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Turbulence in wall-wake flow downstream of an isolated dune

Sankar Sarkar and Subhasish Dey

Sankar Sarkar

Physics and Applied Mathematics Unit
Indian Statistical Institute, Kolkata
India

Introduction

- Flow over and downstream of an isolated dune is a subject of immense importance in several fields of environmental and engineering sciences due to its practical implications in river management.
- In addition to the practical application, it allows a considerable theoretical insight in wake flows.
- Due to the geometrical features, a dune can be considered as a bluff-body in hydraulics. Earlier studies showed that the flow downstream of a bluff-body is complex.
- Considering 2-D fixed dune as a bluff-body and studying the flow characteristics downstream of the dune in the context of bursting and the TKE budget remains absent till date.

Objective of the Present Study

To characterize the turbulent flow downstream of an isolated dunal bedform mounted on a rough bed experimentally. Attention has been paid particularly to the following:

- Higher-order moments
- Turbulent bursting
- TKE budget downstream of a fixed, rough 2-D dune.
- The streamwise velocity and Reynolds shear stress (RSS) are presented as a reference.

Experimental Setup

- Experiments were performed in a rectangular flume of 20 m long, 0.5 m wide and 0.5 m high.
- Acrylic sidewalls facilitated to have a visual observation of the flow in the flume.

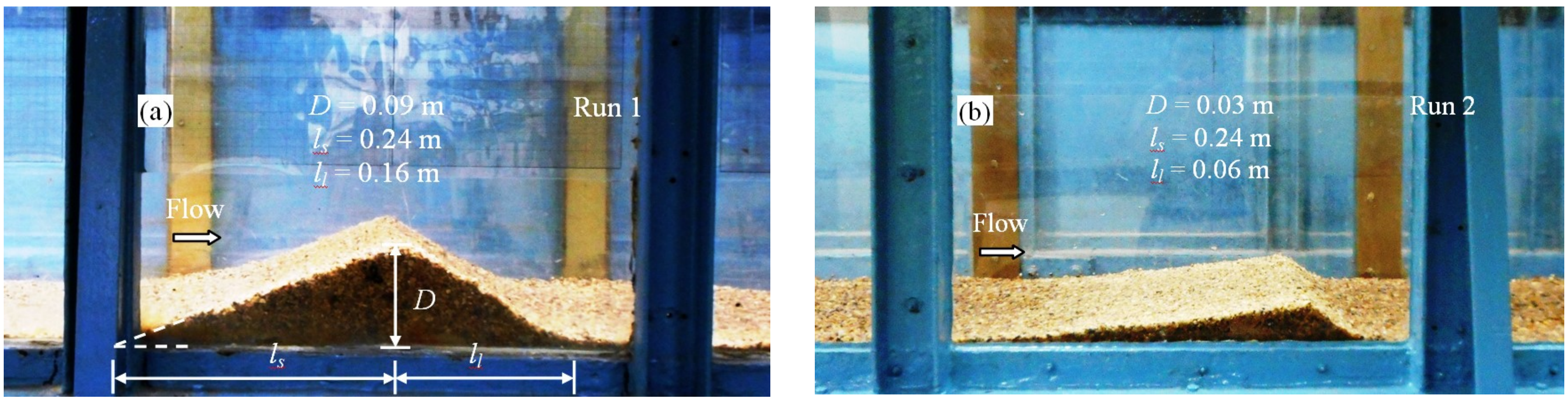


Fig. 1 Photographs of the dunal structures for (a) Run 1 and (b) Run 2.

Experimental Parameters

Run	h (m)	d_{50} (mm)	$\overline{U}$ (m s^{-1})	S (%)	$u_{*1,\,S}$ (m s^{-1})	$u_{*2,\,RSS}$ (m s^{-1})	R	F	R_*
1	0.30	2.49	0.44	0.03	0.030	0.027	528000	0.256	74.7
2	0.30	2.49	0.44	0.03	0.030	0.025	528000	0.256	74.7

h = depth of flow
d_{50} = median size of gravel
u_* = the approach shear velocity,
R_* = the shear-particle Reynolds number
$\overline{U}$ = the depth-averaged approach velocity
S = bed slope
R = Reynolds number ($= 4\,\overline{U}\,h/\nu$)
F = Froude number ($= \overline{U}\,/(gh)^{0.5}$)

