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TURBULENT FLOW OVER DUNES: EXPERIMENTAL DETERMINATION

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Abstract. Sand dunes are frequently found in both nature and industry. Barchans are a type of dunes characterized by the presence of two tips pointing downstream in the direction of the fluid flow. These dunes appear mainly under unidirectional flows and with limited sediment supply. In natural environments barchan dunes are found in deserts and river beds, and in industrial applications they can appear in petroleum pipelines, causing pressure drops and flow obstruction. The presence of the dune perturbs the fluid, and some turbulent flow features are not fully understood. In this configuration, strong perturbations are observed in the fluid flow, with the wake of the upstream barchan interacting with the downstream dune. In this experimental investigation, heaps of glass beads were placed in a rectangular channel made of transparent material and were entrained by a turbulent water flow, forming two barchan dunes that interacted with each other. The fluid flow was characterized by two-dimensional particle image velocimetry (2D-PIV). We report results for two cases: (i) single dune, and (ii) two barchans inside the channel. Mean and fluctuation fields were obtained, and the velocities and stresses computed.

Keywords: granular bed, barchan dunes, turbulent flow, PIV

1. INTRODUCTION

The transport of solid particles entrained by a fluid flow is frequently found in both industry and nature. A situation found in nature is when sand grains are transported by a flow predominantly unidirectional and with limited supply of sediments. Under these conditions, dunes with a remarkable crescentic shape with horns pointing downstream are formed (Herrmann and Sauermann, 2000; Bagnold, 2012), these bedforms being known as barchan dunes. These dunes are usually found in deserts, but they are also present in rivers and on the surface of extraterrestrial environments (Breed *et al.*, 1979; Bourke, 2010; Ernstsens *et al.*, 2005; Konsoer *et al.*, 2016). The characteristic length scales of barchans vary over several orders of magnitude depending on the environment, ranging from centimeters in fluvial channels to hundreds of meters in aeolian domains (Bagnold, 2012; Franklin and Charru, 2011; Bristow *et al.*, 2018). The shape and size selection of dunes, their dynamics behavior, and even their stability remain as open issues (Hersen *et al.*, 2004), as well as the interaction between barchans by collision processes, where the presence of a turbulent flow causes a morphological change in the bed and sediment transport (Assis and Franklin, 2021). A simple scenario consists of the interaction between two barchans. In this configuration, strong perturbations are observed in the fluid flow, with the wake of the upstream barchan interacting with the downstream dune. To carry out a direct observation of these processes in which the barchans evolve and interact is unfeasible, given the long timescales, an alternative being the creation of dunes in a controlled way and using shorter scales. This latter setup could help to improve our knowledge about the dynamics of the interaction. On the other hand, aeolian dunes have received more attention than underwater barchans, where turbulence is widely accepted as a promoter of the morphodynamics of bedforms (Best, 2005). Dunes in underwater environments have been studied in recent years (e.g. Franklin and Charru (2011); Charru and Franklin (2012); Alvarez and Franklin (2018); Bristow *et al.* (2018). Franklin and Charru (2011) using particle image velocimetry (PIV) recorded the morphology and flow associated with isolated and mobile barchans. While their results provided detailed measurements of the mean velocity and turbulent fluctuations, they analyzed the case of a single dune. This work presents the characterization of a turbulent water flow inside a rectangular cross-section channel interacting with barchans composed of glass beads. The characterization of the flow field was carried out by the two-dimensional particle imaging velocimetry (2D-PIV) technique for two cases: i)

isolated dune and ii) having the interaction of two barchan dunes with a lateral offset.

