MULTI-SCALE SIMULATIONS AND ANALYSIS ON WINDBLOWN SAND MOVENMENTS

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Summary Based on real-time and synchronous measurements of wind velocities and PM10 concentrations during sand-dust storm events happened in Minqin, north-western China, this paper reveals the existence of LSMs and VLSMs in near-surface flow field and identifies a region where they coexist. Several new laws about the variation of the temporal and spatial scales of LSMs and VLSMs with the distance from the wall and Reynolds number are given out. In addition, VLSMs containing significant energy play a leading role in the transportation of PM10 dust particles above 8m, and contribute an effect to dust particles' motions in the near-wall region. A representative model for wind fluctuations is put forward as a basis for simulations of windblown sand movements regarding non-steady incoming flow and multi-field coupling effects. Consequently, quantitative simulations of aeolian landforms including sand ripples and dune fields are realized.

As a kind of meteorological disaster that has a wide-ranging influence, sand-dust storms can be categorized into solid-gas two-phase flow from the perspective of fluid mechanics with a high Reynolds number up to 10^8. Aiming to stretch current understanding of high Reynolds number wall turbulence to atmospheric boundary layer flow as well as to reveal the key characteristics and underlying rules of this phenomenon, this paper presents high-frequency and synchronous field observation results of three-dimensional wind field and PM10 concentration data during more than 20 whole sand-dust storm events—regarding different stages involved in a sand-dust storm, i.e., the ascending, stable and descending stages—happened in Minqin, which is considered as one of the most severely desertified areas in China. Statistical analysis on measured data displays two typical types of turbulent structures at the stable stage, that is, Large Scale Motions (LSMs) in near-wall region and Very Large Scale Motions (VLSMs) in a region away from the wall (Fig.1a). It is also found that: 1) a transition region can be identified between the former two regions at a distance about 0.01~0.05δ from the wall; 2) both the frequencies of the streamwise modes of LSMs and VLSMs remain almost constants with varying heights, but tend to be two higher values (within the range of 0.003Hz~0.02 and 0.01~0.3Hz respectively) with increasing Reynolds number (from 1.4×10^7 to 1.37×10^8), both the streamwise spatial scales of LSMs and VLSMs display a trend of first increase and then decrease with the increasing of Reynolds number, and the required Reynolds number at which the peak occur increases with height. Different from existing available experimental observations, the streamwise spatial scales increase with height in a logarithmically linear, rather than a linear [1] manner, the energy ratios of VLSMs display a slightly decaying rather than a strengthening trend[2] with increasing Reynolds number (see the insert subfigures of Fig.1a).

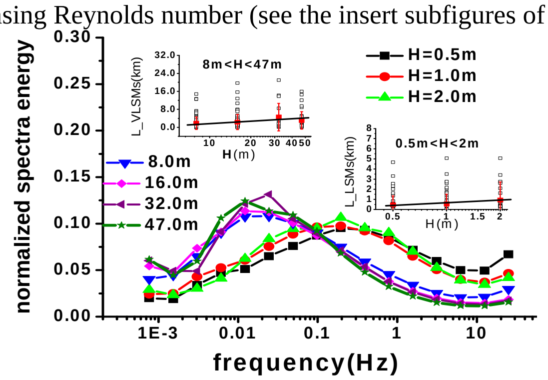

Fig. 1a The variation of the averaged normalized spectra energy with frequency for 12.5m/s $<V_{10m}$ <15m/s (Insert subfigures: The variations of the streamwise scales of LSMs & VLSMs with height)

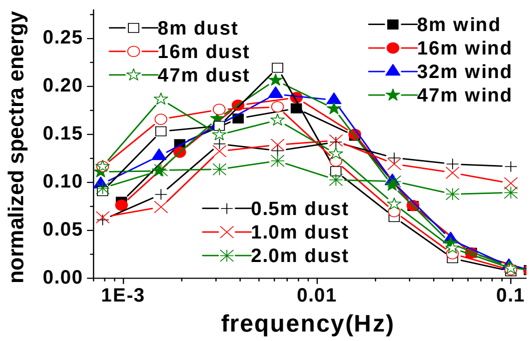

Fig. 1b The averaged normalized spectra energy of PM10 concentrations ranging from 0.5 to 47m, and wind velocities from 8 to 47m

It is also found from the experimental results that there exists a general upward air flow within 8-47m during the sand-dust storm events in Miqin, in which the vertical wind speed at 8m is higher than 16m and 32m, but slightly less than 47m. Moreover, the frequency of the spanwise mode of LSMs and VLSMs gradually decrease with height and are about one order of magnitude smaller than streamwise ones. Such discrepancy might be due to the different influence in spanwise and streamwise directions from wall surface to large eddies below 47m, which is also the reason for "plume" phenomenon in sand-dust storms. The measured PM10 dust concentration has a peak value at 16m which might be raised from the strong convection near 8m and consequently an aggregation of dust particles near 16m. Normalized energy spectrum of PM10 concentrations measured above 8m display coherent structures which have the same frequency as the streamwise mode of VLSMs. Below 2m, dust concentration has a weak correlation with LSMs but show an unapparent energy-ratio peak corresponding to the dominant frequency of VLSMs (Fig.1b). It therefore can be concluded that VLSMs containing significant energy play a leading role in the transportation of PM10 dust particles above 8m, and contribute an effect to dust particles' motions in the near-wall region below 2m.

