

Experiment on Dust Flux During Duststorm Periods over Desert Area*

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ABSTRACT

The present study investigates the characteristics of turbulent transfer and the conditions for dust emission and transport using the dust concentration and micrometeorological data obtained during dust events occurring in the spring of 2004 over the Hunshandake desert area. The turbulent exchange coefficients and turbulent fluxes of momentum and heat are calculated. The relationships between dust flux, friction velocity, and wind speed are also explored. The results show that thermal turbulence is dominant during daytime of non-dusty days. The dynamic turbulence increases obviously and the sensible heat flux reduces by different degrees during dust events. There is an efficient downward transfer of momentum before duststorm occurrence, and both the dynamic turbulence and the thermal turbulence are important in the surface layer. The dynamic turbulence even exceeds the thermal turbulence during severe duststorm events. The values of dust flux vary in the range of $-5-5$, $-30-30$, and $-200-300 \mu\text{g m}^{-2} \text{s}^{-1}$ during non-dusty days, blowing dust, and duststorm events, respectively. A slight upward transport of dust is observed during non-dusty days. The dust flux gradually varies from positive to negative during duststorm periods, which indicates the time evolution of dust events from dust rising to stably suspending and then deposition. The dust flux is found to be proportional to u_*^3 . The threshold values of wind speed and friction velocity are about 6 and 0.4 m s^{-1} , respectively.

Key words: turbulent transfer, dust flux, threshold friction velocity, dust event, Hunshandake desert area

1. Introduction

Duststorm is a kind of severe weather phenomenon occurring over arid and semi-arid regions. Large quantities of studies on desertification, the temporal and spacial distributions of duststorms, their generation, structure, and monitoring have been carried out since the last century (Hankin, 1921; Idso et al., 1972; Josepl et al., 1980). And our understanding on many aspects of duststorm has increased significantly over the past decades, such as mechanisms for dust generation, the atmospheric circulation patterns, temporal and spacial distributions, predictions

and simulations of dust events, the physical and chemical properties of dust particles, estimates of dust emission, transport and deposition, etc. (Chun et al., 2001; Fang et al., 1997; Goutorbe et al., 1994; In and Park, 2003; Liu et al., 2004; Niu and Zhang, 2002; Pye, 1987; Shao, 2005; Westphal et al., 1988; Zhang et al., 2003; Zhu et al., 1999). Although the precision of the input parameters of dust emission models has been greatly improved due to the improvement of the observations in recent years, large uncertainties on quantitative calculations of dust emission fluxes remain for the lack of direct measurements of dust emission in dust source areas, which limits the further development of dust

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models (Laurent et al., 2006). The occurrence of dust-storms and transport of dust aerosols are closely linked to micrometeorological conditions. The energy and momentum exchanges between the earth's surface and the atmosphere are major contributors to dust uplifting. Studies on the relationships between dust rising and micrometeorological conditions would help in understanding the mechanisms of dust generation and transport. By now, there have been few studies on quantitative measurements of dust flux.

The Hunshandake desert area located in XilinGol of Inner-Mongolia is one of the major dust sources in China. Strong winds prevail in this arid area. It lies in the pathway of the southward transport of dust plumes originating from the east of mid-Mongolia (Qian et al., 2006), resulting in the frequent occurrence of dust events there (Wang et al., 2002a, b). Based on the data obtained during the IOP (intensive observation period) of duststorm events over the Hunshandake desert area in the spring of 2004, this paper investigates the characteristics of turbulent transfer, and the conditions for dust emission and transport over sand surface. The vertical dust flux is estimated by using the aerodynamic method. The relationships between dust flux, friction velocity, and wind speed are also explored.

2. Site and data

The observational site is located at the south edge of the Hunshandake desert area, with an average elevation of 1250 m. About 10 km to the east of the site is the agricultural crop field. Instruments are installed on a monitoring tower of 20-m high. The observational variables include wind direction, wind speed, temperature, and humidity at 4 levels, respectively, as well as radiation components and dust mass concentration. The turbulent fluctuations of wind velocity, temperature, and dust concentration are also documented. The data are recorded automatically and continuously for 24 h, and averaged over 30 min after the strict quality control.

