

# Impact of Turbulence on Aeolian Sand and Dust Entrainment: Results from Wind-tunnel Experiment

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**Abstract.** We hypothesize that large eddies play a major role in the entrainment of aeolian sand and dust particles. To test this, wind-tunnel experiments are carried out to measure the entrainment rate of various particle sizes under different flow conditions. Wind tunnel flows are usually neutrally stratified with no large eddies which typically develop in convective atmospheric boundary layers. Here, a novel technique is applied by deploying a piece of randomly fluttering cloth to generate large eddies similar to convective eddies in atmospheric boundary layers, which we call quasi-convective turbulence. The characteristics of quasi-convective turbulence are analyzed with respect to neutral turbulence in the Monin-Obukhov similarity framework, and the probability distributions of surface shear stress are examined. We show that for given mean flow speed and in comparison with neutral flow conditions, quasi-convective turbulence increases the surface shear stress and alters its probability distribution, and hence substantially enhances the entrainment of sand and dust particles. Our hypothesis is thus confirmed by the wind-tunnel experiments. We also explain why large eddies are important to aeolian entrainment and transport.

## 1 Introduction

The entrainment of sand and dust particles is among the most important quantities to determine in aeolian studies. Based on Bagnold (1941), Owen (1964) showed that the vertically integrated saltation flux,  $Q$ , can be expressed as

$$Q = \begin{cases} c_0 \frac{\rho}{g} u_*^3 \left(1 - \frac{u_{*t}^2}{u_*^2}\right) & \text{for } u_* > u_{*t} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where  $c_0$  is the Owen coefficient,  $\rho$  air density,  $g$  acceleration due to gravity,  $u_*$  friction velocity and  $u_{*t}$  threshold friction velocity. By definition,  $u_* = \sqrt{\tau/\rho}$  is a descriptor of the surface shear stress,  $\tau$ . It has been shown in numerous studies that Eq. (1) is valid in general, but  $c_0$  scatters over a wide range if Eq. (1) is fitted to  $Q$  observations (Gillette et al., 1996, 1997; Leys, 1998; Liu et al., 2018). While the large scatter of  $c_0$  is not yet fully explained, it is most likely because both  $u_*$  and  $u_{*t}$  are stochastic variables and hence saltation driven by atmospheric boundary-layer (ABL) turbulent flows is also turbulent

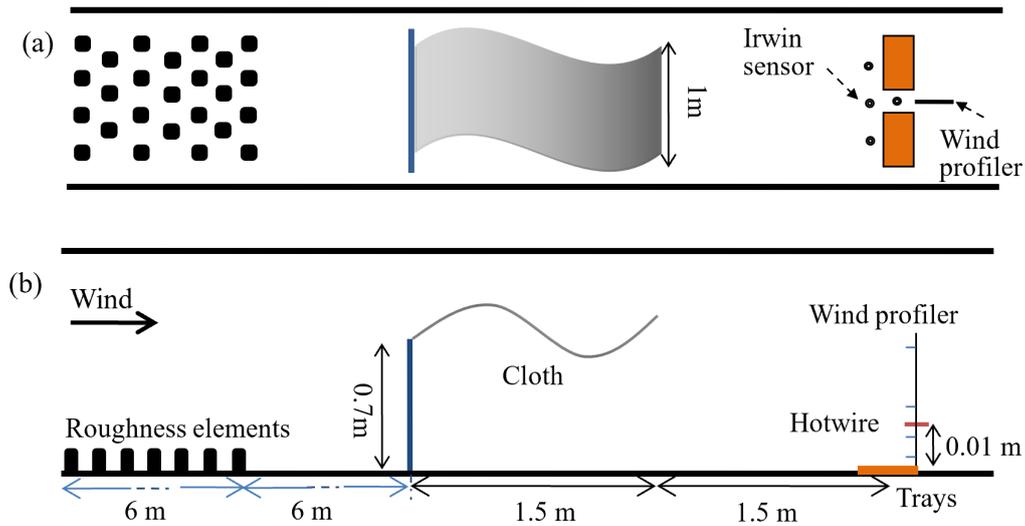
20 (Butterfield, 1991, 1998). In this sense, Eq. (1) is valid only for mean quantities,  $\bar{Q}$  and  $\bar{u}_*$ , if we assume  $u_{*t}$  is constant [this assumption is sufficient for the purpose of our study, but see Shao (2008), Raffaele et al. (2016), Liu et al. (2018), and Li et al. (2020) for discussions on  $u_{*t}$  as a stochastic variable].

