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Cross-plane stereo-PIV measurements in a refractive-index-matched environment of flow associated with barchan dunes immersed in a turbulent boundary layer

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1 Introduction

Barchan dunes are crescent-shaped bedforms that form in aeolian (i.e., wind-driven) environments (including both Earth and other planets, such as Mars) as well as subaqueous environments. Under the forcing of the aloft turbulent boundary layer, they migrate downstream at a rate inversely proportional to their size, which results in complex interactions between neighboring dunes of disparate scales. In particular, it has been observed that dunes will interact at a distance, causing changes in morphology without contacting each other, which is thought to be driven by the way dunes modify the local flow field Bristow et al. (2018); Assis and Franklin (2020).

In this study, the coherent structures formed in the wakes of barchan dunes are investigated using measurements of the flow over fixed-bed (i.e., solid) barchan models, both in the wake of an isolated barchan and the interdune region between interacting barchans (Fig. 1(a)). Furthermore, the interactions between the flow structures shed by the dunes and the structures in the incoming boundary layer are analyzed.

2 Methods

Experiments are conducted in the Large-scale Refractive-Index-Matching (LS-RIM) flume at the University of Notre Dame. Transparent models of barchan dunes were fabricated using a combination of 3D printing and casting to obtain transparent acrylic models for configurations including a baseline isolated case and a series of dune–dune collision configurations (Fig. 1(a)). The models were immersed in a turbulent boundary layer in the LS-RIM, with Reynolds number $Re_\tau \approx 1800$ and boundary layer thickness $\delta = 52.5$ m such that $H/\delta \approx 0.2$. The RIM approach involves using an aqueous solution of sodium iodide (≈63% by weight) as the working fluid, rending the models effectively invisible and thus facilitating unimpeded data collection around the bedform configuration. This technique minimizes reflections of laser sheet off the model and floor surfaces, allowing for higher accuracy measurements in these critical regions.

The flow field was measured using high frame-rate stereo-PIV in the y–z cross-stream plane at several streamwise positions. Images were captured at 20, 350 and 700 Hz with two 4MP Phantom v641 cameras, equipped with Schiempflug mounts, oriented at 45° relative to the test section side-wall (Fig. 1(a)). Due to the high refractive index of sodium iodide (≈1.49), solid acrylic prisms were mounted to the side-wall, with glycerin filling the air gap. The 20 Hz measurements enabled well-converged measurements of the mean statistics, while the higher sampling rates captured in time-resolved dynamics. Illumination was achieved with a Northrop Grumman Patara dual-cavity Nd:YLF laser capable of 50 mJ per pulse at up to 1 kHz.

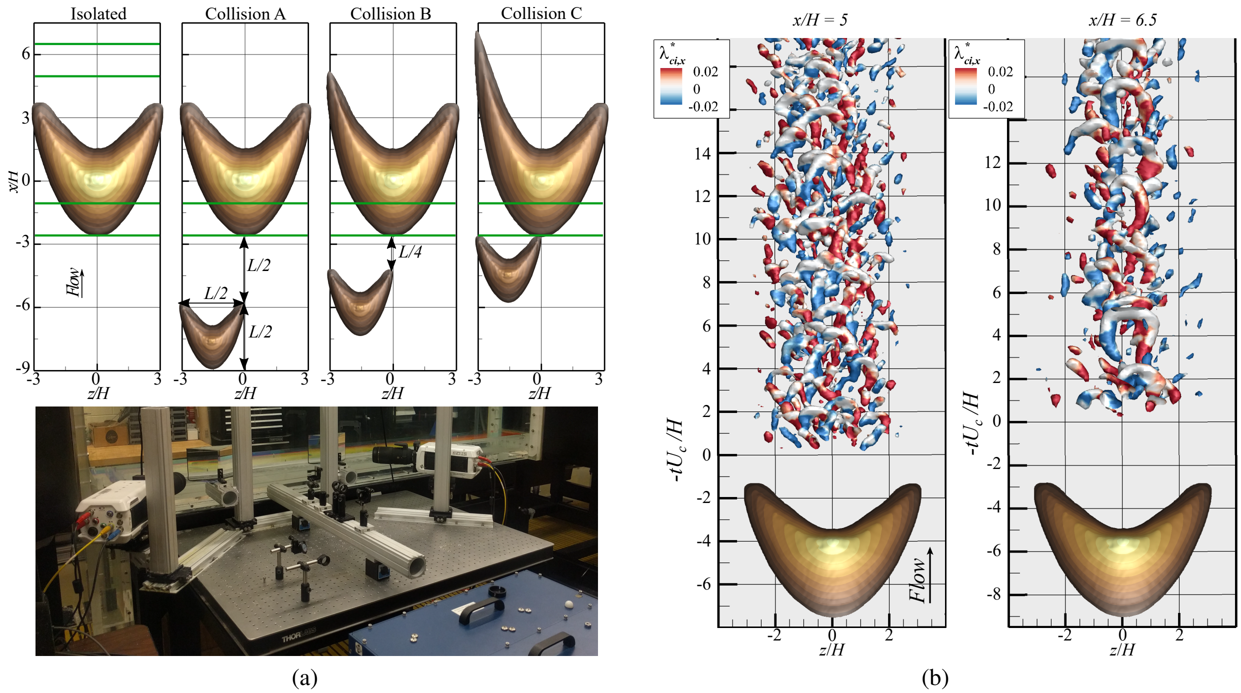

Figure 1: (a) Dune model configurations with laser sheet positions indicated and experimental setup below. (b) Pseudo-3D flow reconstructions from two different measurement planes in the isolated barchan wake.

3 Results

Careful application of Taylor's hypothesis, using a uniform convection velocity, allowed for pseudo-3D volumes of the flow to be reconstructed over limited domains. An example of these results is shown in Fig. 1(b), wherein isosurfaces of 3D swirling strength show evidence of hairpin-like vortices populating the wake of an isolated barchan. Similar results are seen in the interdune region (not shown here). These results should not be mistaken for an instantaneous volume of the flow field, due to the limitations of Taylor's hypothesis here, but rather a time series of flow structures that have advected through the measurement plane. Further analysis of vortex shedding dynamics associated with these structures using wavelet analysis and amplitude modulation indicates that they interact with large-scale motions in the overlying boundary layer, which impinge on the dune and excite the shear layer.

4 Summary

Unique access to the high Reynolds number flow field around a complex 3D bedform was achieved in a refractive-index-matched environment. High frame-rate measurements in the cross-plane elucidate the structures shed by barchan dunes, and provides important information about how these dunes not only interact with each other, but also the aloft boundary layer. Work remains, however, to close the loop in terms of understanding sediment transport implications, as only fixed-bed models are used herein to model the flow field without particle loading.

References

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