Aerodynamic surface stress intermittency and conditionally averaged turbulence statistics: insights for Aeolian processes

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Introduction

Aeolian erosion can be regularly observed in flat, arid agricultural landscapes. ‘Saltation’ is one of the responsible modes of sediment transportation in which sediment grains are partially suspended in air.

This process is activated by the surface stress induced by the basal layer of air flow. It has been reported that surface stress, τ^w, is intermittent (Grant and Marusic, 2012; Mathis et al., 2013) due to turbulent variations in friction velocity, $u_\star$.

Previous studies reported the presence of ‘superstructures’ in wall bounded flows (Hutchins and Marusic, 2007a) and it has been confirmed by several other researchers. The structure inclination angle for neutral surface layer is reported to be around 15° but an increased angle up to 34° is reported with decreasing stability (Carper and Porte-Agel, 2004).

Our study focuses on importance of surface stress intermittency and the effect of coherent, large- and very-large-scale motions in aeolian processes. Further, the effects of surface heating (unstable stratification) are examined in the convectively stratified atmospheric boundary layer.

Large-eddy simulation (LES)

Technique for modeling turbulent flow, $\tilde{u}$, in realistic conditions: Solve momentum transport equation:

$$\frac{\partial \tilde{\boldsymbol{u}}}{\partial t} + \frac{1}{2}\nabla(\tilde{\boldsymbol{u}}\cdot\tilde{\boldsymbol{u}}) - \tilde{\boldsymbol{u}}\times\tilde{\boldsymbol{w}} = -\frac{1}{\rho}\nabla\tilde{p} - \nabla\cdot\boldsymbol{\tau} + \boldsymbol{\Pi}\,\hat{\boldsymbol{\imath}} + Ri_\tau\,\rho^\star\hat{\boldsymbol{k}} \quad \mathbf{(1)}$$

Tilde denotes grid-filtered quantity $\left(\tilde{\boldsymbol{u}}(\boldsymbol{x},t) = G_\Delta \star \boldsymbol{u}(\boldsymbol{x},t)\right)$,
$\boldsymbol{\tau} = \widetilde{\boldsymbol{u}\otimes\boldsymbol{u}} - \tilde{\boldsymbol{u}}\otimes\tilde{\boldsymbol{u}} \equiv$ subgrid-scale stress tensor,
$\boldsymbol{\Pi} = \{u_\tau^2/H = 1,0,0\} \equiv$ imposed pressure-gradient forcing,
$u_\tau \equiv$ friction velocity and $H =$ domain depth.

Incompressible $\tilde{\boldsymbol{u}}$ is maintained by computing the divergence of **Eq.1**, applying $\nabla\cdot\tilde{\boldsymbol{u}} = 0$, and solving the resultant pressure Poisson equation. $\boldsymbol{\tau}^d$ evaluated using eddy viscosity modelling approach,
$\boldsymbol{\tau} - \frac{1}{3}\boldsymbol{\delta}\,Tr(\boldsymbol{\tau}) = -2\nu_t\tilde{\boldsymbol{S}}$, where $\nu_t = (C_s\Delta)^2|\tilde{S}| \equiv$ turbulent viscosity, $C_s =$ Smagorinsky coefficient,
$\tilde{\boldsymbol{S}} = \frac{1}{2}(\nabla\tilde{\boldsymbol{u}} + \nabla\tilde{\boldsymbol{u}}^T) \equiv$ resolved strain-rate tensor,
and $|\tilde{S}| = (2\,\tilde{\boldsymbol{S}}:\tilde{\boldsymbol{S}})^{1/2}$.