Our question here is how turbulence influences the entrainment of sand and dust particles into the atmosphere. Numerous studies on aerodynamic sand and dust entrainment have been carried out (e.g., Greeley and Iversen, 1987; Anderson and Haff, 25 1988, 1991; Loosmore and Hunt, 2000; Doorschot and Lehning, 2002; Jia and Wang, 2021), but in all these studies, flow is assumed to be steady and the impact of turbulence on the entrainment is neglected. In reality, atmospheric flows are always turbulent, and aeolian processes also. Butterfield (1991, 1998) investigated the behavior of saltating grains in unsteady flows and found that both the frequency and strength of wind gusts influence the rate of sand transport. Stout and Zobeck (1997) observed that saltation intermittently occurs even when  $u_* < u_{*t}$ , a phenomenon known as saltation intermittency. Xuan (2004) 30 concludes that turbulence decreases  $u_{*t}$  or the threshold wind velocity  $u_t$  and increases  $Q$  or the vertical flux (the dust emission rate). Klose and Shao (2012) and Klose et al. (2014) developed a parameterization scheme for dust emission by convective turbulence and explained how dust emission can be produced by large eddies in weak mean wind conditions. Comola et al. (2019) draw on extensive field measurements to show that neglecting saltation intermittency causes biases in the timing and intensity of predicted fluxes. Shao et al. (2020) reported that saltation in unstable ABLs is generally more fully developed than 35 in stable ABLs.

It should be pointed out that saltation intermittency in the sense of Stout and Zobeck (1997) is a special case of saltation fluctuation at  $u_* \sim u_{*t}$ , because in general if  $u_* = \bar{u}_* + u'_*$  and suppose  $u'_* > 0$ , then  $Q = Q(\bar{u}_*) + Q'$  with  $Q' > 0$ . The saltation intermittency Stout and Zobeck (1997) studied is for the case  $\bar{u}_* = u_{*t}$  and  $Q(\bar{u}_*) = 0$  but  $Q' > 0$ . The above discussion suggests that the turbulent (or probabilistic) behavior of  $u_*$  is of great importance to  $Q$  and naturally also to sand and dust 40 entrainment. Because the turbulent behavior of  $u_*$  is closely related to ABL turbulence, our hypothesis is thus that ABL turbulence profoundly influences the entrainment of sand and dust particles.

In stable and neutral ABLs, turbulence is generally weak and more homogeneous and isotropic, but in unstable (or convective) ABLs, strong due to buoyancy production of turbulent kinetic energy and less homogeneous and isotropic due to the presence of large eddies. It is therefore particularly interesting to study the influences of convective turbulence on aeolian pro- 45 cesses. Khalfallah et al. (2020) pointed out that dust particle size at emission is dependent on ABL stability. Shao et al. (2020) compared some features of saltation and dust emission in convective and stable ABLs based on the field observations of the Japan-Australian Dust Experiment (JADE, Ishizuka et al., 2008, 2014), but due to the limitations of the field measurements, the role of turbulence in aerodynamic sand and dust entrainment could not be explicitly examined. We are thus motivated to acquire additional data to test our hypothesis.

50 Wind tunnel is a powerful tool for studying aeolian problems under controlled flow conditions (Rasmussen and Mikkelsen, 1991; Alfaro et al., 1997; Brown et al., 2008; Zhang et al., 2014). However, wind-tunnel experiments are often limited to neutral flows because most wind tunnels do not have the capacity of generating convective eddies. Here we apply a simple forced-perturbation technique (using a piece of randomly fluttering cloth) to generate quasi-convective turbulence, namely, turbulence in a neutrally stratified flow but with characteristics of convective turbulence. Aerodynamic sand and dust entrainment rates



**Figure 1.** (a) Top view of the wind-tunnel configuration; (b) Side view of the wind-tunnel configuration. A piece of randomly fluttering cloth in the wind tunnel enables the generation of quasi-convective turbulence.

55 under various mean-wind and quasi-convective turbulence conditions are measured. We use these wind-tunnel data to study how and why turbulence influences the aerodynamic sand and dust entrainment rate.

## 2 Wind-tunnel Experiment and Instrumentation

We carried out the experiment in the Lanzhou University wind tunnel which is specially designed for aeolian studies. The technical details of the wind tunnel can be found in Zhang et al. (2014) and hence only the most relevant information is given here. Fig.1 shows the wind-tunnel configuration for the experiment. The working section of the tunnel is about 15 m long, with the first 6 m being the roughness-element section for generation of a turbulent boundary layer. One end of the piece of cloth is attached to a horizontal bar located 6 m downstream the roughness-element section and 0.7 m above the tunnel floor, and the other end is allowed to flutter freely. Two trays (285 mm wide, 150 mm long and 13 mm deep) are placed 1.5 m downstream the end of the fluttering cloth. The trays filled with sand are mounted flush to the tunnel floor. Each tray is placed on an electronic balancer which measures the mass loss from the tray with a precision of 0.01 g in the range 5 kg. Four Irwin sensors are mounted in front and between the trays and a wind profiler is located between the trays, next to a hotwire anemometer fixed at 10 mm height.

The wind profiler is a rack of ten pitot tubes placed at the levels of 6.5, 10, 15, 30, 60, 120, 201, 351 and 501 mm above the tunnel floor for measuring the profile of the mean flow speed, while the hotwire anemometer measures turbulent fluctuations with a sampling frequency of 1000 Hz. Irwin sensors (Irwin, 1981) are omnidirectional devices for measuring the surface shear

stress, which have been used successfully in a number of earlier studies (e.g. Wu and Stathopoulos, 1993; Walter et al., 2012). We manufactured the Irwin sensors used in this study ourselves according to the dimensions given in Gillies et al. (2007). The Irwin-sensor pressure differences are sampled at a frequency of 100 Hz using a scan valve attached to a pressure transducer (ZOC33). Prior to the wind-tunnel experiment, the Irwin sensors are calibrated in the wind-tunnel against the wind profiler for various flow conditions, by comparison of the shear stresses measured by the two devices.

