

Separating Emitted Dust from Total Suspension in Airflow Based on Characteristics of PM10 Vertical Concentration Profiles over a Gobi Surface in Northwestern China Postprint

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Abstract

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the transport of suspended dust in its path is by far a more efficient and realistic option for small areas that are often exposed to dust storms. This study provides some theoretical basis for correctly estimating PM10 concentrations in the Gobi areas.

Full Text

Preamble

Separating Emitted Dust from Total Suspension in Airflow Based on the Characteristics of PM10 Vertical Concentration Profiles on a Gobi Surface in Northwestern China

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such as surface renewal or an increase in soil moisture, the friction velocity will not necessarily correlate with the other two factors. Therefore, for the Gobi surface, compared to limiting dust emissions from upwind directions, restricting the transport of suspended dust in its path is by far a more efficient and realistic option for small areas that are often exposed to dust storms. This study provides some theoretical basis for correctly estimating PM10 concentrations in Gobi areas.

Keywords: PM10; vertical concentration profiles; dust emission rate; saltation intensity; suspensions; Gobi surface

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1 Introduction

The upward ejection of soil particles and their horizontal transport with airflow represent two distinct subprocesses of the overall aeolian process [?, ?, ?, ?]. Large particles are transported only short distances during a single saltation or “creep” event [?, ?]. Thus, the net surface upward sand flux is zero in steady-state saltation. For small dust particles (e.g., PM10 particles), the net upward dust flux is approximately equal to the dust emission flux due to the long-term and long-distance transport associated with dust suspension [?, ?, ?]. Therefore, suspension above the ground surface during an erosion event comprises both locally emitted dust and dust transported from upwind directions. In other words, locally emitted dust represents only a portion of the suspension measured in local airflow.

To date, no technological means exist that can separate emitted dust from aeolian suspension for the purpose of directly studying dust emissions during aeolian processes. Currently, field studies on dust emissions and transport employ two main methods. The first involves using passive traps to collect aeolian horizontal mass, from which the amount of suspension transport is obtained by separating dust from the total mass collected [?, ?, ?, ?, ?]. The second method utilizes active aerosol monitors (e.g., TSI DustTrak) to monitor suspension concentrations in airflow [?, ?, ?, ?, ?, ?]. Compared to aerosol monitoring, the traditional trap method suffers from poor measurement accuracy, low collection efficiency, and disparities in collection efficiency between sand and suspended materials. Moreover, the aerosol monitoring method can provide more reliable data continuously and automatically, with less human disturbance to suspension transport under

aeolian sand flow conditions [?, ?]. However, neither method offers a good solution for directly correlating dust emissions to field observations. Consequently, measurements of flux-concentration relationships are typically used to indirectly reflect dust emissions [?, ?, ?, ?, ?, ?]. Studies have shown that correlations exist among vertical dust flux, horizontal suspension flux, and dust emission flux, but these relationships remain unclear [?, ?, ?, ?, ?].

Based on aeolian-driven horizontal masses at various heights above the ground surface, Fryrear and Saleh (1993) investigated saltation and suspension using mathematical models. They hypothesized that the intersection point represented the transition height between the saltation layer and the suspension layer, where the transport mode shifts from saltation to suspension. However, dust particles can also be suspended within the saltation layer. Moreover, soil particles with diameters less than 20 μm are typically adsorbed onto larger particles or aggregates by electrostatic forces, making them more difficult to be directly lifted by airflow. Such particles are mainly emitted through saltation bombardment and subsequently suspended in airflow [?, ?]. All such particles can significantly alter the vertical profile of near-surface suspension concentration during wind erosion. Therefore, changes in suspension concentrations in the saltation layer cannot be ignored, and the vertical profile model should be studied in a piecewise manner, incorporating parameters to express changes in wind conditions and saltation intensity.

Previous studies on the vertical concentration profiles of suspensions have achieved notable advances. For suspended particulate matter, if the ratio of particle settling velocity (w_s) to friction velocity (u_*) is less than 0.100, the particles move in a near-gaseous manner [?, ?, ?]. A threshold friction velocity (u_{*pt}) that allows suspended PM10 to move with airflow must therefore exist [?, ?]. Shao (2008) estimated the settling velocity for particles up to 10 μm at approximately 0.008 m/s and then calculated u_{*pt} as 0.080 m/s. When $u_* < u_{*pt}$, the vertical concentration is irregularly distributed. When $u_* > u_{*pt}$, the vertical concentration profile of suspensions becomes regular and closely related to atmospheric properties (e.g., wind speed, turbulent diffusion, etc.). The vertical concentration profile of suspensions represents an idealized mathematical expression that describes the profile under these conditions. By theoretically analyzing the solution of the turbulent diffusion equation under equilibrium conditions, two expressions have been derived for concentration profiles: the power-law profile and the logarithmic profile [?, ?, ?]. The power-law profile is used to describe the vertical concentration profile of suspensions above surfaces that actively emit snow and mineral dust [?, ?, ?, ?]. However, Kind (1992) concluded that experimental data derived from the power-law profile for blowing snow experiments were based on erroneous boundary conditions at the surface of the particle bed, and that the logarithmic profile can more accurately describe the vertical concentration profiles of suspensions. Gillies and Berkofsky (2004) supported this conclusion using continuous observations of vertical concentration profiles of suspensions outside the saltation-affected layer. Both the power-law and log-law models

derive from the same steady-state, horizontally homogeneous solution of particle transport (with the turbulent diffusion approximation), but the power-law model represents the solution in the limit of zero net flux (larger dust particles), whereas the log-law model represents the solution in the limit of zero settling (smaller dust particles) [?, ?, ?].