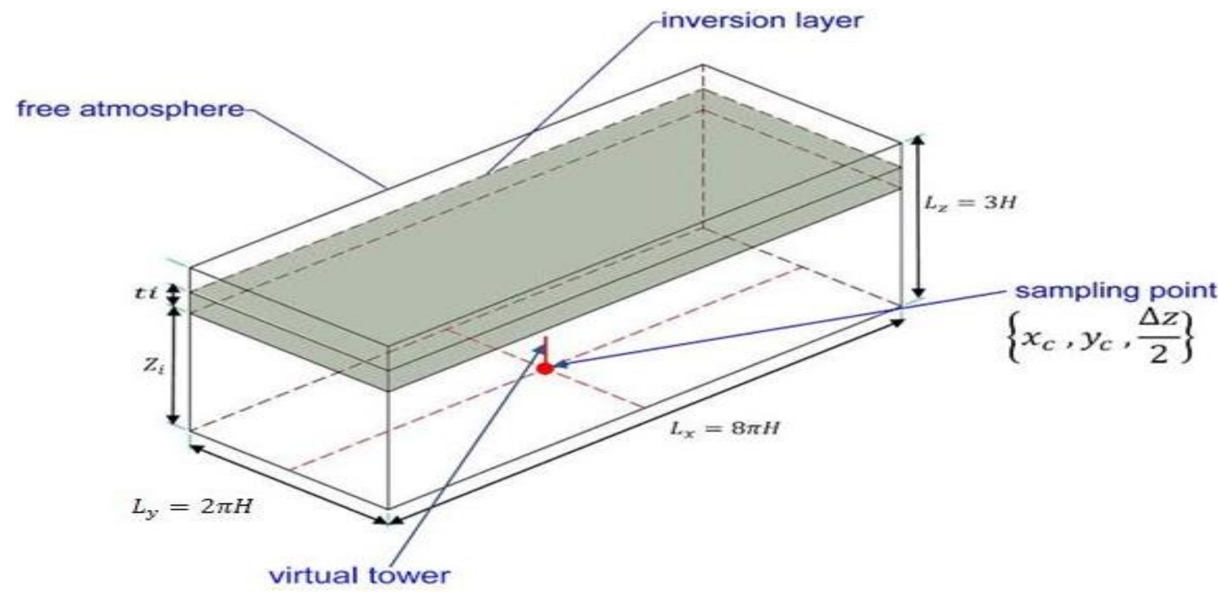
The non-dimensional Richardson number defined as

$$Ri_\tau = -\frac{g}{\rho}\frac{\partial\rho^\star}{\partial z}\Big|_s\frac{H^2}{u_\tau^2}$$

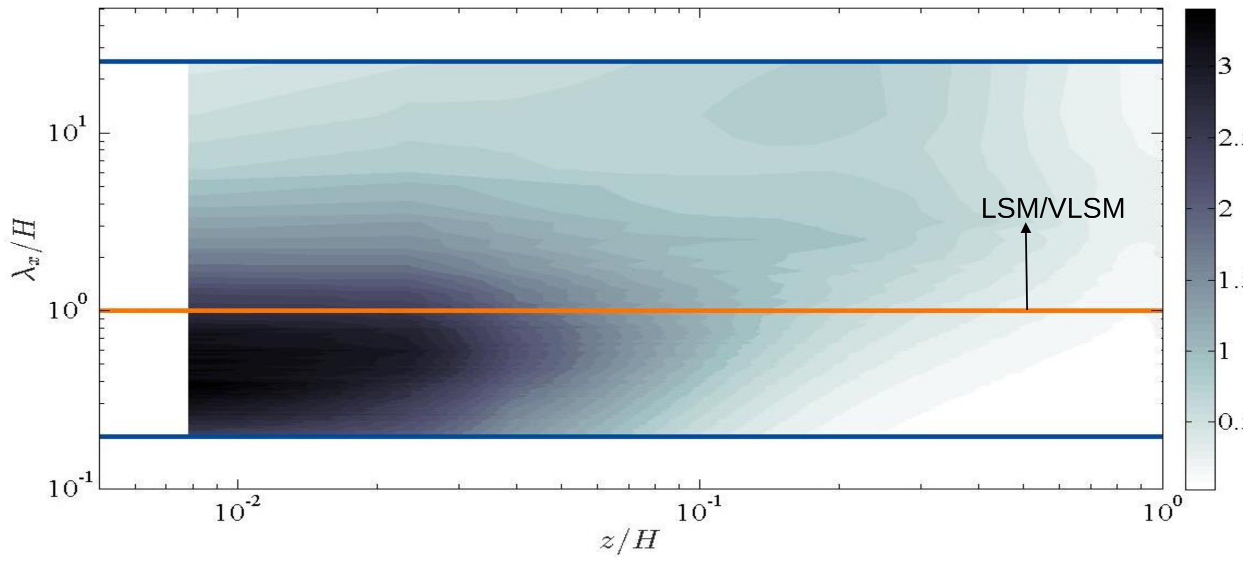
where $\frac{\partial\rho^\star}{\partial z}|_s$ is the imposed free-surface gradient. Increasing Ri_τ is physically equivalent to increasing the imposed surface stratification. When $Ri_\tau < 0$, a positive density gradient is imposed at the free surface, corresponding to unstable stratification.