3. Theory

According to the Monin-Obukhov similarity the-

ory, the turbulent parameters can be calculated from the gradients of wind speed, temperature, and humidity as

$$\begin{aligned} u_* &= \kappa \bar{u}_2 / [\ln(\frac{z_2}{z_0}) - \Psi_M(\frac{z_2}{L})], \\ \theta_* &= \kappa (\bar{\theta}_2 - \bar{\theta}_1) / [\ln(\frac{z_2}{z_1}) - \Psi_H(\frac{z_2}{L}) + \Psi_H(\frac{z_1}{L})], \\ q_* &= \kappa (\bar{q}_2 - \bar{q}_1) / [\ln(\frac{z_2}{z_1}) - \Psi_q(\frac{z_2}{L}) + \Psi_q(\frac{z_1}{L})], \end{aligned} \quad (1)$$

where u_* , θ_* , and q_* are friction velocity, temperature scale, and specific humidity scale for the surface layer, respectively; $\bar{u}$ is the wind speed at z level; $\bar{\theta}_1$, $\bar{\theta}_2$ and $\bar{q}_1$, $\bar{q}_2$ are potential temperatures and specific humidities at z_1 and z_2 levels, respectively; L is the Obukhov length; $\kappa=0.4$ is the Von-Karman constant; $\Psi_M(\frac{z}{L})$, $\Psi_H(\frac{z}{L})$, and $\Psi_q(\frac{z}{L})$ are stability correction functions for velocity, potential temperature, and specific humidity, respectively, and they have the following forms

$$\begin{aligned} \Psi_M &= \begin{cases} 2\ln(\frac{1+x}{2}) + \ln(\frac{1+x^2}{2}) \\ -2\arctg x + \frac{\pi}{2} \\ -5\frac{z}{L} \end{cases} \quad \begin{matrix} \frac{z}{L} < 0 \\ \frac{z}{L} \geq 0 \end{matrix} \\ \Psi_H = \Psi_q &= \begin{cases} 2\ln(\frac{1+x^2}{2}) \\ -5\frac{z}{L} \end{cases} \quad \begin{matrix} \frac{z}{L} < 0 \\ \frac{z}{L} \geq 0, \end{matrix} \end{aligned} \quad (2)$$

where $x = (1 - 16\frac{z}{L})^{\frac{1}{4}}$.

Suppose the turbulent characteristic of dust mass concentration is similar to that of temperature and humidity under the hypothesis that dust mass concentration is a scalar during the same dust episode and at a certain area. A dust mass concentration scale can be defined as

$$\gamma_* = \kappa (\bar{\gamma}_2 - \bar{\gamma}_1) / [\ln(\frac{z_2}{z_1}) - \Psi_\gamma(\frac{z_2}{L}) + \Psi_\gamma(\frac{z_1}{L})], \quad (3)$$

where γ_1 and γ_2 are the dust mass concentrations at z_1 and z_2 levels, and $\Psi_\gamma(\frac{z}{L})$ is the stability correction function for dust concentration in the form

$$\Psi_\gamma = \Psi_H = \Psi_q. \quad (4)$$

Similar to the sensible heat flux and latent heat flux, the dust flux can be defined as

$$F = \alpha u_* \gamma_*, \quad (5)$$

where α is a coefficient, and $\alpha=10$ is used here. A positive dust flux denotes upward dust transport, and a negative one represents downward dust deposition.

4. Results

Figure 1 shows the time evolution of dust concentration during two dust events occurring in March 15–16 and 27–28, 2004 over the Hunshandake desert area. It was clear that during March 12–13 and 24–25, the maximum wind speed is less than 6 m s^{-1} , and the mean dust concentration is around $40 \mu\text{g m}^{-3}$, which is considered as the background dust concentration on non-dusty days. The mean dust concentration on blowing dust days during March 15–16 is $120 \mu\text{g m}^{-3}$, and the maximum value is about $200 \mu\text{g m}^{-3}$. During March 27–28, the peak value of dust concentration is higher than $1000 \mu\text{g m}^{-3}$, and the averaged values on March 27 and 28 are 750 and $410 \mu\text{g m}^{-3}$, respectively. The dust concentration during the blowing dust events of March 15–16 and the duststorm event on March 28 follows a three fold increasing relationship reported by Qian et al. (2006). The mean dust

concentration on March 27 is lower than the results by Qian et al. (2006), which may be due to the upper limit of the dust sampler being set to $1000 \mu\text{g m}^{-3}$.