In this study, we conducted a 12-day field observation of wind speed, saltation, and PM10 concentrations at various heights on a Gobi surface. We examined the expressions used for near-surface PM10 vertical concentration profiles with and without saltation and utilized the concentration transition height (TSA) between the saltation-affected layer and airflow-transport layer to identify regular patterns in dynamic dust emissions with decreasing soil erodibility on the Gobi surface as wind erosion progressed. Additionally, based on the relationship between PM10 vertical concentration profiles, u_* , and saltation intensity, we proposed a mathematical method from a new perspective to separate dust emitted locally from aeolian suspensions transported from upwind directions in the saltation-affected layer during aeolian processes. Finally, we further discussed the transition between horizontal suspension flux and dust emission flux as well as changes in their proportions during aeolian processes.

2.1 Experimental Site

Field observations were conducted on a flat, bare area of the Gobi desert within Dunhuang City, Gansu Province, northwestern China (39°46 N; 94°24 E), from 31 March to 10 April, 2017. Dispersed particle size analysis using a vibrating screen machine and a Malvern Mastersizer laser diffractometer (Malvern Instruments, Malvern, UK) revealed that the average particle size of sediment in the 0–1 cm soil layer was approximately 708 μm , with particles finer than 10 μm in diameter comprising approximately 5.5% of the total. Gravel covered 30.0%–40.0% of the total land area in the study region, primarily ranging from 2 to 6 cm in diameter. The climate is continental arid, with an annual mean temperature of 3.5°C, mean annual precipitation of 120 mm, and annual mean wind speed of 2.700 m/s. The dominant wind direction in this region is northwest, with strong wind events occurring frequently in spring. The recorded maximum instantaneous wind speed reached up to 26.000 m/s at a height of 10.00 m [?, ?].

The study area experienced slight artificial disturbance. After removing weeds from the surface, we used half-full petrol tanks filled with water to flatten the original surface by rolling the tanks back and forth. The square study site, covering an area of 1 hm^2 (100 m \times 100 m), was maintained devoid of weeds and flattened throughout the entire study duration.

2.2 Physical Background of the Dust Concentration Profiles

In this study, we assumed horizontally homogeneous and steady-state conditions, a logarithmic mean horizontal wind, and zero mean vertical wind to simplify the problem and make it tractable. Under these conditions, particle concen-

tration is not impacted by horizontal advection (due to homogeneity), and the two physical processes affecting dust concentration are vertical turbulent transport and gravitational settling. For sufficiently small particles, settling can be neglected, as the dust behaves as a passive scalar. The governing transport equation for dust can be expressed as:

$$w_s c = -\frac{\partial \overline{w'c'}}{\partial z}$$

where w_s (m/s) is the settling velocity; c (mg/m³) is the mean dust concentration; z (m) is the height above the ground surface; and w' (m/s) and c' (mg/m³) are the fluctuations of vertical velocity and concentration (molecular diffusion was neglected), respectively. Using the model from Kind (1992) to calculate mean particle concentration as a function of height, if K-theory (eddy diffusivity model) is applied, the diffusivity K can be expressed as $K = kz u_*$ (where k is the von Kármán constant ($k = 0.4$) from the law-of-the-wall). Integrating both expressions in the vertical direction yields the following power-law equation when there is no net flux at the surface:

$$c(z) = c_r \left(\frac{z}{z_r} \right)^{-w_s/(k u_*)}$$

where c_r (mg/m³) is the dust concentration at reference height z_r (m); and u_* (m/s) is the friction velocity. If there is no settling velocity and net flux, a constant profile can be obtained ($c(z) = c_r$, where $c(z)$ (mg/m³) is the particle concentration at height z). When we assumed no settling velocity but a positive net flux (Φ , mg/(m · s)), the log-law profile can be expressed as follows:

$$c(z) = -\frac{\Phi}{k u_*} \ln \left(\frac{z}{z_r} \right) + c_r$$

2.3 Instrumentation and Data Analysis

During the field observation period, a mast with nine rotating-cup anemometers, a mast with four sets of aerosol monitoring devices, and a set of automatic weighing sand traps were installed in a row oriented perpendicular to the dominant wind direction (Fig. 1 [Figure 1: see original paper]).

The vertical profile of wind speed was monitored using rotating-cup anemometers (010C, Metone Inc., Washington, USA) installed at heights of 0.05, 0.10, 0.20, 0.30, 0.50, 0.75, 1.00, 2.00 and 3.00 m above the ground surface (Fig. 1a). All anemometers were calibrated in a wind tunnel at the State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China. These anemometers recorded mean wind speed at 30 s intervals using a data logger with a resolution of 0.100 m/s and a measuring range of

0.300–30.000 m/s. In this study, only wind speed data that remained relatively constant within 10 min periods (where the ratio of standard deviation to mean wind speed was less than 0.150) were utilized.