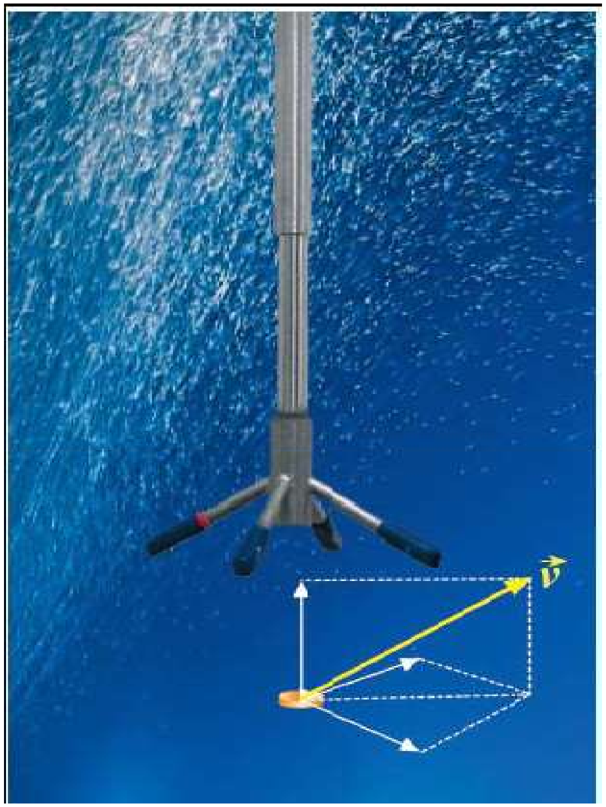


Fig. 2 Vectrino

- Acoustic frequency: 10 MHz.
- Sampling rate : 100 Hz.
- Sampling volume: 6 mm diameter Height:1 – 4 mm.
- Duration of sampling: 300 s.
- *Vectrino* signal correlation values: ≥ 70%
- SNR (signal-to-noise ratio): ≥ 17
- Spike removal: *Acceleration thresholding method* (Goring and Nikora 2002)
- Locations of the velocity measurements: x/l = –0.5, –0.25, 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.3, 1.7, 2.1, 2.5, and 3.3
- The velocity components u, v, and w were in the streamwise (x), spanwise (y), and vertical (z) directions, respectively.