A key requirement for our experiment is to generate turbulence in the wind tunnel with characteristics similar to convective turbulence. In convective ABLs, large eddies develop due to buoyancy production of turbulent kinetic energy. While horizontal velocity fluctuations are approximately Gaussian distributed, vertical velocity fluctuations are typically non-Gaussian with a positive skewness. Convective turbulence is difficult to generate in wind-tunnel flows which are usually neutrally stratified. In our experiment, we use a ‘forced perturbation’ technique to generate turbulence in the wind-tunnel flow, that has the characteristics similar to convective turbulence, in particular, with energy containing large eddies and a positively skewed asymmetric probability distribution function (PDF). Such turbulence is here referred to as quasi-convective turbulence. Forced perturbation is achieved by using a piece of cloth which flutters randomly in the wind-tunnel flow to produce small eddies, and flaps irregularly to produce large eddies, superposed on the background turbulence. Although quasi-convective turbulence is not the same as convective turbulence, the forced-perturbation method is both simple and efficient to remedy the critical deficit of wind-tunnel flows which lack of large eddies.

The wind tunnel is a blow tunnel, with the inlet flow speed controlled by a rotating fan. For our experiment, the fan speed is fixed for each run between 7000 and 12000 rpm. We call the runs with forced perturbation WP-runs and those with no forced perturbation NP-runs. The entrainment of four particle size groups are measured for various flow and turbulence combinations, as listed in Table 1. For each run, at least three successful repetitions are made and the measurement period for each repetition is 5 minutes. Four different soils are used in the experiment, labelled as S1, S2 etc. The mean particle size of the four soils are 75, 140, 215 and 398  $\mu\text{m}$ . The particle size distributions are approximately log-normal. We use NP07\_S1 to denote the NP-run for fan speed 7000 rpm and soil S1 and name following this convention the other runs.

## 2.1 Results

### 2.1.1 Forced Perturbation

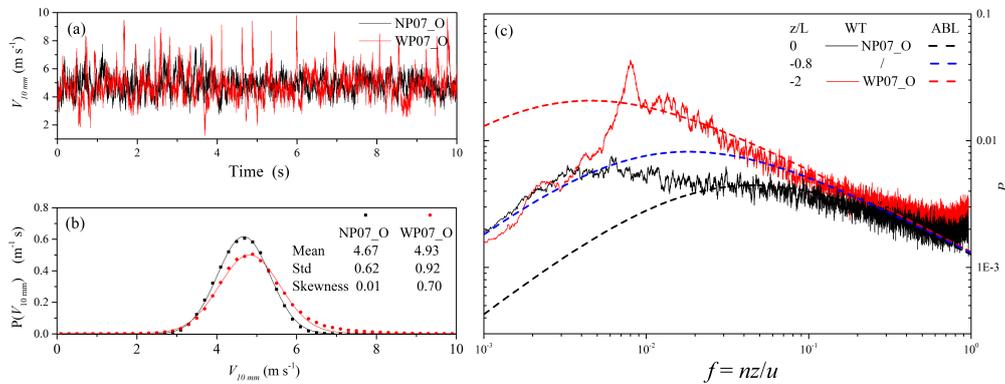
We first examine whether turbulence generated using the forced-perturbation technique has the desired features of convective turbulence. In Fig. 2, the characteristics of  $V_{10\text{mm}}$  (flow velocity sensed by the hotwire anemometer) are compared between the NP07\_O and WP07\_O runs, including its time series, PDF and power spectrum. As  $V_{10\text{mm}}$  is measured using a one-dimensional hotwire, it is the resultant velocity of its horizontal component,  $u_{10\text{mm}}$ , and vertical component,  $w_{10\text{mm}}$ . As seen, the force-perturbation technique effectively generates quasi-convective turbulence, as turbulence for the WP07\_O run has an increased variance and a positive skewness, while turbulence for the NP07\_O run is weaker and almost Gaussian distributed.

In the MOST (Monin-Obukhov Similarity Theory) framework,  $\zeta = z/L$ , with  $z$  being height and  $L$  the Obukhov length, is used as a measure of ABL stability: the ABL is stable, neutral and unstable for  $\zeta > 0$ ,  $= 0$  and  $< 0$ , respectively. Kaimal

**Table 1.** Summary of wind-tunnel experiments

Particle size	Fan speed	Repetitions									
	( $\times 1000$ rpm)	7	7.5	8	8.5	9	9.5	10	10.5	11	12
		NP/WP	NP/WP	NP/WP	NP/WP	NP/WP	NP/WP	NP/WP	NP/WP	NP/WP	NP/WP
O (no soil)		1	/	1	/	1	/	1	/	1	1
S1 (75 $\mu\text{m}$ )		5/3	/	5/5	/	5/5	/	5/5	/	5/5	3/5
S2 (140 $\mu\text{m}$ )		5/5	/5	5/5	/4	5/5	3/3	3/	/	/	/
S3 (215 $\mu\text{m}$ )		5/5	/	5/5	/5	5/5	/	5/5	5/	6/	/
S4 (398 $\mu\text{m}$ )		3/3	/	3/5	/	3/5	/	5/5	/	5/5	5/

NP = no perturbation; WP = with perturbation.