4.1 Characteristics of turbulent transfer in the surface layer

Figure 2 illustrates the temporal variations of the turbulent exchange coefficients for momentum (K_M) and heat (K_H) during March 12–17 and 24–29 over the Hunshandake desert area. Both K_M and K_H show obvious diurnal variations. The peak values of K_M and K_H usually appear near noon on non-dusty days, with values 0.3 and $1.0 \text{ m}^2 \text{ s}^{-1}$, respectively. K_M is smaller than K_H , implying that the thermal turbulence is greater than the dynamic turbulence during daytime of non-dusty days over the Hunshandake desert area, the turbulent exchange of heat is dominant. This agrees with the results obtained by Sun et al. (2002) over desert areas. During blowing dust days of March 15–16, the peak values of K_M and K_H occur around 1530 BT, which lag behind non-dusty days, with values 0.92 and $1.0 \text{ m}^2 \text{ s}^{-1}$, respectively.

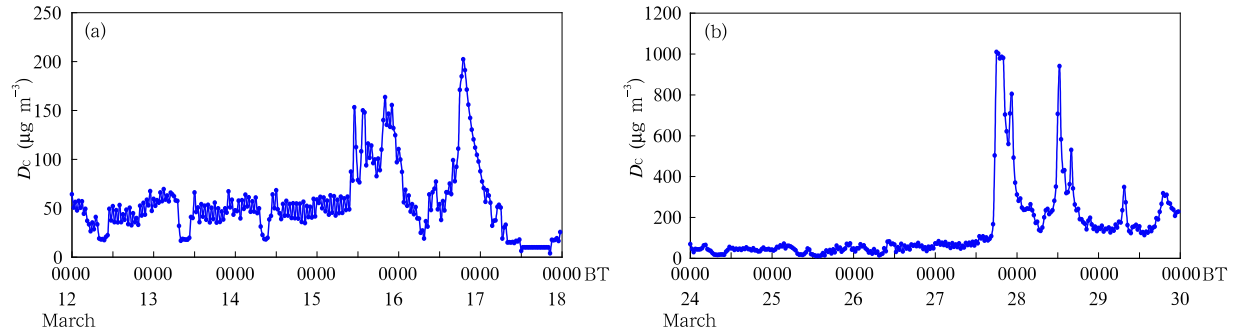


Fig.1. Temporal variations of dust concentration during (a) March 12–17 and (b) March 24–29, 2004 over the Hunshandake desert area.

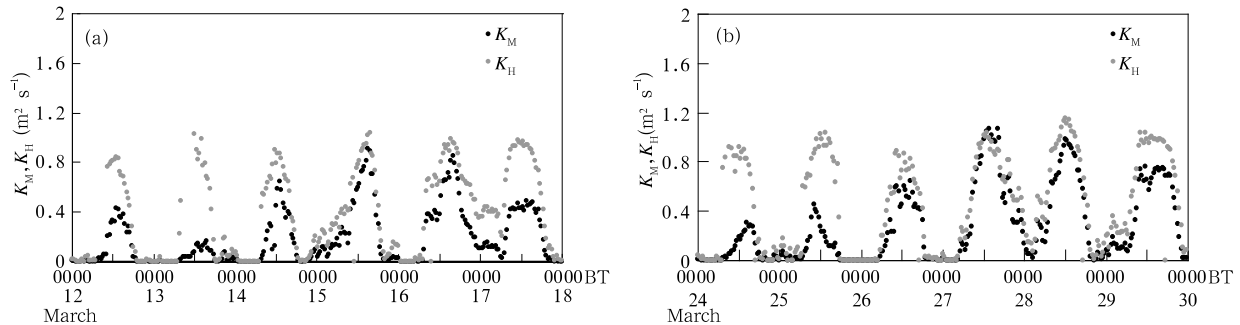


Fig.2. Temporal variations of turbulent exchange coefficients during (a) March 12–17 and (b) March 24–29, 2004 over the Hunshandake desert area.

blowing dust days is more significant than that on duststorm days. This is due to the different weather conditions during the dust events. It was cloudy on blowing dust days, while clear on duststorm days. On the other hand, the blowing dust persists for long time, including noon and afternoon, when the solar radiation and sensible heat exchange are intense. While the onset of the duststorm event on March 27 began near sunset and the dust episode on March 28 was relatively short lived, therefore the reduction of net radiation and sensible heat flux was not so obvious as that on the blowing dust days.