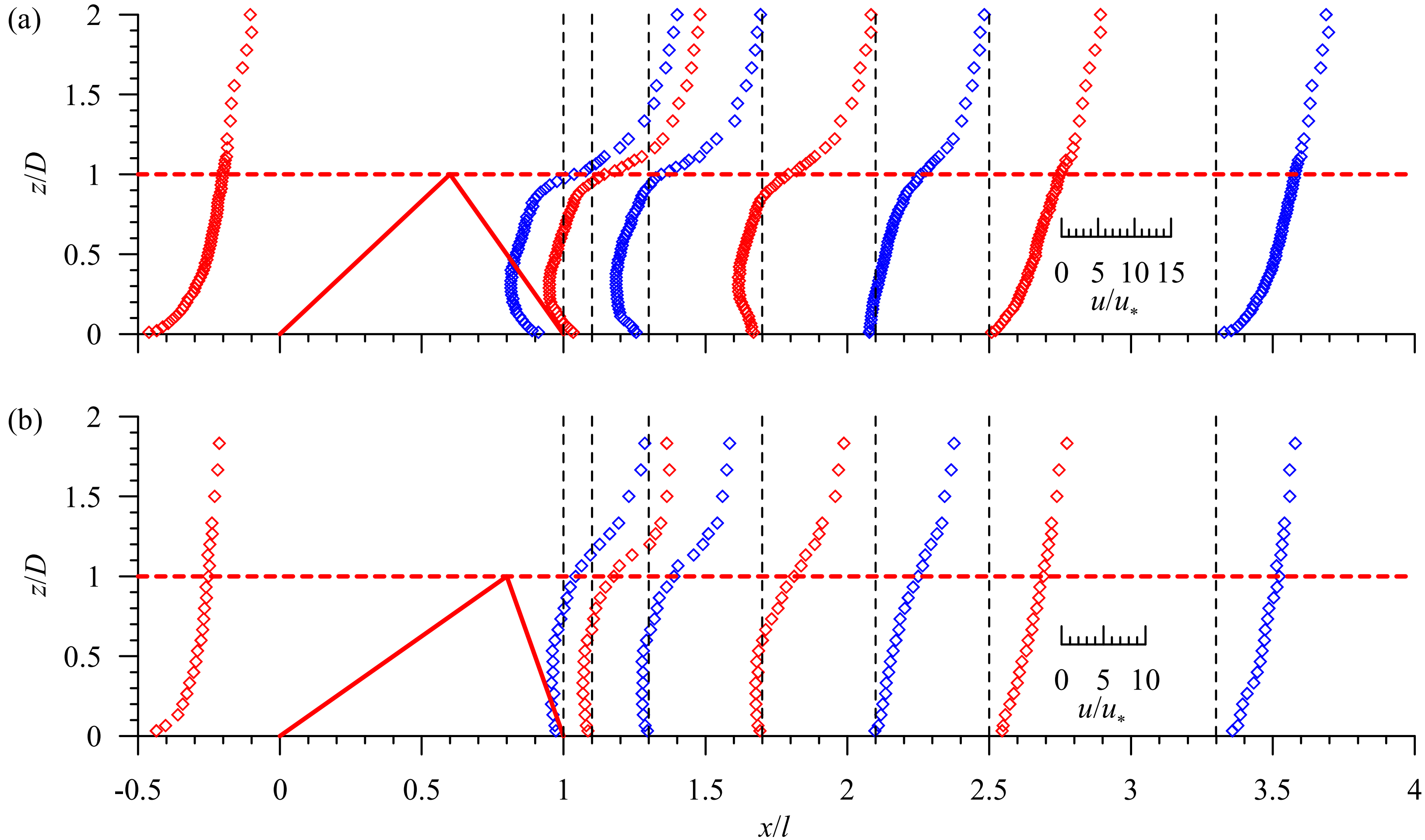
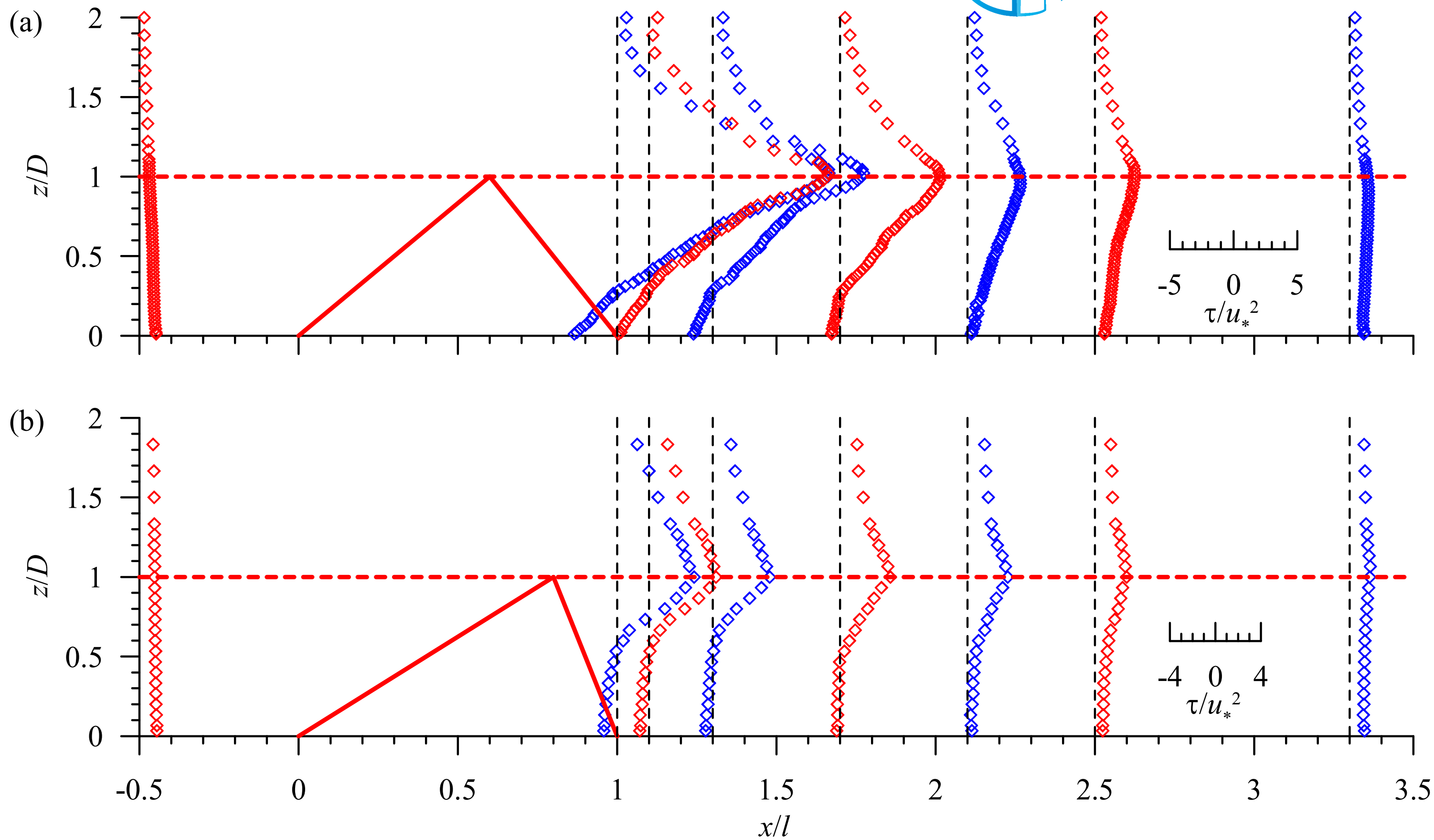


Fig. 3 Vertical profiles of nondimensional streamwise velocity u/u_* at different streamwise distances for Runs 1 and 2

- In the immediate downstream of the dune (x/l = 1), the wall-shear flow passing the dune separates from the crest of the dune giving birth a reversed flow zone due to the reversal streamwise velocity.
- The flow zone is called the near-wake zone that lasts up to $x/l \approx 1.7$.
- At further downstream, the reversed flow disappears and the streamwise velocity that has a velocity defect starts recovering the undisturbed upstream profile in the far-wake zone ($2.1 \leq x/l \leq 2.5$).
- At $x/l \approx 3.3$, the velocity profile almost follows the undisturbed upstream profile.
- Above the vertical distance $z/D = 1.5$, the values of u/u_* remain almost same irrespective of the streamwise distance x/l.