Conditional sampling

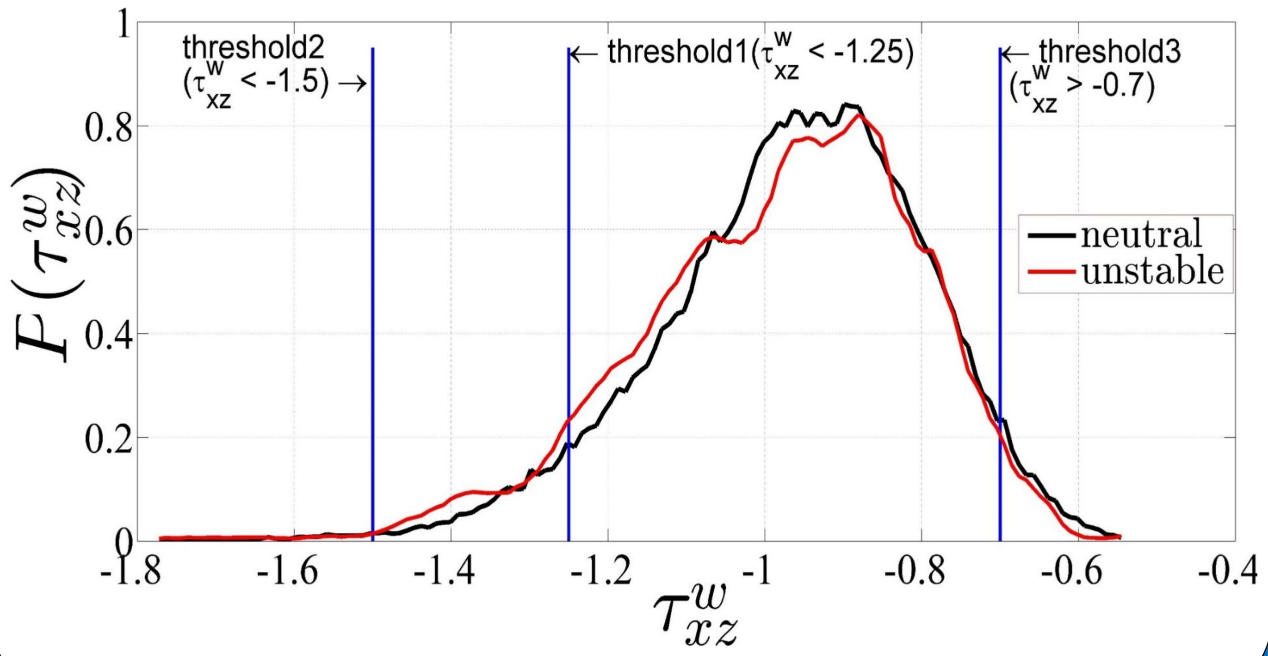
A significant streamwise and wall-normal extent is considered for the computational domain in modeling neutral and unstable ABL to capture large scale turbulent structures.



Pre-multiplied energy spectrum of fluctuating streamwise velocity, $\frac{k_x E_{\tilde{u}'\tilde{u}'}}{u_\star^2}$, indicates domain extent L_x and domain depth H required to resolve large- and very-large scale motions present in the flow.



Our sampling point is located very closer to the base of the domain and we recorded a time-series of aerodynamic surface stress at this point. A Probability Distribution Function (PDF) of the surface stress τ_w is generated for both neutral and unstable cases.