4.2 Estimation of dust flux

The temporal variations of the dust concentration and its difference between heights 3 and 15 m during blowing dust event of March 15–16 and dust storm event of March 27–28 are illustrated in Fig.5. The difference of dust concentration between heights 3 and 15 m varies in a range of $\pm 20 \mu\text{g m}^{-3}$ on blowing dust days. During duststorm events, the difference of dust concentration ranges from -100 to $200 \mu\text{g m}^{-3}$. The value of the difference $\Delta D_C = D_{C,3\text{m}} - D_{C,15\text{m}}$ is positive at the dust outbreak stage during the blowing dust and duststorm events, i.e., the dust concentration at 3-m level is higher than that at 15-m level as the dust concentration begins to rise, and dust particles are transported upward. With the evolvement of the dust events, the dust concentration at 3-m level falls being lower than that at 15-m level, which is much clearer for duststorm events. The possible reasons are analysed as follows: once the dust particle is in motion, its path

depends on the budget between the gravity force and the aerodynamic drag (Clark et al., 2004), and the latter is closely related to the wind velocity. The aerodynamic drag is larger at higher wind speeds, and larger dust particles can be lifted to a certain level apart from the surface. When aerodynamic drag decreases with the decreasing wind speed, the larger dust particles deposit under the gravity force, while the smaller dust particles remain suspended in the air. Thus the dust concentration at 3-m level is higher than that at 15-m level at the beginning of dust events. With the decreasing of the wind speed, the inverse situation may appear. The simplifying assumptions supposed here are that the density of dust particles is uniform, and the gravity of dust particles mainly depends on the particle size.

Figure 6 shows the temporal variations of dust flux during non-dust, blowing dust, and duststorm days in March 2004. The values of dust flux differ under different weather conditions. It varies in a range of $\pm 5 \mu\text{g m}^{-2}\text{s}^{-1}$ under non-dusty weather conditions. The dust emission amounts on March 12 and 24 are 56.32 and 54.39 mg m^{-2} , respectively. The value of dust flux during blowing dust period is between -30 and $30 \mu\text{g m}^{-2} \text{s}^{-1}$, and the dust emission amounts on March 15 and 16 are 79.75 and 179.48 mg m^{-2} , respectively. The value of dust flux during dust storm period ranges from -200 to $300 \mu\text{g m}^{-2} \text{s}^{-1}$, with dust emission amounts 455.32 and 76.11 mg m^{-2} on March 27 and 28, respectively. Slight upward dust transport can be observed during non-dusty days over the Hunshandake desert area. And the dust emission

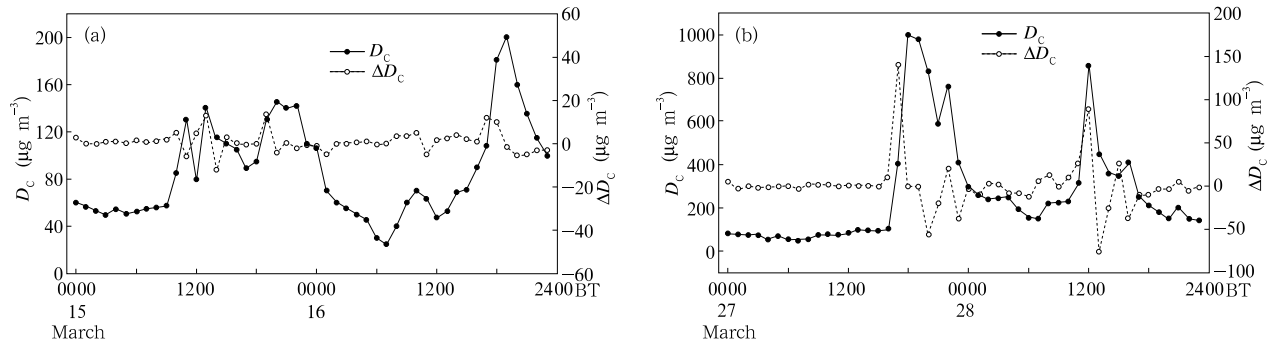


Fig.5. Temporal variations of the dust concentration (D_C) and its difference (ΔD_C) between heights 3 and 15 m during (a) blowing dust event of March 15–16 and (b) duststorm event of March 27–28, 2004.