2. EXPERIMENTAL DEVICE

The experimental device consisted of a water reservoir, two centrifugal pumps, a flow straightener, a 5-m-long channel, a settling tank, and a return line. The flow straightener was a divergent-convergent nozzle filled with $d = 3 \text{ mm}$ glass spheres, the function of which was to homogenize the flow profile at the channel inlet. The channel had a rectangular cross-section (width = 160 mm and height $2\delta = 50 \text{ mm}$) and was made of transparent material. Figure 1 shows the scheme of the experimental loop. The channel test section was 1 m long and started 40 hydraulic diameters (3 m) downstream of the channel inlet. The particles were placed in the channel test section, which was previously filled with water, the turbulent flow was completely developed in the test section. We used black glass beads, with density $\rho_s = 2500 \text{ kg/m}^3$ and mean diameter $d = 0.20 \text{ mm}$). The grains settled in the water at rest and formed a conical heap. Next, a water flow was imposed in the channel, and then the heap deformed into a barchan dune.

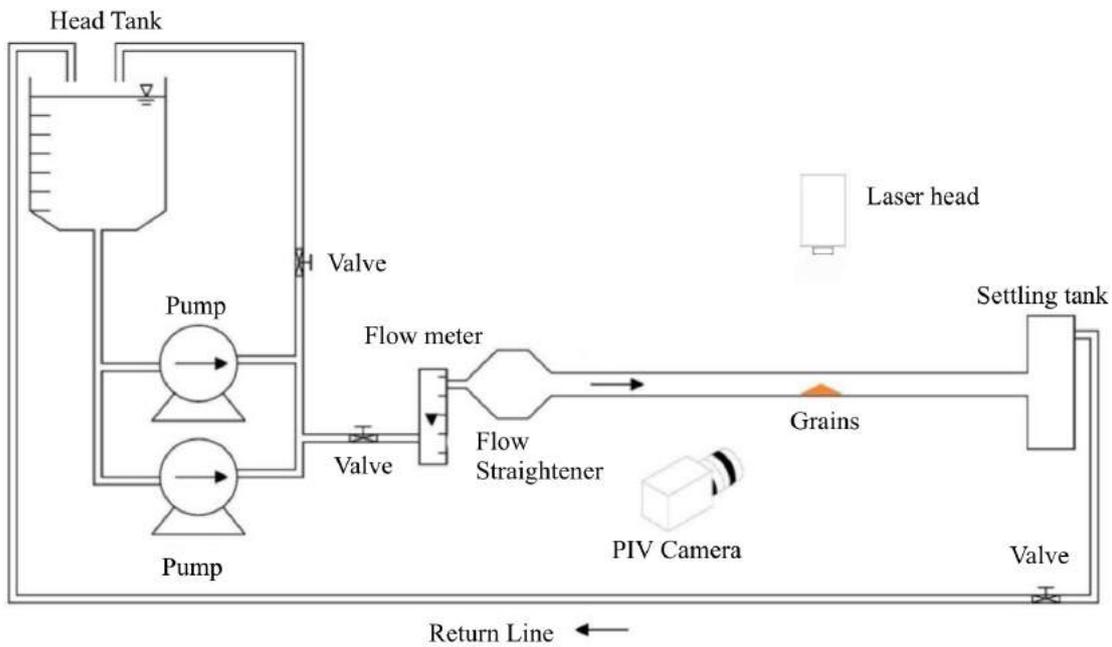


Figure 1. Schematic of the experimental loop. (Modified from Alvarez *et al.* (2021)).