**Figure 2.** (a) A section of 10s of the  $V_{10\text{mm}}$  time series for the NP07\_O and WP07\_O runs; (b) probability density functions of  $V_{10\text{mm}}$  (estimated using a time series of 300s); (c) normalized power spectra of  $V_{10\text{mm}}$  for WP07\_O and NP07\_O compared with field-observed power spectra in atmospheric boundary layer (Kaimal et al., 1972).  $Z_{0\text{WT}}$  is  $1.33 \times 10^{-2}$  mm and  $Z_{0\text{ABL}}$  is set to 3.10 mm (Wiernga, 1993).

et al. (1972) examined the characteristics of surface-layer turbulence using the MOST and found that the nondimensionalized power spectra of ABL quantities collapse to universal functions with  $\zeta$  being the only parameter. They showed that as the ABL stability decreases, the inertial subrange extends to lower frequencies. Plotted in Fig. 2(c) are the normalized power spectra of  $V_{10\text{mm}}$  for WP07 and NP07, denoted as PWP07 and PNP07, respectively. Following Kaimal et al. (1972), we express the normalized frequency as  $f = nz/u$  (with  $n$  being frequency) and normalized energy spectral density as

$$P = nS(n)\bar{u}_*^{-2}\phi_\epsilon^{-2/3} \quad (2)$$

110 with  $S$  being the energy density per frequency and  $\phi_\epsilon$  the MOST similarity function for the dissipation rate of turbulent kinetic energy

$$\phi_\epsilon = 1 + 0.5|\zeta|^{2/3} \quad (3)$$

following Kaimal and Finnigan (1994), our analysis does not involve the cases of  $\zeta > 0$ . For the wind-tunnel runs,  $nS(n)$  is obtained by analyzing the horizontal wind velocity component measured by the hotwire,  $\bar{u}_*$  is measured by the Irwin sensor  
 115 and  $\phi_\epsilon$  is calculated by using Eq. (3) with  $\zeta = 0$  for the NP07\_O run and  $\zeta = -2$  for the WP07\_O run. For comparison, the ABL velocity power spectra, denoted as PABL, for three different stabilities  $\zeta = 0, -0.8$  and  $-2$  are plotted. An empirical form given by Kaimal et al. (1972)

$$P_{ABL} = 105f/(a + 33f)^{5/3} \quad (4)$$

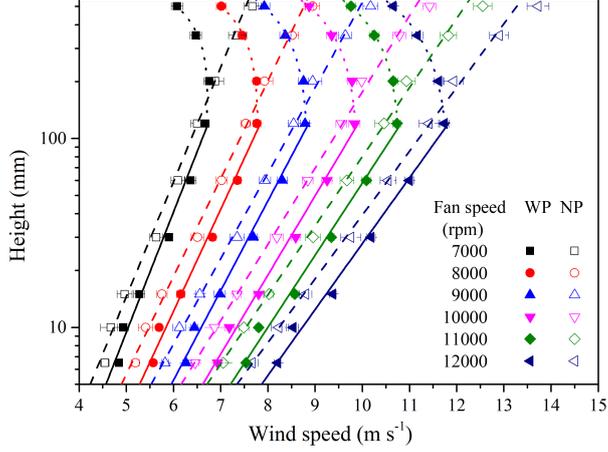
where  $a$  is an empirical constant set to 1, 0.4 and 0.1 for  $\zeta = 0, -0.8$  and  $-2$ , respectively. Note that in Fig. 2(c),  $P_{ABL} \times$   
 120  $z_{0WT}/z_{0ABL}$  is plotted, where  $z_{0WT}$  is the roughness length for the wind-tunnel flows and  $z_{0ABL}$  that for the ABL flows. The ratio  $z_0/L$  is the MO number which was excluded in Kaimal et al. (1972) and the exclusion is justified because the differences in  $z_0$  in their data are not large. However, because  $z_{0WT}$  (Table 2) is two orders of magnitude smaller than  $z_{0ABL}$ , the effect of  $z_0/L$  needs to be considered and hence the mentioned multiplication is necessary.

Fig. 2(c) reveals that  $P_{NP07}$  and  $P_{WP07}$  are almost the same in the (normalized) frequency range of  $f < 3 \times 10^{-3}$ , as  
 125 turbulence in this frequency range is attributed to the upstream roughness elements. They are also the almost the same in the high frequency range of  $f > 0.1$ . In the energy containing range  $3 \times 10^{-3} < f < 0.1$ ,  $P_{WP07}$  shows much increased energy with respect to  $P_{NP07}$ , implying that the forced perturbation technique generated large eddies in the wind-tunnel flow.