τ is the Reynolds shear stress relative to mass density ρ of water, defined by $-\overline{u'w'}$

Fig. 4 Vertical profiles of nondimensional Reynolds shear stress RSS at different streamwise distances

- Upstream of the dune ($x/l = -0.5$), the RSS-profile follows a linear law.
- Immediate downstream of the dune ($x/l = 1$), the RSS-profile starts with a small negative value in the proximity of the bed and increases with an increase in vertical distance.
- Above the crest, the RSS decreases with z/D and above $z/D = 1.5$, the RSS becomes almost similar to that of upstream.
- The amplification of RSS value starts decreasing with an increase in the streamwise distance and at $x/l \approx 3.3$, the RSS-profiles becomes almost similar to that of upstream ($x/l = -0.5$).
- The RSS in wake flow is influenced by the dune up to a vertical distance of approximately 1.75 times the height of the dune and a streamwise distance of approximately 2.5 times the length of the dune.

Third-Order Correlations of Velocity Fluctuations

Third-order correlations are directly correlated to the turbulent coherent structures due to preservation of their signs.

Third-order correlations m_{jk} are expressed as: $m_{jk} = \overline{\tilde{u}^j \tilde{w}^k}$, $j + k = 3$

$$m_{30} = \overline{\tilde{u}^3} = \overline{u'u'u'} / \left(\overline{u'u'}\right)^{1.5} \qquad m_{03} = \overline{w'w'w'} / \left(\overline{w'w'}\right)^{1.5}$$

$$m_{21} = \overline{u'u'w'} / \left(\overline{u'u'}\right) \times \left(\overline{w'w'}\right)^{0.5} \qquad m_{12} = \overline{u'w'w'} / \left(\overline{u'u'}\right)^{0.5} \times \left(\overline{w'w'}\right)$$

$m_{30} \rightarrow$ The skewness of u', streamwise flux of $\overline{u'u'}$

$m_{21} \rightarrow$ The advection of $\overline{u'u'}$ in *vertical*-direction

$m_{12} \rightarrow$ The advection of vertical Reynolds normal stress $\overline{w'w'}$ in x-direction