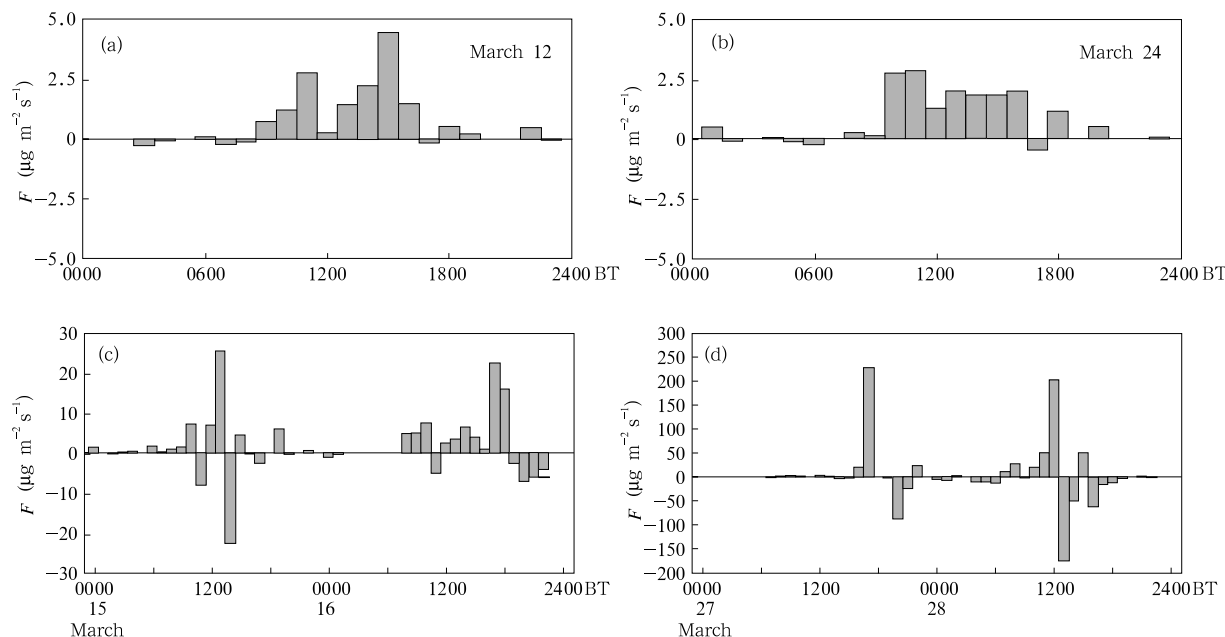


Fig.6. Temporal variations of dust flux in the time period of (a) 12, (b) 24, (c) 15–16, and (d) 27–28 March 2004 over the Hunshandake desert area.

amounts are different during blowing dust and dust-storm events. Shen Zhibao et al. (2003) estimated the dust emission rates over the Gobi desert in Dunhuang during two weak dust events occurring in April 2002, and concluded that the maximum dust emission rate was $2.77 \times 10^{-8} \text{ kg m}^{-2} \text{ s}^{-1}$, which is comparable to the values obtained during blowing dust event of 15–16 March 2004 over the Hunshandake desert area.

Dust flux gradually varies from positive to negative at the dust outbreak stage. This suggests that the upward dust transport is a dominant process at the beginning stage, as the dust event continues, the upward and downward transports tend to be balanced, and finally deposition prevails.

4.3 Dust emission and its relationship with friction velocity and wind speed

Surface friction velocity (u_*) is one of the key parameters to determine dust emission in source regions (Gillette and Passi, 1988; Lu and Shao, 1999; Shen Yanbo et al., 2003). Wind tunnel experiments and field observations show that a friction velocity exceeding a given threshold is necessary to initiate particle motion, which is called threshold friction velocity (u_{*t}). Several investigations (Gillette and Passi, 1988;

Shao et al., 1993; 1996) suggested that the vertical dust flux is proportional to u_*^n , with n ranging from 2 to 5. Taking the soil surface strength into consideration, Lu and Shao (1999) pointed out that for hard surfaces the dust emission rate is more likely to be proportional to u_*^3 , while for soft surfaces, the dust emission rate is more likely to be proportional to u_*^4 . A large data scatter exists when field measurements of dust emission rate are plotted against u_* , due to the large variation in soil conditions, both $F \propto u_*^4$ and $F \propto u_*^3$ relationships can be observed.

The relationship between the vertical dust flux and friction velocity over the Hunshandake desert area is obtained by using the least square regression method (Fig.7), and it can be expressed as

$$\lg u_* = 0.3415 \cdot \lg F - 0.5877. \quad (6)$$

Thus after some manipulations, we obtain

$$F = 10^{1.72} \cdot u_*^{2.93}. \quad (7)$$

It is found that the vertical dust flux is approximately proportional to the third power of u_* over the Hunshandake desert area during dust events, with correlation coefficient $R=0.748$. Shen Zhibao et al. (2003) reported that the dust emission rate F is