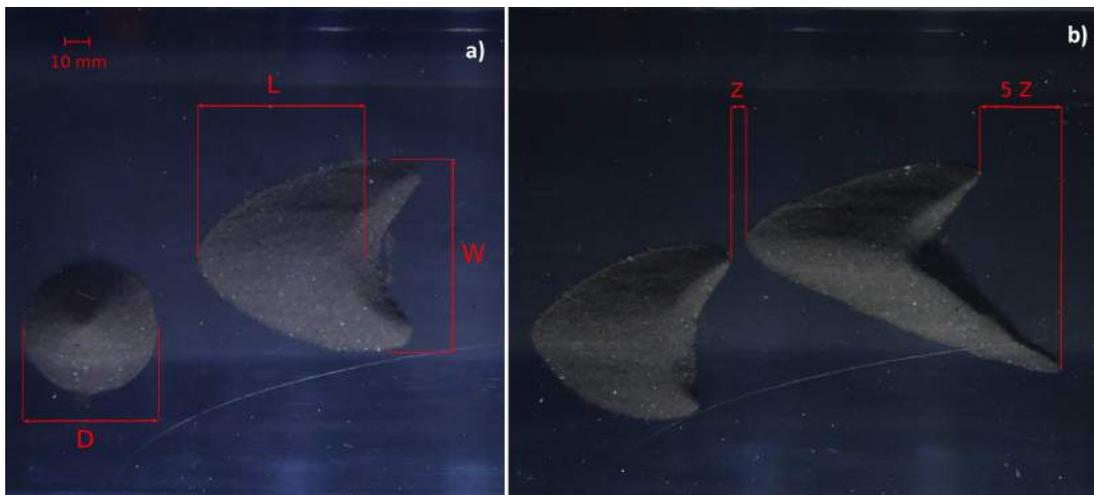


Figure 2. Photo of the setup for the case of interacting dunes. a) Initial condition with the dune downstream already formed and the upstream dune as a conical pile. b) Dunes after the downstream barchan was deformed by the presence of the upstream one. In this position the PIV process was carried out over the larger dune.

The experiments were conducted in two stages. During the first stage, the flow interacted with the granular material for a period of 320 *s* to obtain the characteristic shape of the barchans, the same time applied to the two considered cases (isolated dune and interacting dunes). For the interaction of two barchans, we allowed an additional period of 240 *s* until the upstream dune was formed (see Fig. 2b), in both cases the flow velocity was 7.5 m^3/h . In the second stage, we carried out the data acquisition by means of 2D-PIV, at this point the water flow was reduced to 5 m^3/h for recording the instantaneous flow fields. Data acquisition was performed in the downstream dune when we had interacting dunes. The velocity reduction allowed the dune to be at rest while the PIV device acquired the image pairs. Figure 2 shows the setup for the case with interacting dunes. After the downstream dune reached its crescentic shape, we placed another pile of grains considering a lateral displacement (Fig. 2a). While the upstream dune evolved to its characteristic shape the downstream barchan experienced an elongation of one of its horns (Fig. 2b). This arrangement of barchans was developed following the same experimental conditions (mass of granular material, flow velocity and interaction time) of the case named fragmentation-chasing reported by Assis and Franklin (2021). On average, the isolated dune and the downstream barchan (without considering the horn's deformation) had similar dimensions (length, $L = 55\text{ mm}$ and width $W = 62\text{ mm}$). The PIV data acquisition was carried out once the upstream dune was formed and before the collision between the dunes and the ejection of a small barchan from the elongated horn took place. Before doing the PIV process, we reduced the flow velocity and the separation distance between the dunes Z was 5 *mm*. The length of the deformed horn was equal to $5Z$.

We define the velocity U_b as the ratio between the volumetric flow rate measured and the cross section of the channel. In our experiment, U_b was set to 0.17 *m/s*. The PIV software Davis took care of the synchronization of the CCD (charge coupled device) camera with the light source (double cavity Nd:YAG Q-switched laser) and allowed obtaining pairs of images with a frequency of 4 *Hz*. The laser sheet was positioned in the vertical symmetry plane of the dune. A total of 2000 pairs of images were acquired for each position of the camera in the longitudinal direction, in total there were three sets of image acquisitions, including the unperturbed zone, the barchan, and the zone downstream of the dune crest. To calculate the instantaneous velocity fields, cross-correlations were done by using the functionalities of the Davis software. We use an interrogation area of 16 *px* × 16 *px* with 50% overlap corresponding to 256 interrogation zones, and with a spatial resolution of 0.22 *mm* × 0.22 *mm*. Finally, the velocity fields were analyzed using Matlab scripts written during this work. The instantaneous fields were averaged in time and spatially in the streamwise direction.