Fig. 2(c) also shows that it is generally difficult for the wind tunnel to reproduce the turbulence observed in the ABL. Clearly, compared with  $P_{ABL}(\zeta = -0.8)$  and  $P_{ABL}(\zeta = -2)$ ,  $P_{NP07}$  lacks energy in the frequency range of  $3 \times 10^{-3} \sim 1 \times 10^{-1}$ .  
 130 In contrast, power spectral density in this frequency range is substantially increased if forced perturbation is applied as a comparison of  $P_{WP07}$  and  $P_{NP07}$  reveals. It is seen that  $P_{WP07}$  is fairly similar to  $P_{ABL}(\zeta = -2)$ , although it still lacks energy for  $f < 10^{-2}$ . In summary, Fig. 2 shows that the forced-perturbation technique is effective in generating quasi-convective turbulence which has a degree of similarity with ABL convective turbulence. This simple technique can be further optimized (e.g. by using a combination of fluttering cloths of different materials and different dimensions) to overcome the critical lack of  
 135 convective eddies in wind-tunnel flows, which has so far seriously limited the usefulness and generalization of the wind-tunnel results.

### 2.1.2 Mean Wind Profile and Shear Stress

Fig. 3 shows the mean wind profiles measured using the pitot tubes. For height  $z$  smaller than 0.2 m, the mean wind profiles are for both NP runs and WP runs are approximately logarithmic. In the WP runs, the flow speed for  $z > 0.2$  m is reduced due to  
 140 the fluttering cloth which acts as a momentum sink. For a given fan speed, the fluttering cloth not only enhances the turbulent kinetic energy (Fig. 2) but also modifies the wind profile for  $z < 0.2$  m to one more similar to wind profile in convective ABL.



**Figure 3.** Mean flow speed profiles for different fan speeds and the NP and WP runs

Based on the MOST, the similarity relationship between the mean flow speed,  $\bar{U}$ , can be expressed as

$$\bar{U}(z) = \bar{u}_*/\kappa[\ln(z/z_0) + \Psi_m] \quad (5)$$

where  $\kappa$  is the von Karmen constant, and

$$155 \quad \Psi_m = \int_{z_0}^z (1 - \phi_m) d \ln z \quad (6)$$

and

$$\phi_m = (1 - \gamma_m \zeta)^{-1/4}, \zeta \leq 0 \quad (7)$$

being the similarity function. For ABL flows,  $\gamma_m = 16$  is an empirical coefficient (Businger et al., 1971). For the NP runs,  $\Psi_m = 0$  is assumed. By fitting Eq. (5) to  $\bar{U}$  measured at  $z < 0.2$  m, we estimate  $\bar{u}_*$  and  $z_0$ . The shear stress  $\bar{\tau} = \rho \bar{u}_*^2$  (here, air density  $\rho = 1.2 \text{ kg m}^{-3}$ ) is then used to calibrate the shear stress measured using the Irwin sensor,  $\bar{\tau}_{\text{Irwin}}$ . For the WP runs,  $\Psi_m$  cannot be set to zero due to the quasi-convective turbulence generated, but as both  $\gamma_m$  and  $L$  are unknown for the quasi-convective turbulent flows, it is sensible to write Eq. (7) as

$$\phi_m = (1 - \eta_m z)^{-1/4} \quad (8)$$

with  $\eta_m \sim \gamma_m/L$ . By combining the  $\bar{U}$  measurements at  $z < 0.2$  m and the shear stress measured using the Irwin sensors for the WP runs,  $\eta_m$  can be estimated. The results are summarized in Table 2.

Table 2 shows that forced perturbation leads to a slightly increased  $\bar{u}_*$ . The deployment of the forced-perturbation technique results in an increase of  $\bar{\tau}$  by about 25% at fan speed 7000 rpm to about 15% at fan speed 12000 rpm. As pointed out in several

**Table 2.** Friction velocity  $\bar{u}_*$  and roughness length  $z_0$  estimated for runs with and with no forced perturbation and different wind-tunnel fan speeds.

Fan speed ( $\times 1000$ rpm)	NP		WP			
	Profile( $\Psi_m = 0$ )		Profile( $\Psi_m \neq 0$ )		Irwin	
	$u_*$ ( $\text{ms}^{-1}$ )	$z_0$ (mm)	$u_*$ ( $\text{ms}^{-1}$ )	$z_0$ (mm)	$\eta_m$ ( $\text{mm}^{-1}$ )	$u_*$ ( $\text{ms}^{-1}$ )
7	0.29	0.0133	0.31	0.0147	-0.0229	0.32
7.5	/	/	0.34	0.0151	-0.0213	0.34
8	0.34	0.0146	0.36	0.0158	-0.0200	0.37
8.5	/	/	0.39	0.0166	-0.0188	0.39
9	0.38	0.0159	0.41	0.0156	-0.0178	0.42
9.5	0.40	0.0125	0.44	0.0165	-0.0168	0.44
10	0.43	0.0164	0.46	0.0166	-0.0160	0.47
10.5	0.47	0.0207	/	/	/	/
11	0.47	0.0176	0.50	0.0165	-0.0145	0.51
12	0.51	0.0166	0.55	0.0162	-0.0133	0.55