$m_{03} \rightarrow$ The skewness of w', the vertical flux of $\overline{w'w'}$

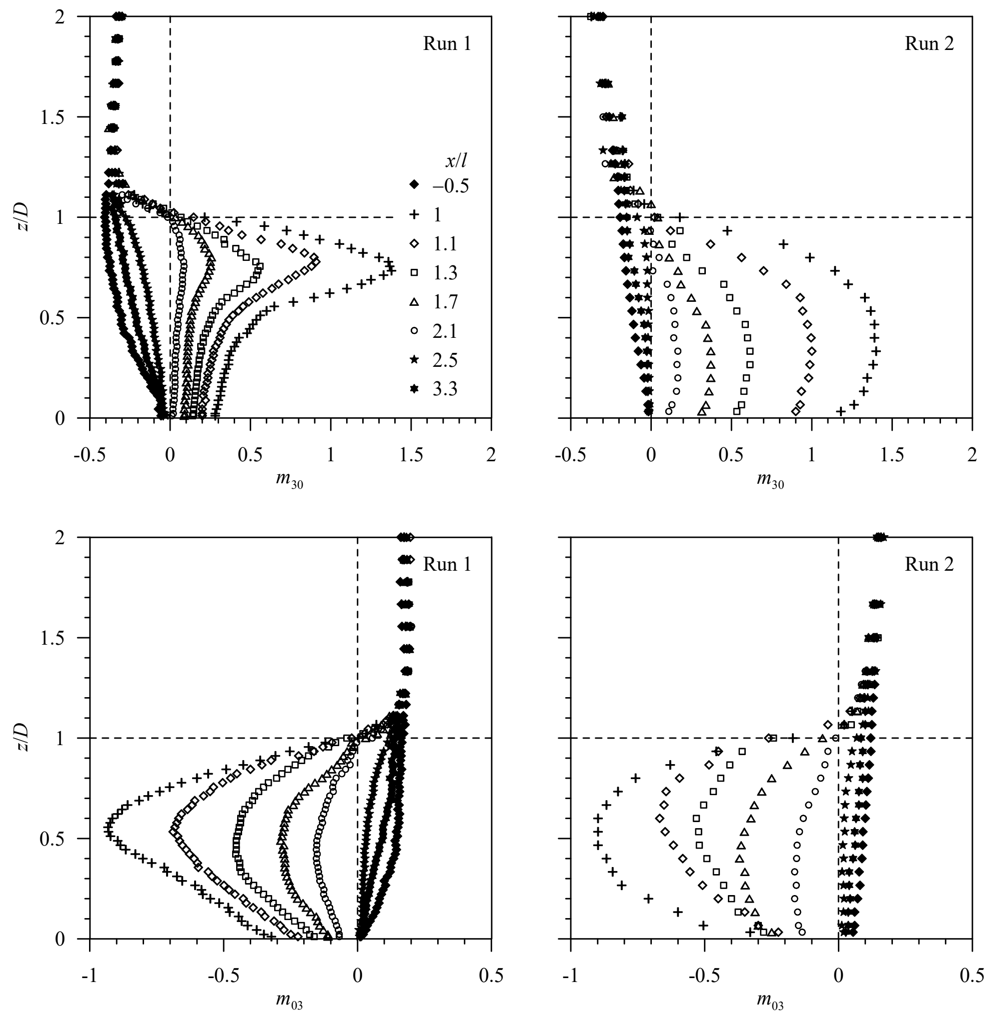


Fig. 5 Vertical profiles of third-order moments (skewness or flux of Reynolds normal stresses) m_{30} and m_{03}

- Upstream of the dune (x/l = –0.5), the m_{30} and m_{03} start with a small negative and positive values, respectively, in the vicinity of the bed and increase with an increase in vertical distance without changing their signs.
- Downstream of the dune (x/l = 1–2.1), the m_{30} and m_{03} profiles possess interesting characteristics. They start with a small positive and a negative value, respectively, near the bed and increase gradually with an increase in vertical distance until they attain their peak positive and negative values at $z/D \approx 0.75$ and 0.5, respectively.
- With a further increase in z/D, the m_{30} and m_{03} decrease rapidly and change their signs at $z/D = 1$, and above that they become almost invariant of z/D.
- These features gradually disappear with an increase in streamwise distance x/l. However, the m_{30} and m_{03} profiles are almost similar to those in the upstream at $x/l = 3.3$.

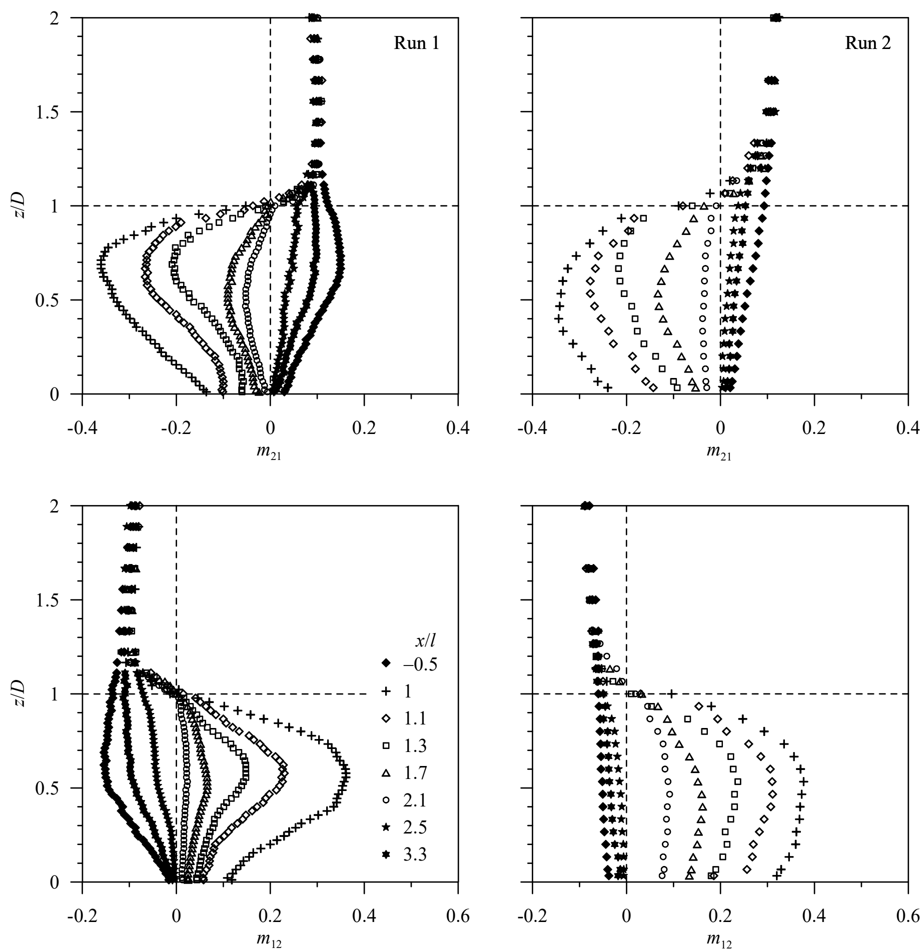


Fig. 6 Vertical profiles of third-order moments (advection of Reynolds normal stresses) m_{21} and m_{12}

