolated barchan, reconstructed using Taylor's hypothesis.