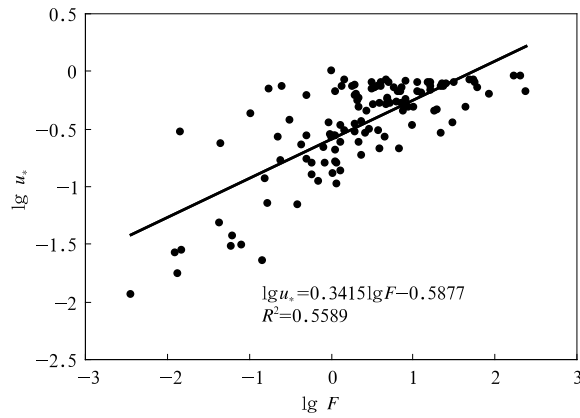


Fig.7. The relationship between dust flux and friction velocity over the Hunshandake desert area in March 2004.

proportional to u_*^2 over the Gobi desert in Dunhuang. This suggests that the source strength is different over the two dust source areas.

Figure 8 shows the relationships between dust

concentration and wind speed, and friction velocity over the Hunshandake desert area on 16 and 27 March 2004, respectively. The dashed lines separate each of the figures into two parts. The dust concentration increases with the increasing wind speed or friction velocity for the right parts. While for the left parts, the distribution of dust concentration is mainly concentrated into two groups, with wind speed below 3 m s^{-1} and wind speed above 7.5 m s^{-1} . The similar distribution was observed on March 27. The former group with lower wind speed is attributed to the background concentration, and the latter one is related to the pre-emission stage. The threshold wind speeds for dust emission are 6.5 and 5.6 m s^{-1} for the blowing dust and duststorm events, respectively. And the threshold friction velocities for the two cases are 0.43 and 0.39 m s^{-1} , respectively. We therefore estimate that the threshold values of wind speed and friction velocity over the Hunshandake desert area are 6 and