- Upstream of the dune ((x/l = –0.5), the m_{21} and m_{12} have small positive and negative values, respectively, near the bed and increase with an increase in vertical distance up to a certain depth.
- Thereafter, they decrease becomeing almost invariant of vertical distance for $z/D > 1.1$.
- Downstream of the dune (x/l = 1–2.1), the m_{21} and m_{12} start with small negative and positive values, respectively, near the bed and increase with an increase in vertical distance attaining their peak values.
- However, as one moves further downstream, the signs of the m_{21} and m_{12} start changing until their signs become same as that of upstream at $x/l > 2.1$.
- Importantly, the m_{21} and m_{12} follow the similar profiles to those of the upstream at $x/l = 3.3$.

Turbulent bursts

Described as a sequence of quasi-cyclic process of ejection events and sweep events.

Ejection: A low-speed fluid streak subject to separation due to a local and temporary adverse pressure gradient. This causes the coherent, low-speed fluid to entrain into the main body of the flow.

Sweep: The ejected fluid which remains as a result of retardation is brushed away by high-speed fluid that approaches the bed in a process called the sweep.

Quadrant Analysis

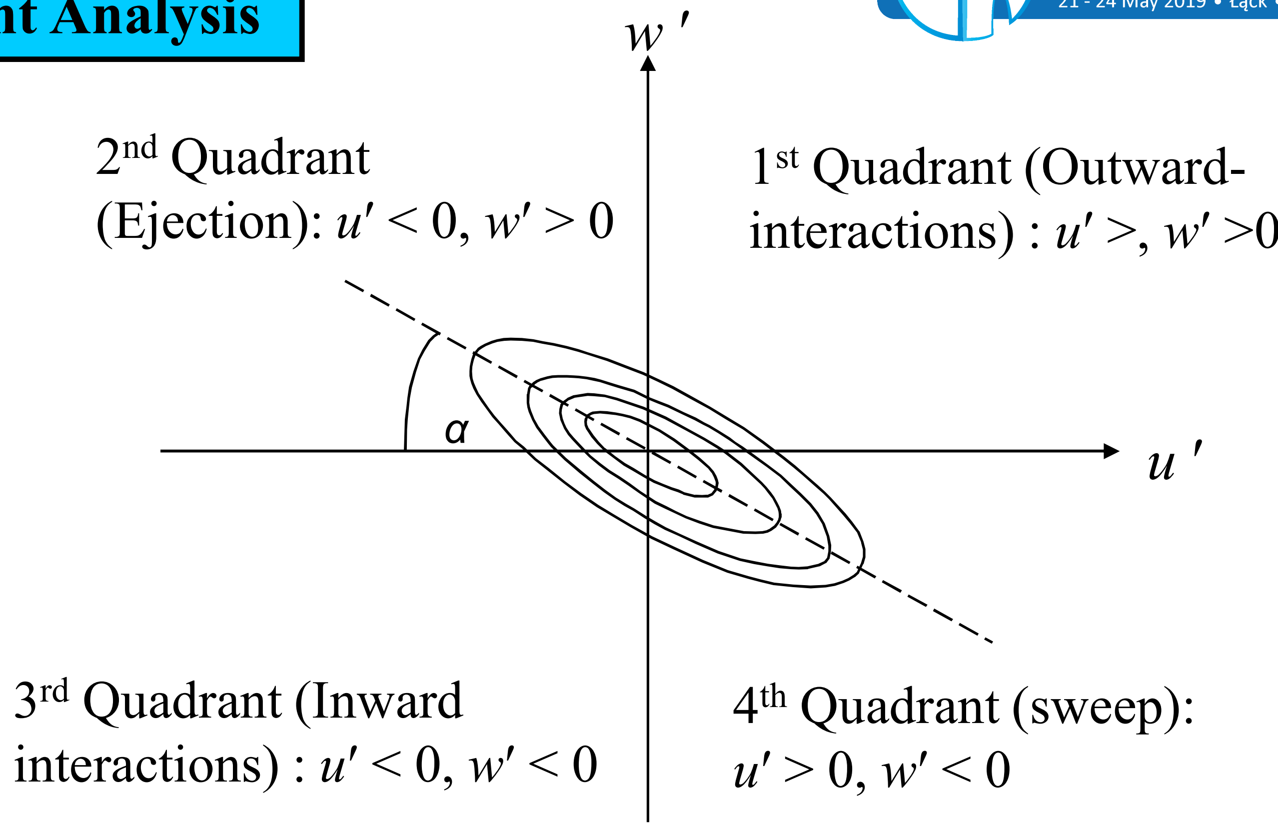


Fig. 7 Quadrant plots of velocity fluctuations (u', w') on $u'w'$-plane.