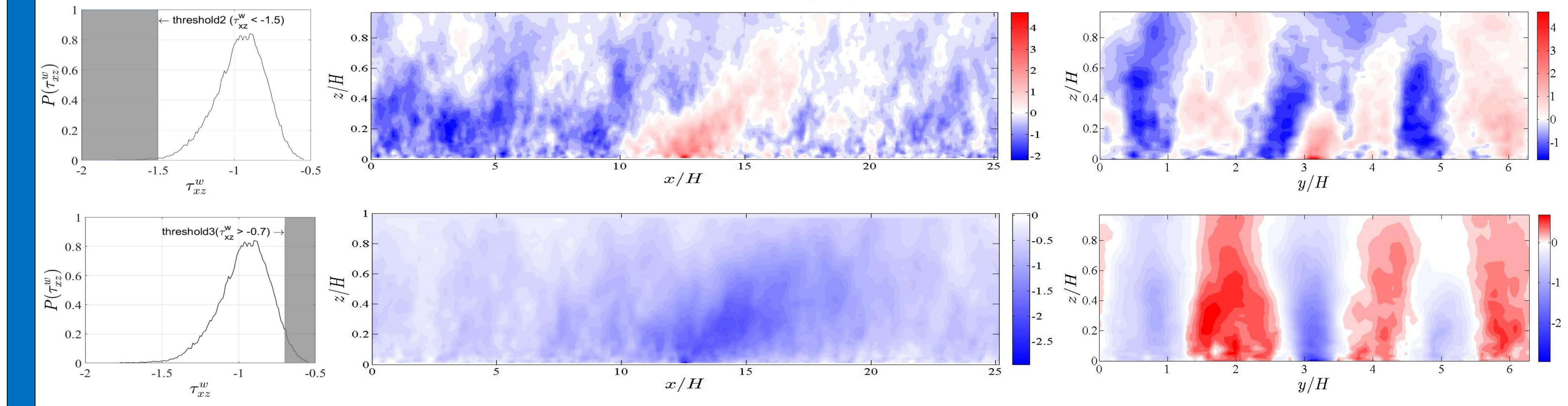


Both the PDFs are negatively skewed (skewed toward extreme stress events which are less likely to occur). **Events corresponding to this region undergo sediment mobilization**.

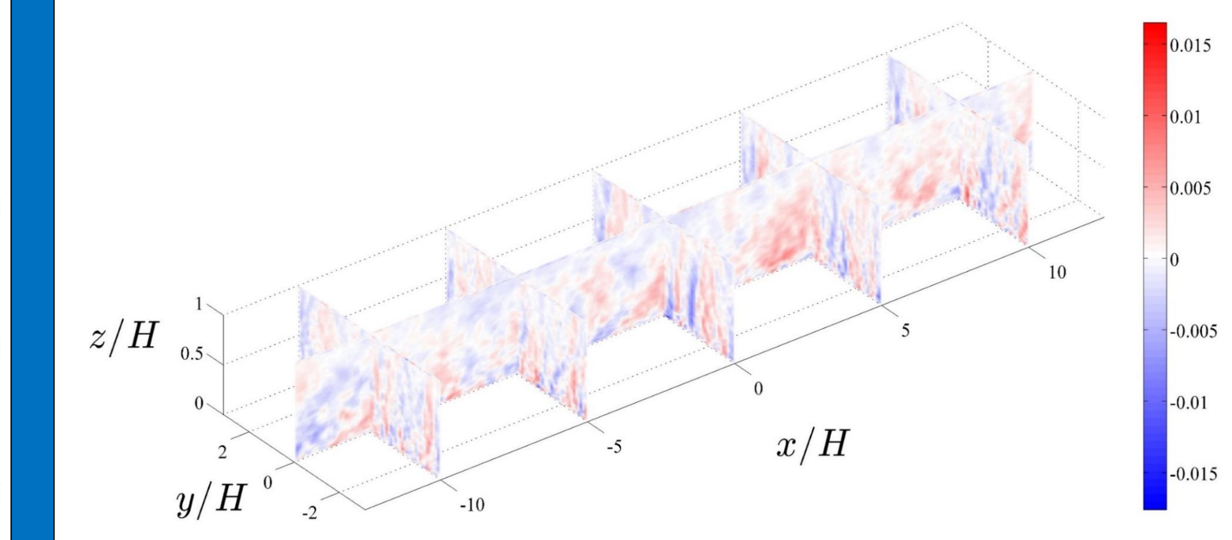
The velocity field is conditionally averaged based on threshold stresses with the aim of identifying turbulent geometries responsible for high and low stress events.