earlier studies Klose and Shao (2012), Li et al. (2020) and Shao et al. (2020), we emphasis again that surface shear stress  $\tau$  is a stochastic variable, which satisfies a probability distribution function  $p(\tau)$ . To facilitate discussions, we explicitly write

$$160 \quad \tau = \bar{\tau} + \tau' \quad (9)$$

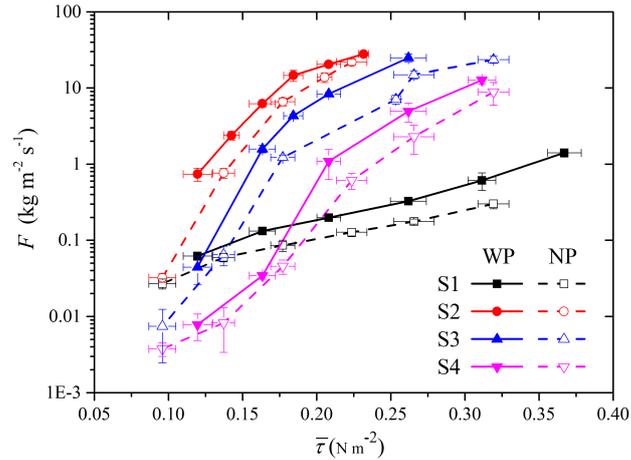
with  $\tau'$  being the perturbation of  $\tau$ .

### 2.1.3 Aeolian Sand/Dust Entrainment in Quasi-convective Turbulence

The emission rate of sand and dust particles,  $F$ , is estimated from the mass loss of the trays as

$$F = \frac{1}{I} \sum_{i=1}^{i=I} \frac{\Delta m_i}{A \Delta T_i} \quad (10)$$

165 where  $\Delta m_i$  is the mass loss from the tray during in the  $i$ th run with runtime  $\Delta T_i$ ,  $A$  is the tray surface area and  $I$  is the number of repetitions. Fig. 4 shows that the emission rates of the various particle-size groups measured in the NP and WP runs. It is seen that for all four soils, for given  $\bar{\tau}$ , the emission rate for the WP runs are substantially larger than that for the NP runs. This result suggests that in addition to the mean surface shear stress,  $\bar{\tau}$ , the surface shear stress perturbations,  $\tau'$ , significantly influence the emission rate,  $F$ . As  $\tau'$  is related to the structure of boundary-layer turbulence, it can be stated  
170 that the structure of boundary-layer turbulence significantly influences the entrainment rate: for a given mean surface shear



**Figure 4.** Emission rate of four different soils observed in the NP and WP runs.

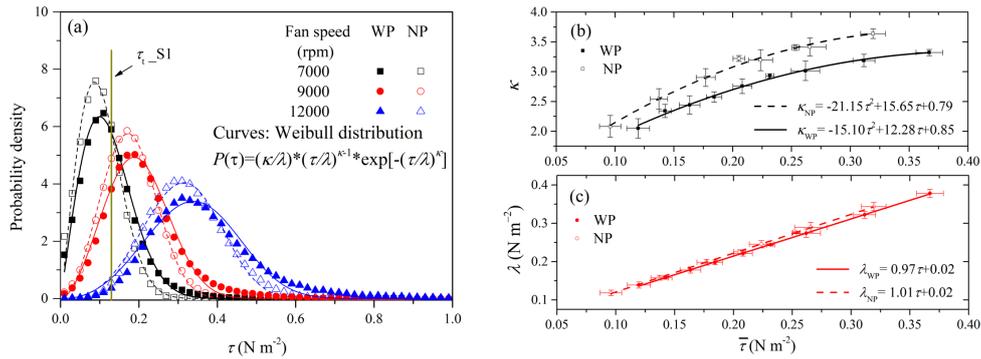
stress, convective turbulence is much more efficient in lifting particles from the surface into the air. This finding is consistent with the observations of the Japan-Australian Dust Experiment (JADE), as presented in the recent study of Shao et al. (2020), i.e., aeolian sand transport and dust emission are much more intensive in convective ABLs than in stable ABLs. Using the  $\tau$  measurements of the Irwin sensor, we estimate the PDF of  $\tau$ ,  $p(\tau)$ . Klose et al. (2014) and Shao et al. (2020) suggested that  $p(\tau)$  is approximately Weibull distributed and positively skewed. Fig. 5 show as example  $p(\tau)$  for the NP and WP runs for fan speed 7000, 9000 and 12000 rpm. As seen, the forced-perturbation results in significantly different PDF of  $\tau$  by slightly increasing  $\bar{\tau}$  and clearly increasing the probability of large  $\tau$ . It is this increase in the probability of large  $\tau$ , that explains the differences between the  $F \sim \bar{\tau}$  dependency between the NP and WP runs seen in Fig. 4. The structure of ABL turbulence, reflected here in  $p(\tau)$ , significantly influences the sand and dust entrainment and saltation fluxes, because these aeolian quantities depend non-linearly on  $\tau$ . As explained in (Shao, 2008, sect 6.12.4), for a given particle size, the entrainment rate  $F$  can be expressed as