3. RESULTS AND DISCUSSION

Quantities such as mean velocity components and turbulent statistics were averaged in time. To analyze the turbulent flow in the vertical plane of symmetry (crossing the central section of the barchans), we present in Figure 3 the time-averaged fields of the longitudinal (U) and vertical (V) velocity components normalized by the fluid velocity (U_b). Figure 3a shows U field for the isolated dune and Fig. 3b for the case with interacting dunes. In both cases, U has positive values on the stoss slope (region upstream of the crest) and negative values on the lee side (downstream of the crest), the latter due to the recirculation region. It should be noted that the field of view captured does not allow visualizing the recovery of the fluid, in addition to this, the leeward side is blocked by the horns between the light source and the camera (Charru and Franklin, 2012). Figures 3c and 3d show the time-averaged vertical V field normalized by U_b . For the single dune (Fig. 3c), V reaches maximum acceleration along the stoss slope and decreases just upstream of the crest. For the case with two dunes (Fig. 3d), V decreases at a distance $x \approx 3h$ upstream of the crest. There is a gap downstream of the crest, where the flow slows down and creates a recirculating flow that is extremely unstable, with frequent vortex shedding. After $x/h = 4$ there are not significant differences of the velocity distribution for the two considered cases.

A quantitative analysis is presented in Figure 4 with mean longitudinal U and vertical V velocity profiles normalized by the fluid velocity U_b at a constant relative height above the dune. The dune's height h in the two cases (single and interacting dunes) was almost kept constant and equal to 5 *mm*. The elevation at which data was acquired was set to $0.15h$, the dashed line in Figs. 4b and 4d shows this elevation over the dune, a position on the normal axis that remains within the limits described in the work of Jackson and Hunt (1975) for inner boundary layer depth. In Fig. 4, blue (s-d) and black (f-d) lines represent the single dune and interacting dunes cases, respectively. The mean normalized longitudinal velocity U/U_b (Fig. 4a) shows a decreasing trend until it approximately meets the beginning of the dune. When the flow interacts with the barchan, it accelerates to a maximum value at the position of $x/h = 0$ and $x/h \approx 3$ for the isolated dune and interacting barchans, respectively. After the flow leaves the dune's crest, U abruptly decreases and reaches negative values indicating that the fluid enters the leeward recirculation zone. Afterward U returns to be positive showing the flow recovery. Figure 4c shows the average profile of the vertical velocity V/U_b , this in general registers a trend similar to U/U_b .