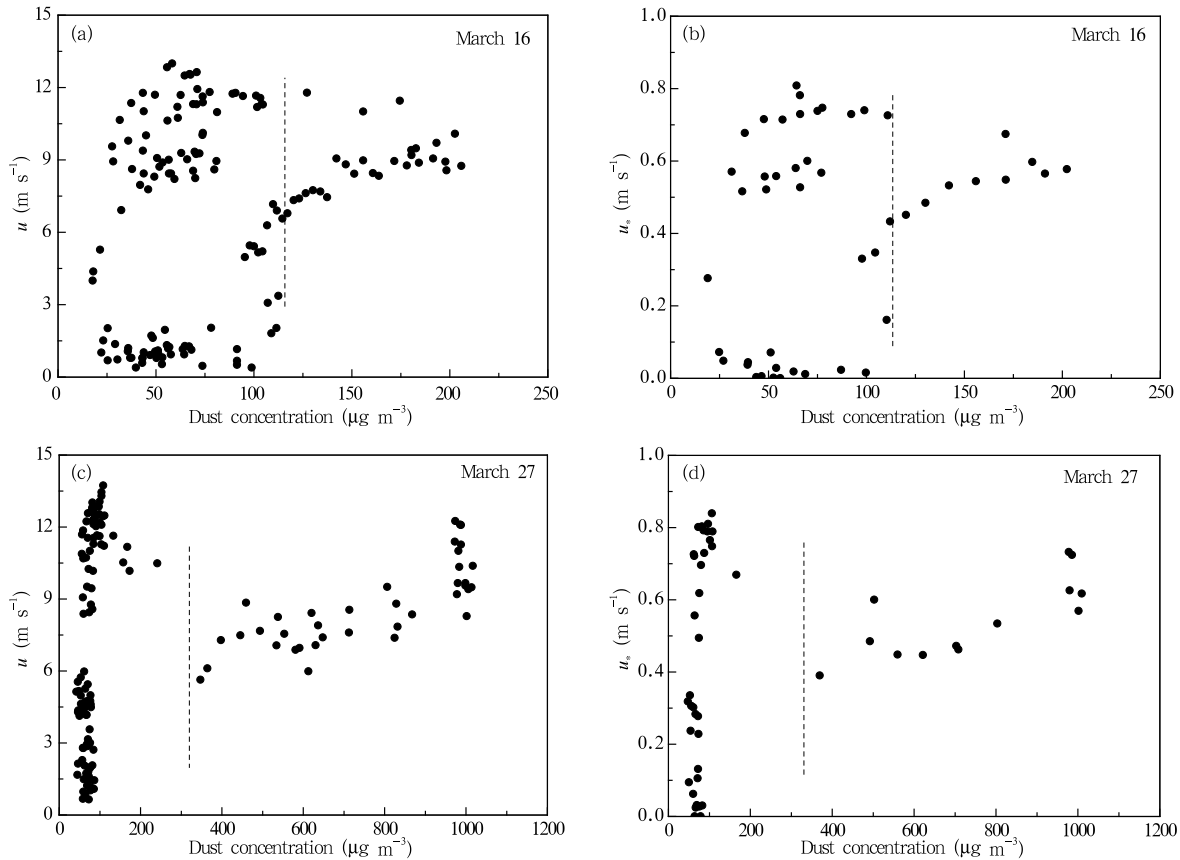


Fig.8. Relationships between dust concentration and wind speed u (a, c), and friction velocity u_* (b, d) over the Hunshandake desert area on 16 and 27 March 2004, respectively.

0.4 m s^{-1} , respectively. Shen Yanbo et al. (2003) estimated that the threshold wind speed and threshold friction velocity over the desert in Dunhuang are 7 and 0.5 m s^{-1} , respectively, which are slightly larger than the values over the Hunshandake desert area. This is due to the different soil particle size distributions over the two dust source areas, with finer soil particles over the Hunshandake desert area (Cheng et al., 2005).

5. Conclusions

In this paper, we have analysed the characteristics of dust concentration, turbulent properties, and dust flux, based on the data during IOP in the spring of 2004 over the Hunshandake desert area. The values of threshold wind speed and threshold friction velocity are estimated. The main conclusions are as follows:

(1) The turbulent viscosity of momentum K_M during dust events is much larger than that during non-dusty days, with mean maximum values 1.1 and $0.3 \text{ m}^2 \text{ s}^{-1}$, respectively. During daytime under clear skies, thermal turbulence exceeds dynamic turbulence and the sensible heat transfer is a dominant turbulent exchange process. Dynamic turbulence increases significantly during dust events, and dominates over thermal turbulence during the severe duststorm event. The turbulent transfer of momentum and sensible heat both contribute greatly to the turbulent exchanges. During the blowing dust and the duststorm events, the momentum flux increases markedly, while the sensible heat flux decreases by different degrees.

(2) At the outbreak stage of the dust events, the dust concentration at 3-m level is larger than that at 15-m level, indicating an upward transport of dust particles. After the dust concentration attaining its maximum, the difference of dust concentration between heights 3 and 15 m gradually changes from positive to negative, due to the deposition of large dust particles.

(3) The values of dust flux range in -5 – 5 , -30 – 30 , and -200 – $300 \mu\text{g m}^{-2} \text{ s}^{-1}$ during non-dusty days, blowing dust, and duststorm events, respectively. A slight upward transport of dust is measured during non-dusty days over the Hunshandake desert area. The value of dust flux gradually varies from positive

to negative, which indicates the time evolution of dust events from dust rising to stably suspending and then deposition.

(4) The dust flux is approximately proportional to the third power of friction velocity over the Hunshandake desert area, and the expression is in the form $F = C \cdot u_*^3$. The threshold values of wind speed and friction velocity are 6 and 0.4 m s^{-1} , respectively.

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REFERENCES

- Businger, J. A., J. C. Wyngaard, Y. Izumi, et al., 1971: Flux-profile relationships in the atmospheric surface layer. *J. Atmos. Sci.*, **28**, 181–189.
- Cheng Tiantao, Lu Daren, Chen Hongbin, et al., 2005: The size distribution of dust aerosol particles in Onqin Daga Sandland. *Chinese Journal of Atmospheric Sciences*, **29**(1), 147–153. (in Chinese)
- Chun, Y., K. Boo, J. Kim, et al., 2001: Synopsis, transport, and physical characteristics of Asian dust in Korea. *J. Geophys. Res.*, **106**(D16), 18461–18469.
- Clark, I., P. Assamoi, J. Bertrand, et al., 2004: Characterization of potential zones of dust generation at eleven stations in the southern Sahara. *Theor. Appl. Climatol.*, **77**(3), 173–184.
- Fang Zongyi, Zhu Fukang, Jiang Jixi, et al., 1997: Research of Chinese Sand Storms. China Meteorological Press, Beijing, 164 pp. (in Chinese)
- Gillette, A. D., and R. Passi, 1988: Modeling dust emission caused by wind erosion. *Journal of Geophysical Research*, **93**(D11), 14233–14242.
- Goutorbe, P., T. Lebel, A. Tinga, et al., 1994: HAPEX-Sahel: A large-scale study of land atmospheric interactions in the semi-arid tropics. *Annales Geophys.*, **12**, 53–64.
- Hankin, E. H., 1921: On dust raising winds and descending currents. *India Met. Memoirs*, **22**, Part VI.
- Idso, S. B., R. S. Ingram, and J. M. Pritchard, 1972: An American Haboob. *Bull. A.M.S.*, **53**, 930–935.
- In, H. J., and S. U. Park, 2003: Estimation of dust emission amount for a dust storm event occurred in April 1998 in China. *Water, Air, and Soil Pollution*, **148**, 201–221.