$$F = \gamma \sqrt{\tau / \rho} (\tau - \tau_t) \quad (11)$$

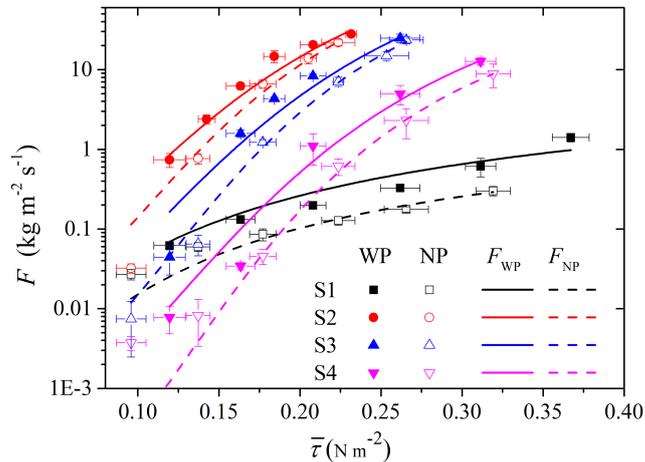
with  $\gamma$  being an empirical efficiency parameter for dust entrainment, and  $\tau_t$  is the threshold shear stress for particle entrainment. The threshold is in general a stochastic variable (Raffaele et al., 2016; Liu et al., 2018), but for simplicity, we assume it is constant for given particle size. To account for the fluctuations of  $\tau$ , we estimate

$$F = \int_{\tau_t}^{\infty} \gamma \sqrt{\tau / \rho} (\tau - \tau_t) p(\tau) d\tau \quad (12)$$

for the four soils S1, S2, S3 and S4 tested,  $\tau_t$  is estimated to be 0.13 Nm<sup>-2</sup>, 0.27 Nm<sup>-2</sup>, 0.31 Nm<sup>-2</sup> and 0.35 Nm<sup>-2</sup>, respectively. Fig. 6 shows that Eq. (12) fits well to the measurements for all runs. Eq. (12) reveals that convective turbulence



**Figure 5.** (a) Probability density function of surface shear stress  $\tau$  for NP and WP runs with fan speed 7000, 9000 and 12000 rpm. The dashed gray line marks the threshold shear stress for S1 ( $\tau_{t\_S1}$ ). The symbols are the results from the Irwin sensors and curves the Weibull distributions. By fitting the Weibull distributions to the respective data of the various runs, the corresponding shape and scaling parameters are estimated and plotted against the mean shear stress  $\bar{\tau}$  in (b) and (c), respectively.



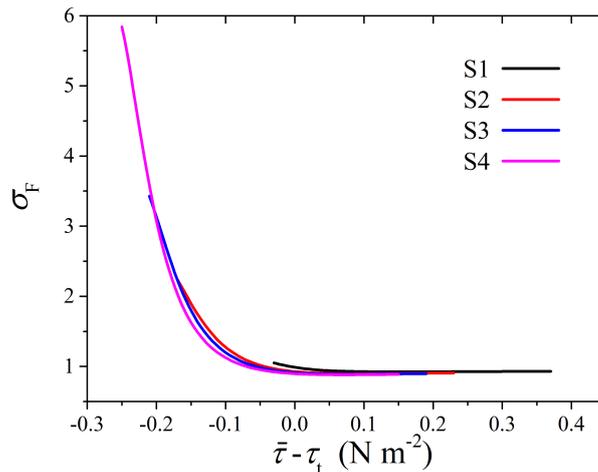
**Figure 6.** Estimated entrainment rates with and without forced perturbation. The dots are experimental data and lines derive from Eq. (12).

may influence both the efficiency parameter  $\gamma$ , and the statistical behavior of the term,  $\int_{\tau_t}^{\infty} \gamma \sqrt{\tau/\rho} (\tau - \tau_t) p(\tau) d\tau$ . To facilitate  
 190 discussion, we write Eq. (12) as

$$F = \bar{\gamma} \int_{\tau_t}^{\infty} \sqrt{\tau/\rho} (\tau - \tau_t) p(\tau) d\tau \quad (13)$$

**Table 3.** Threshold shear stress  $\tau_t$  and empirical parameter  $\gamma$  for test surfaces.

soil type	$\tau_t$ (Nm <sup>-2</sup> )	$\bar{\gamma}_{NP}$ (m <sup>-2</sup> s <sup>2</sup> )	$\bar{\gamma}_{WP}$ (m <sup>-2</sup> s <sup>2</sup> )	$\bar{\gamma}_{NP}/\bar{\gamma}_{WP}$
S1	0.13	3.00	8.25	2.75
S2	0.27	3560.86	4121.62	1.16
S3	0.31	2818.35	3584.11	1.23
S4	0.35	695.08	1282.87	1.85