A detection function is given by:

$$\lambda_{i,H}(z,t)=\begin{cases}1, & \text{if } (u',w') \text{ is in quadrant } i \text{ and if } |u'w'| \geq H(\overline{u'u'})^{0.5}(\overline{w'w'})^{0.5} \\ 0, & \text{otherwise}\end{cases}$$

the contributions to $-\overline{u'w'}$ from the quadrant i outside the hole region of size H is estimated by

$$\langle u'w' \rangle_{i,H} = \lim_{T\to\infty}\frac{1}{T}\int_0^T u'(t)w'(t)\lambda_{i,H}(z,t)dt$$

Thus, the fractional contribution $S_{i,H}$ to $-\overline{u'w'}$ form each event is:

$$S_{i,H} = \frac{\langle u'w' \rangle_{i,H}}{\overline{u'w'}}$$

The sum of contributions from different bursting events at a point is unity, that is

$$\sum_{i=0}^{i=4}[S_{i,H}]_{H=0} = 1$$

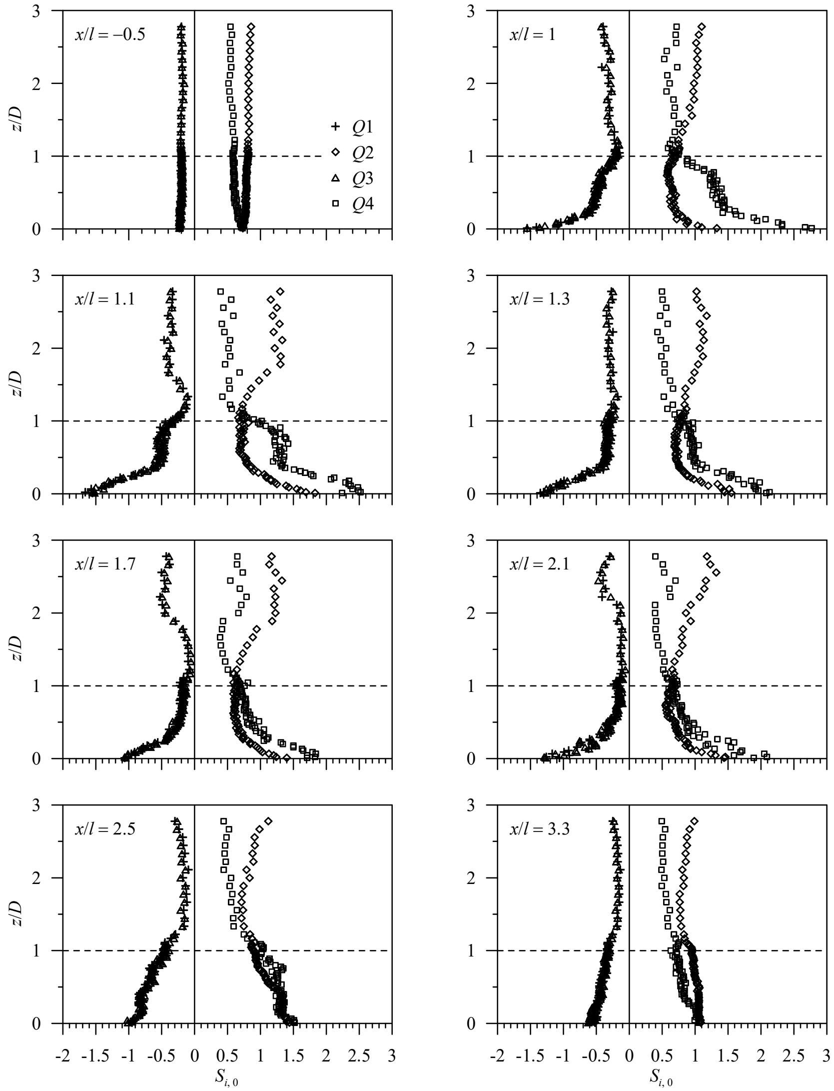


Fig. 8 Variations of $S_{i,0}$ with z/D at different streamwise distances for Run 1.

- Upstream of the dune ($x/l = -0.5$), the $Q2$ and $Q4$ events are the most and the second-most contributing events, respectively, to the production of RSS, whereas the $Q1$ and $Q3$ events remain insignificant across the flow depth.
- Downstream of the dune ($1 \leq x/l \leq 2.1$), all the events have a large augmentation below the crest with predominating $Q4$ events.
- At $x/l = 2.5$, the contributions from the $Q2$ and $Q4$ events become almost equal below the crest.
- At further downstream ($x/l = 3.3$), the $Q2$ events dominate $Q4$ events.
- Above the crest ($z/D > 1$), the $Q2$ is the most contributing events irrespective of the values of x/l.