Analysis on wind-velocity time series measured at a 50Hz frequency illustrate that horizontal wind speeds at different heights below 2m all approximately follow Gaussian distributions. Therefore, wind spectrum at various heights lower than 2m can be generally written by the following representative formula:

$$S_u(f) = C_1 n z u_*^2 / \bar{u}[n(C_2 + C_3 nz/\bar{u})^{5/3}] \quad (1)$$

In which, $\bar{u}(z)$ represents the average wind speed at z; u_* is the frictional wind speed; n is the frequency of wind velocity signal; C_1, C_2 and C_3 are fitting parameters. When C_1=105, C_2=0.3, C_3=33, formula (1) gives a better description of the measured wind spectrum compared with existing Simiu-spectrum [3] or Kaimal-spectrum [4], especially for the low-frequency part, see in Fig. 2a. Based on this, a numerical model is proposed to simulate the evolution of windblown sand movements under various average wind speed and fluctuation conditions, one of the simulated sand-saltation intensity time series is showed in Figure 2b. Through analyzing the influence of mean wind velocity and fluctuation variance to sand saltations, this paper presents for the first time a prediction formula for sand transportation rate in terms of mean wind velocity and turbulence intensity:

$$Q = A[1+\exp(120I - 0.84u_m + 11.55)]^{-1}, \quad A = 0.037\exp(\frac{u_m}{6.76}) - 0.1, \; R^2 = 0.99 \quad (2)$$

In which, Q is sand transportation rate; u_m is mean wind velocity; I is turbulence intensity; A is a fitting parameter. Different from previous models expressing sand transportation rate only in term of friction wind speed, formula (2) incorporates both the effect of non-steady characteristics of actual wind field and average wind stress to windblown sand transportation, see in Fig. 2c.

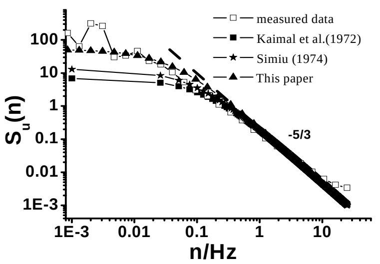

Fig 2a. Comparison of measured wind spectrum at 2m with predicted values given by formula (1) together with other spectrum.

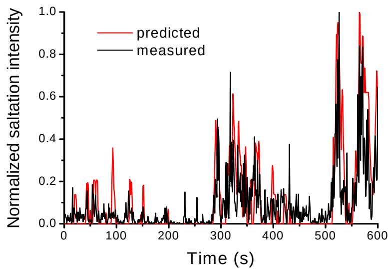

Fig 2b. Comparison of simulated normalized saltation intensity time series with measured data for u_m=8.8m/s at 2m

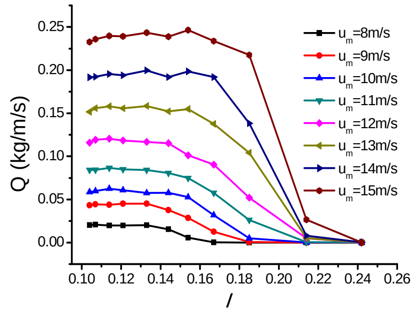

Fig 2c. Variations of sand transportation rate with turbulent intensity for various mean wind velocities given by simulations.

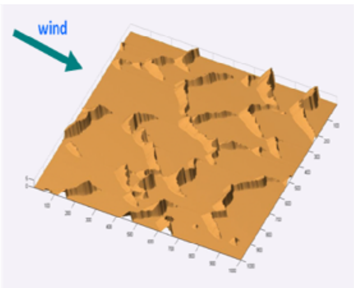

Fig. 3a Simulated barchans dune field (with u_*=0.5m/s, D=0.3mm, H=0.8m, S=3km×3km).

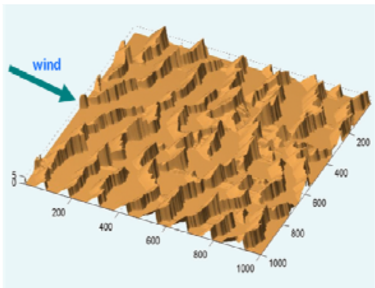

Fig. 3b Simulated transverse dune field (with u_*=0.5m/s, D=0.3mm, H=4m, S=5km×5km).

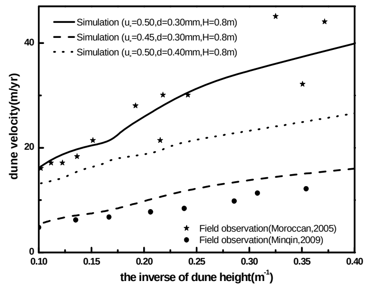

Fig. 3c Comparison of dunes' migration speed vs. dune height between simulated results and field observations (symbols are observation results, lines are simulation results).

In addition, we establish a trans-scale theoretical scheme to realize quantitative simulations to the formation and evolution of an aeolian dune field which covers an area of hundreds of square kilometers and lasts several centuries, as shown in Fig. 3a-b. Simulation results reveal the influence of wind field, sand diameter and thickness of sand supply to dune patterns and migration speeds etc., and give out the dynamical conditions required for the formation of existing dune types, which all correspond well with existing observations in quantity (Fig. 3c). Such scheme provides an effective way to replay the evolution history of aeolian landforms and predict the expansion speed of desertification.

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References

[1] Tomkins, C. D. & Adrian, R. J. 2003 Spanwise structure and scale growth in turbulent boundary layers. J. Fluid Mech. 490, 37–74.

[2] Hutchins, N. and Marusic, I., Evidence of very long meandering features in the logarithmic region of turbulent boundary layers, J. Fluid Mech., 579, 2007, 1–28.

[3] Simiu, E., Wind Spectra and Dynamic Along wind Response. *Journal of the Structural Division*, **100(9)**: 1897–1910, 1974.

[4] Kaimal, J. C., Wyngaard, J. C., Izumi, Y., O. R. CotéSpectral characteristics of surface-layer turbulence. *Quarterly Journal of the Royal Meteorological Society*, **98**: 563–589, 1972.