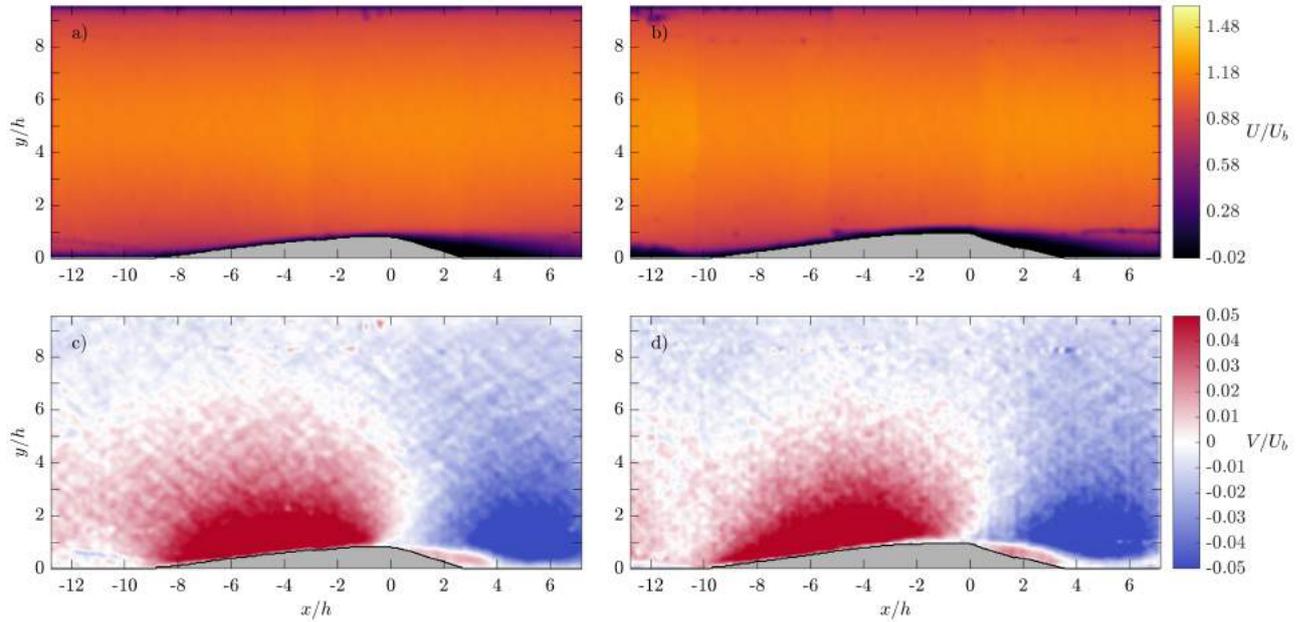


Figure 3. Time-averaged fields of a) (single dune) and b) (interacting case) the longitudinal velocity component U ; and c) (single dune) and d) (interacting case) the vertical velocity component V . U and V are normalized by the flow velocity U_b and obtained from 2,000 instantaneous fields.

Figure 5 shows the profiles of the streamwise of the Reynolds normal ($\overline{u'^2}$, $\overline{v'^2}$) and shear ($\overline{u'v'}$) stresses normalized by the squared shear velocity (u_*^2). In the isolated case, the three components of the Reynolds stress tensor show the highest values above the foot of the dune, that is, around $x/h < -8$ before decreasing by the stoss slope. In the case of interacting dunes, upstream of the beginning of the dune, $x/h < -11$, the three components presenting smaller values than the single case, this is possibly due to the disturbance caused by the upstream dune. In the two cases, along the dunes and even in the wake region, the Reynolds stresses almost maintain the same value as the one at the beginning of the stoss side. Comparing both cases, in the toe region, the Reynolds normal stresses $\overline{u'^2}$ and $\overline{v'^2}$ range approximately between $5-10u_*^2$ and $0-2.5u_*^2$, while the Reynolds shear stress $\overline{u'v'}$ ranges within $0-0.5u_*^2$. These findings agree quite well with the previously reported values. In the case of interacting dunes, we observed a strong peak around $x/h < -5.5$ that might be associated with the effect imposed by the upstream dune and some irregularities in the dune's surface. We recall that our measurements were made on a dune composed of grains, so a rough surface is expected.