**Figure 7.** Relationship between  $\sigma_F$  and excess surface shear stress ( $\bar{\tau} - \tau_t$ ).

A comparison of  $\bar{\gamma}$  for NP and WP runs are shown in Table 3. It is seen, that  $\bar{\gamma}$  is significantly increased for the WP runs, in particular for soils S1 and S4. Next, we estimate the ratio  $\sigma_F$  defined as

$$\sigma_F = \int_{\tau_t}^{\infty} \sqrt{\tau/\rho}(\tau - \tau_t) p_{WP}(\tau) d\tau / \int_{\tau_t}^{\infty} \sqrt{\tau/\rho}(\tau - \tau_t) p_{NP}(\tau) d\tau \quad (14)$$

195 Fig.7 shows the relationship between  $\sigma_F$  and excess surface shear stress ( $\bar{\tau} - \tau_t$ ). A negative exponential law appears to exist. For the conditions with  $\bar{\tau} > \tau_t$  (corresponding to the continuous entrainment defined by Li et al. 2020),  $\sigma_F$  is close to one, indicating relatively small influence from the quasi-convective turbulence. But for the conditions with  $\bar{\tau} < \tau_t$ ,  $\sigma_F$  significantly increase with decreasing  $\bar{\tau} - \tau_t$ , reaching up to 6 at  $\bar{\tau} - \tau_t = -0.25$  Nm<sup>-2</sup>, indicating that the influence of convective turbulence is significant (corresponding to the intermittent entrainment defined by Li et al. 2020). We can thus conclude that convective  
200 turbulence may significantly enhance dust entrainment by alter how shear stress acts on the surface, especially for the cases of intermittent entrainment in weak mean wind conditions.

### 3 Conclusions

In this study, we carried out wind-tunnel experiments and studied the influences of turbulence structure on aerodynamic entrainment of sand and dust particles. We considered  $\tau$  to be a stochastic variable and showed that the probabilistic distribution of  $\tau$  (i.e.  $p(\tau)$ ), in addition to the mean surface shear stress  $\bar{\tau}$ , has a significant impact on aeolian fluxes, since the entrainment rate of sand and dust particles depends non-linearly on surface shear stress,  $\tau$ . Because the fluctuations of  $\tau$  are closely related to the structure of ABL turbulence, aeolian fluxes in ABLs of different stabilities can be substantially different even if  $\bar{\tau}$  is the same. The wind-tunnel experiments provided direct data which show that ABL convective large eddies are of particular importance to the entrainment of sand and dust particle, as they intermittently generate large shear stress on the surface.

Wind-tunnel flows are normally neutrally stratified and do not contain large eddies similar to those in convective ABLs. By examining the power spectra of turbulence for the NP runs, we showed that wind-tunnel turbulence lacks energy containing eddies even compared with ABL flows in neutral conditions, highlighting the deficiency of traditional wind-tunnel experiments on aeolian studies. We showed that the deployment of a piece of fluttering cloth is both simple and effective in generating quasi-convective turbulence. By comparing the power spectra of turbulence for the WP runs and NP runs, we found that the energy density in the large eddy range substantially increased. The energy spectrum of quasi-convective eddies agrees reasonably well with that of turbulence in unstable ABL with  $z/L = -2$ . Although the employment of the forced-perturbation technique did not fully reproduce the energy spectra of convective turbulence, this simple technique can be further developed and optimized to obtain the desired turbulent features and overcome a vital limitation to the wind-tunnel experiments.

By comparing the WP runs and NP runs, we found that quasi-convective turbulence increases the mean value (just as in convective ABLs) as well as the variance and skewness of the surface shear stress, all contributing to the entrainment of sand and dust particles. For a given mean shear stress, the entrainment rate for the WP runs is substantially higher than for the NP runs, i.e., convective turbulence is more effective than neutral turbulence in entraining particles into the atmosphere.

The findings of this study obtained through wind-tunnel observations are consistent with the results of Shao et al. (2020). The latter authors showed based on field observations that the PDF of  $u_*$  profoundly influences the magnitude of saltation flux,  $Q$ . With fixed  $u_*$  mean, a larger  $u_*$  variance corresponds to a larger  $Q$ . Unstable ABL has in general larger  $u_*$  variances which generate stronger saltation bombardment and produce the emission of finer dust particles, and saltation in unstable ABLs is generally more fully developed and saltation bombardment has higher intensity. In a more recent study, Yin et al. (2021) demonstrated using large-eddy simulations that also dust deposition is strongly affected by the structure of turbulence. Together with the earlier studies of Shao (2008), Klose and Shao (2012), Klose et al. (2014), Li et al. (2020), Khalfallah et al. (2020), Shao et al. (2020), and Yin et al. (2021), we have shown the critical importance of taking into consideration of turbulence structure in aeolian studies and partly quantified the impact of turbulence on sand and dust entrainment, saltation fluxes, and dust deposition.

*Data availability.* Data is available from Dr. Zhang (zhang-j@lzu.edu.cn) or Dr. Li (liguang@lzu.edu.cn) on requests.

*Author contributions.* YS and JZ conceived and designed the wind tunnel experiment; JZ, GL, and LS carried out the experiment, performed  
235 the data analyses, and prepared the first draft; YS and NH organized this study and contributed to its conceptualization, discussions, and  
finalization of the paper.

*Competing interests.* The authors declare that they have no conflict of interest.

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