The PDF of unstable stratification shows a higher probability of extreme stress events over the neutrally stratified case. At the same time, the probability of average stresses related to unstable stratification is lower than that of neutrally stratified case.

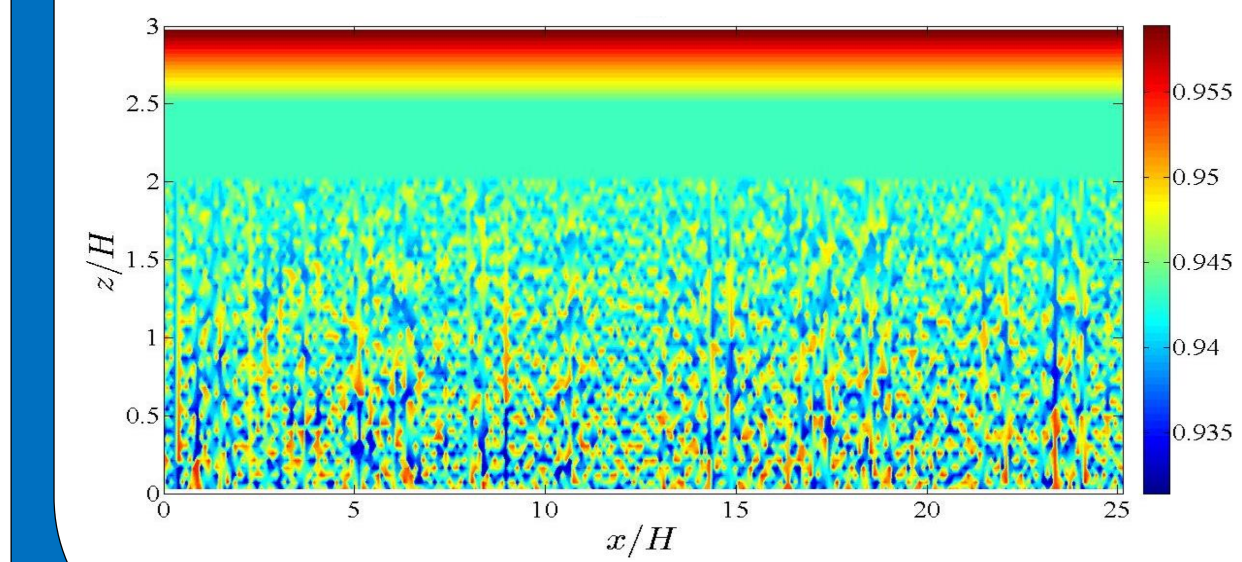
Contours of $\hat{\hat{u}}' = \hat{\tilde{u}} - <\hat{\tilde{u}}>_{xy}$ for high and low stress events for neutrally stratified atmospheric boundary layer



The contours of the conditional streamwise velocity gradient, $\frac{\partial\hat{\tilde{u}}}{\partial x}$ are approximately linearly inclined at a similar angle to the conditional velocity contours.



Temperature field resulting from surface heating: contours of T/T_o where $T_o = 300K$



Conclusion

- PDF of τ_{xz}^w is skewed toward high stress events responsible for aeolian erosion
- Conditional averaging technique indicates the presence of LSMs and VLSMs pertaining to extreme stress events
- The structure inclination angle increases up to 40° from 14° in response to the unstable stratification
- High stress events are likely caused by the passage of large (or very large), inclined coherent structures which are flanked on either side by low-stress regions and the opposite holds true when conditioned on low stress events.

References

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2. J. Sheng, E. Malkiel, and J. Katz. *J.Fluid Mech.*, 633:17-60, 2009.
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