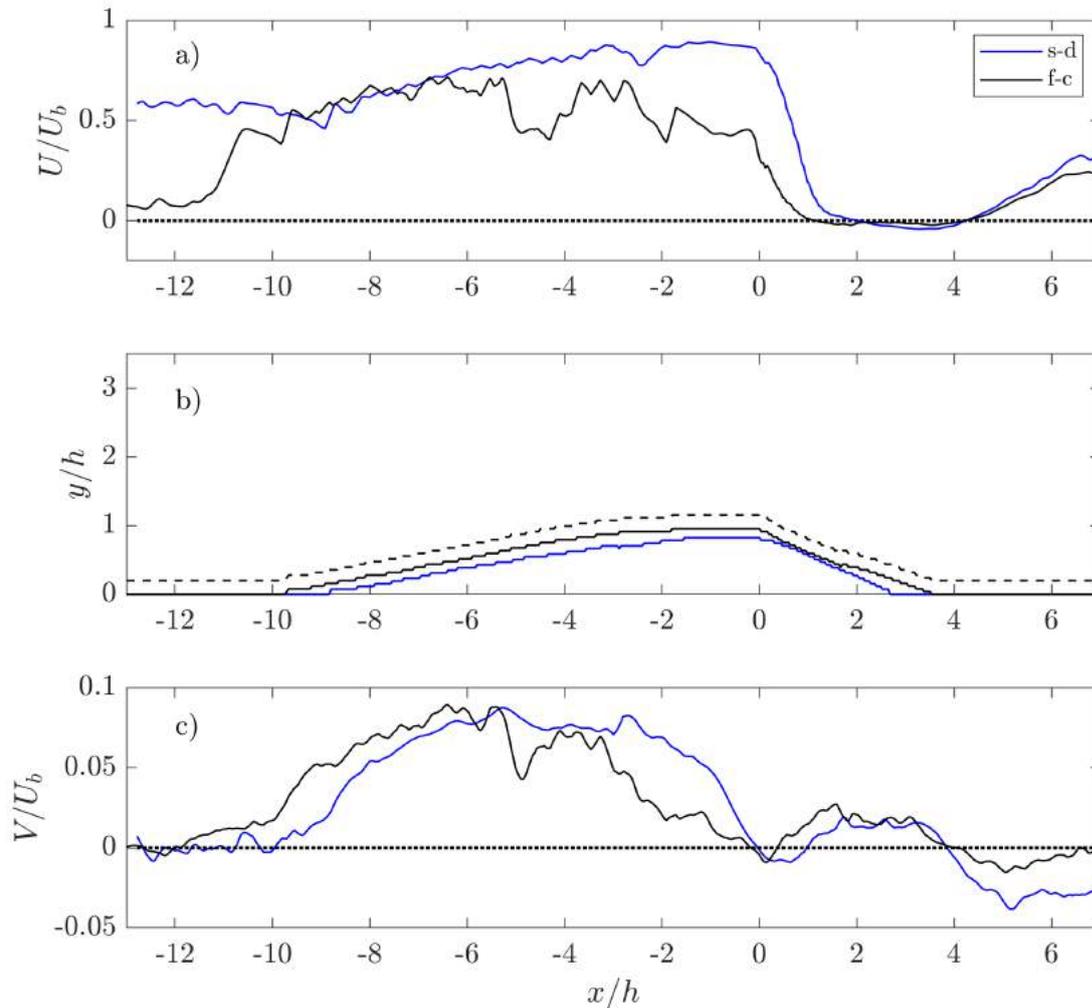


Figure 4. First-order statistics normalized by flow velocity U_b . a) Time-averaged longitudinal velocity, c) Time-averaged vertical velocity, and b) topography of the dune, the dashed line shows the place where data were taken in the longitudinal direction and at 0.15h relative elevation above the bottom surface. Blue and black lines correspond to cases identified as single dune and interaction of two dunes, respectively.

4. CONCLUSIONS

In this study we reported 2D-PIV measurements of a turbulent water flow over a barchan dune composed of glass beads with a mean diameter d equal to 0.2 mm considering two scenarios: i) single dune and ii) interacting dunes. In the second case, all our measurements were made over the downstream barchan. For the case dealing with a single dune, the longitudinal velocity field U shows a wake region having negative values about 2% of U_b , and at elevations between 3-5h above the dune, U is approximately equal to U_b . In the cases with two dunes, when the fluid flow interacts with the barchan, it accelerates to a maximum value at the position $x/h \approx 3$. The field of the vertical velocity V shows two regions of negative and positive values. On the stoss side and the lee side, the fluid flows upward (positive) reaching values of 5% and 1% of U_b , respectively. Far from the wake region, the fluid flows downward (negative) reaching values larger than 5% of U_b . Second-order statistics showed that along a constant relative height above the dune the highest values are reached above the dune's toe and they decrease up the stoss slope. In the case of interacting dunes, we observed a strong peak around $x/h < -5.5$ that might be associated with the effect imposed by the upstream dune and some irregularities in the dune's surface. Although this paper considered the interaction between two dunes in aquatic environment, our findings can help to explain the formation of dunes' fields found in other environmental conditions.