Energy Budget

Turbulent production : $t_P = -\overline{u'w'}\left(\partial u / \partial z\right)$

Turbulent energy diffusion : $t_D = \partial f_{kw} / \partial z$

Viscous diffusion : $v_D = -\upsilon\left(\partial^2 k / \partial z^2\right)$

Turbulent dissipation : ε estimated from the Kolmogorov second hypothesis

Pressure energy diffusion : $p_D = \partial\left(\overline{p'w'/\rho}\right) / \partial z$

The turbulent energy budget relationship : $p_D = t_P - \varepsilon - t_D$

The nondimensional form of these parameters are expressed as T_P, E_D, T_D, P_D $= (t_P, \varepsilon, t_D, p_D) \times (h/u_*^3)$.

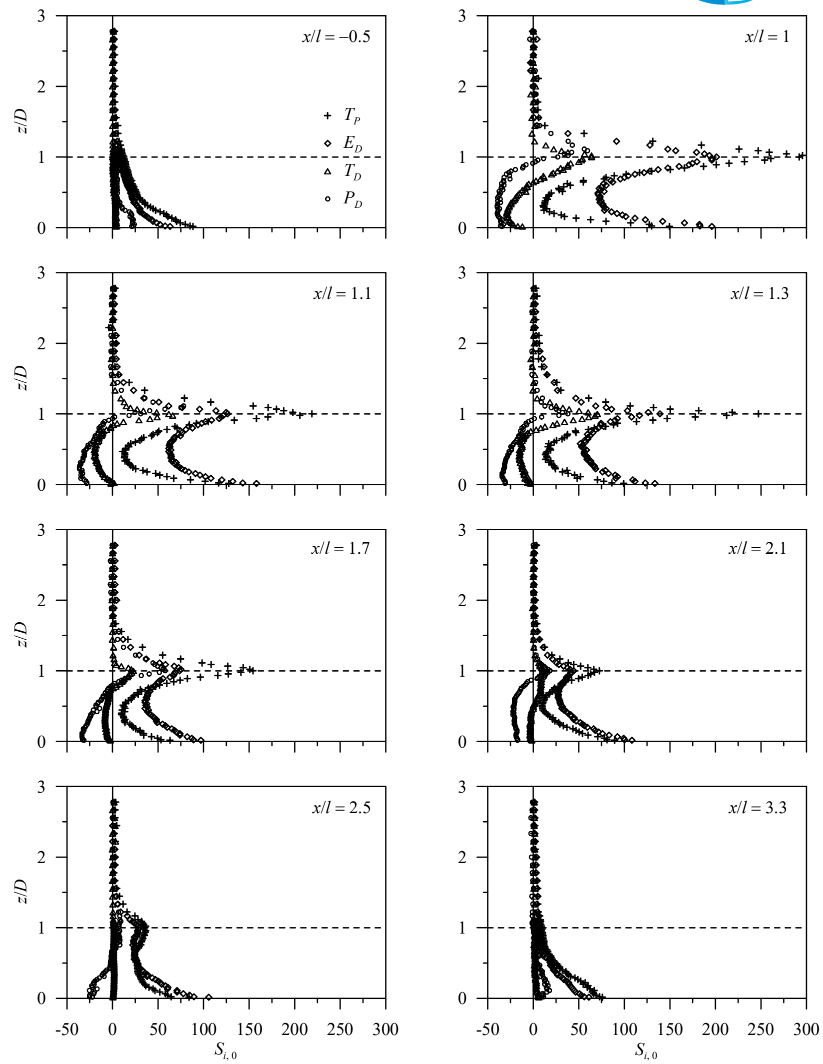


Fig. 9 TKE budget components T_P, E_D, T_D and P_D, as a function of z/D at different streamwise distances for Run 1.

- Upstream of the dune (x/l = –0.5), all the TKE budget components start with positive values with a sequence of magnitude $T_P > E_D > P_D > T_D$ near the bed and decrease with an increase in z/D.
- Above the crest (z/D > 1), they become very small. On the other hand, downstream of the dune (x/l = 1–2.1), the peak values of T_P, E_D, P_D and T_D are observed at the crest.
- The T_P and E_D start with positive values near the bed, whereas P_D and T_D start with negative values for x/l = 1–2.1.
- Downstream of the dune, the amplification of the absolute values T_P, E_D, P_D and T_D are observed in the vicinity of the bed and at the crest, they diminish with an increase in x/l.
- At x/l = 3.3, the T_P, E_D, P_D and T_D profiles become almost similar to those of the undisturbed upstream (x/l = –0.5).

Conclusions

- The third-order moment of velocity fluctuations suggest that downstream of a dune, a streamwise acceleration with a downward flux is prevalent below the crest of the dune.
- Above the crest a strong streamwise retardation prevails with an upward flux.
- The quadrant analysis for turbulent bursting shows that below the crest, the sweeps are the main contributing event
- Above the crest, the ejections are the governing events.
- an amplification of the values of all the turbulent processes that become maximum at the crest.
- All the characteristics in wall-wake flow disappear after a certain distance, signifying the recovery of the turbulence characteristics.

Thank you