- Josepl, P. V., D. K. Raipal, and S. N. Deka, 1980: "Andhi", the convective dust storms of Northwest India. *J. Mausam*, **31**, 431–442.
- Laurent, B., B. Marticorena, G. Bergametti, et al., 2006: Modeling mineral dust emissions from Chinese and Mongolian deserts. *Global and Planetary Change*, **52**, 121–141.
- Liu L. Y., Shi P. J., Gao S. Y., et al., 2004: Dustfall in China's western Loess plateau as influenced by dust storm and haze events. *Atmos. Environ.*, **38**, 1699–1703.
- Lu H., and Shao Y., 1999: A new model for dust emission by saltation bombardment. *Journal of Geophysical Research*, **104**, 16827–16841.
- Niu Shengjie, and Zhang Chengchang, 2002: Comprehensive researches on sand particle uptake and vertical transport of sandstorms in Helan mountain area. *Acta Meteor. Sinica*, **60**(2), 194–204. (in Chinese)
- Pye, K., 1987: *Aeolian Dust and Dust Deposits*. Academic Press, London, 334 pp.
- Qian Zhengan, Cai Ying, Liu Jingtao, et al., 2006: Some advances in dust storm research over China-Mongolia areas. *Chinese Journal of Geophysics*, **49**(1), 83–92. (in Chinese)
- Shao Y., 2005: A similarity theory for saltation and application to aeolian mass flux. *Boundary-Layer Meteorology*, **115**, 319–338.
- Shao Y., M. R. Raupach, and P. A. Findlater, 1993: The effect of saltation bombardment on the entrainment of dust by wind. *Journal of Geophysical Research*, **98**, 12719–12726.
- Shao Y., M. R. Raupach, and J. F. Leys, 1996: A model for predicting Aeolian sand drift entrainment on scales from paddock to region. *J. Soil Res.*, **34**, 309–420.
- Shen Yanbo, Shen Zhibao, Du Mingyuan, et al., 2003: Variational characteristics of some parameters and factors during dusty weather in spring of Dunhuang. *Plateau Meteorology*, **22**(4), 378–384. (in Chinese)
- Shen Zhibao, Shen Yanbo, Du Mingyuan, et al., 2003: Observational result of dust emission rate over sand surface of Gobi desert during dust storm. *Plateau Meteorology*, **22**(6), 545–550. (in Chinese)
- Sun Jiming, Xiao Wenan, Niu Shengjie, et al., 2002: Turbulent transfer features of the surface layer over desert area in a dust and sand weather. *Journal of Nanjing Institute of Meteorology*, **25**(4), 489–495. (in Chinese)
- Wang Geli, Lu Daren, and Li Hongzhou, 2002a: Analysis of a sand devil event in Hunshandake sandy land. *Meteorological Monthly*, **28**(7), 13–17. (in Chinese)
- Wang Geli, Lu Daren, and You Li, 2002b: Analyses of climatic characteristics on Hunshandake dust storm. *Climatic and Environmental Research*, **7**(4), 433–439. (in Chinese)
- Wang G. X., Tuo W. Q., and Du M. Y., 2004: Flux and composition of wind-eroded dust from different landscapes of an arid inland river basin in north-western China. *Journal of Arid Environments*, **58**, 373–385.
- Westphal, D. L., O. B. Toon, and T. N. Carlson, 1988: A case study of mobilization and transport of Saharan dust. *J. Atmos. Sci.*, **45**, 2145–2175.
- Zhang X. Y., Gong S. L., Zhao T. L., et al., 2003: Sources of Asian dust and role of climate change versus desertification in Asian dust emission. *Geophys. Res. Lett.*, **30**(24), 2272, doi: 10.1029/2003GL01826.
- Zhu Fukang, Jiang Jixi, Zheng Xinjiang, et al., 1999: Actuality and future of dust storm weather research. *Meteorological Science and Technology*, **4**, 1–8. (in Chinese)