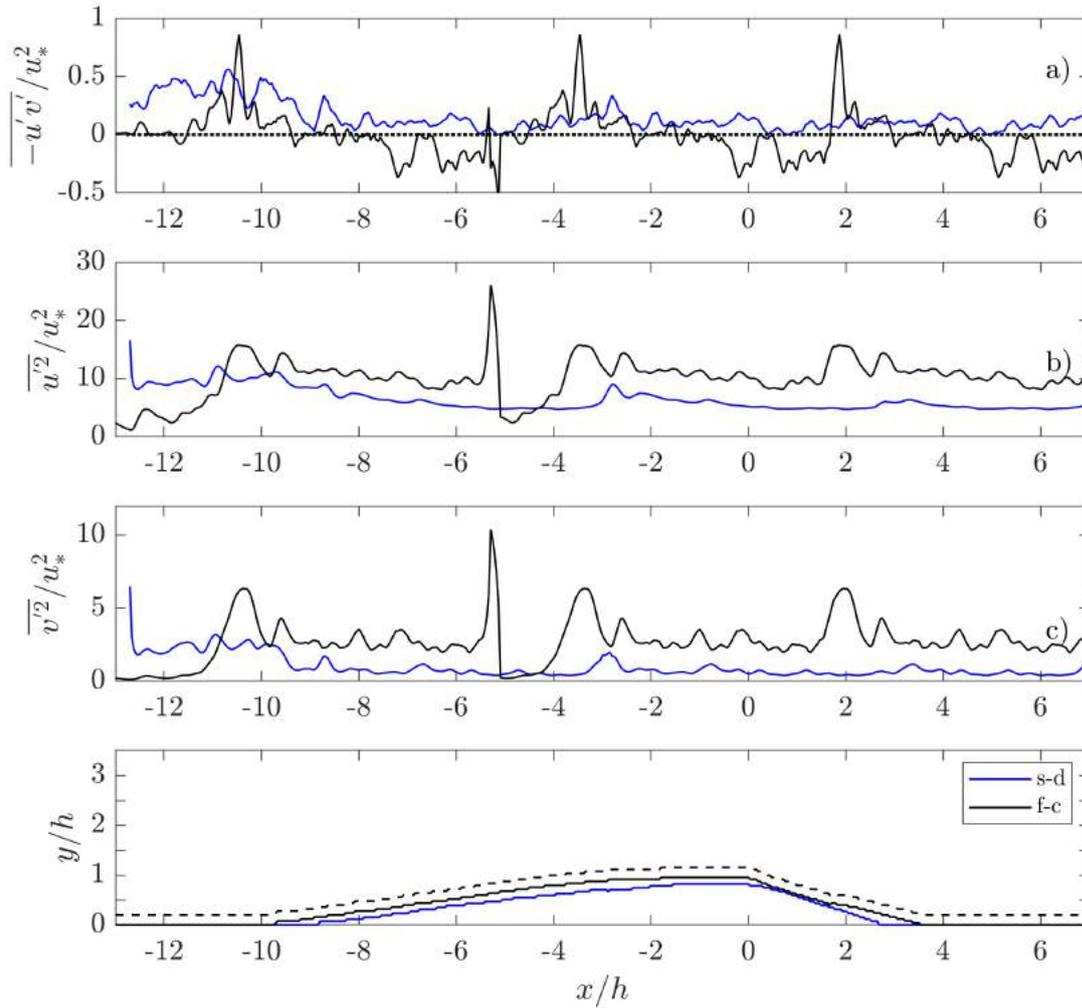


Figure 5. Second-order moments normalized by the squared shear velocity u_*^2 of a) Reynolds shear stress, b) streamwise Reynolds normal stress, c) vertical Reynolds normal stress and d) topography of the dune, the dashed line shows the place where data were taken in the longitudinal direction and at 0.15h relative elevation above the bottom surface. Blue and black lines correspond to cases identified as single dune and interaction of two dunes, respectively.

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