Using least-square regression of the logarithmic law (Eq. 4) for a typical turbulent atmospheric boundary layer fitted to the measured vertical wind speed profile, we calculated u_* and the aerodynamic roughness length (z_0 ; m) at 1 min intervals:

$$u(z) = \frac{u_*}{k} \ln \left(\frac{z}{z_0} \right)$$

where $u(z)$ (m/s) is the wind speed at height z .

We measured PM10 concentrations (mg/m^3) at heights of 0.10, 0.50, 1.00 and 2.00 m above the ground surface using four aerosol monitors (TSI DustTrak 8530, TSI Inc., Shoreview, Minnesota, USA) (Fig. 1b). Aerosol monitors can display and record real-time aerosol readings and have been successfully used to measure suspension concentrations during sandstorms [?, ?, ?, ?, ?]. The monitors had a resolution of $0.001 \text{ mg}/\text{m}^3$, an operating range from 0.001 to $400.000 \text{ mg}/\text{m}^3$, and an overall efficiency between 60.0% and 95.0% [?, ?, ?]. Four aerosol monitors were placed 2.00 m downwind of the mast to reduce measurement interference. Each aerosol monitor was connected to a rubber pipe whose orifice was directed straight upward and fixed on the mast at the specified height. During the observation period, suspended PM10 particles in the air were drawn into the aerosol monitors via the rubber pipe, and the monitors recorded mean PM10 concentration every 5 s.

If the field area is relatively small and the soil texture exhibits high homogeneity—meaning areas devoid of heterogeneous dust sources—the horizontal suspension flux at various heights can be determined by simply measuring the vertical profile of suspension concentration and multiplying the results by wind speed [?, ?]. Accordingly, the horizontal suspension flux (E ; $\text{mg}/(\text{m}^2 \cdot \text{s})$) at height z , the horizontal suspension transport rate (q_d ; $\text{mg}/(\text{m} \cdot \text{s})$), and the horizontal suspension transport amount (Q_d ; mg/m) below a given height (h ; m) above the ground surface during a specific time period were calculated using the following equations:

$$E(z) = c(z) \times u(z)$$

$$q_d = \int_{z_0}^h E(z) dz$$

$$Q_d = \int_{t_1}^{t_2} q_d dt$$

where the aerodynamic roughness length z_0 is 10^{-4} m in this study; t_1 (min) and t_2 (min) are the starting and ending observation times, respectively; and t (min) is the observation period.

The dynamic changes in saltation mass were measured using a set of automatic weighing sand traps every 1 s (Fig. 1c). Although the sand trap had five inlets at different heights, only the sand flux ($\text{kg}/(\text{m}^2 \cdot \text{min})$) measured by the lowest inlet at 0.05 m height ($Q_{z=0.05\text{m}}$) was used to reflect saltation intensity. This was because the mass of collected sand particles in other sand trap inlets was too small to weigh accurately, preventing them from reflecting dynamic changes.

Under low wind speeds (i.e., wind speed at 2.00 m height above the ground surface, $u_{2.00\text{m}} < 2.000$ m/s), the vertical wind speed profile was irregular due to near-surface airflow instability. Moreover, the threshold wind speed at 2.00 m height that enables suspended PM10 particles to move in a near-gaseous manner was also approximately 2.000 m/s, as calculated by Equation 4 with $u_* = u_{*pt}$ for PM10 (approximately 0.080 m/s) and a z_0 value of 10^{-4} m. Therefore, we only analyzed observation data under conditions where $u_{2.00\text{m}}$ exceeded 2.000 m/s and wind speed remained relatively constant (i.e., within 10 min periods where the ratio of standard deviation to mean wind speed was less than 0.150). After filtering, we obtained 20 hours of effective suspension concentration observation data, including one wind erosion event (14:08-18:08 LST) on 5 April 2017.

All fitting analyses and graphs were conducted using Origin 2016 software.

3.1 Vertical Profile of PM10 Concentrations Without Saltation

Using PM10 concentration data from four observation heights (0.10, 0.50, 1.00 and 2.00 m) under wind speeds below the threshold velocity for sand movement (i.e., below approximately 2.000 m/s), we evaluated the applicability of vertical profile models proposed by Prandtl (1953) and Kind (1992) in the study area. We used 10-minute average PM10 concentrations in this analysis. To compare vertical concentration profiles of PM10 across different time periods, we normalized the absolute PM10 concentration data and measurement heights to a reference height of 0.10 m. Least-square regression was used to fit both power-law and logarithmic models to the data (Fig. 2 [Figure 2: see original paper]).

The results clearly demonstrated that the log-law profile model was more suitable for expressing the vertical concentration profile of PM10. This finding is consistent with previous theoretical derivation studies and field experiments [?, ?, ?]. The vertical concentration profile of PM10 can be expressed as follows:

$$\frac{c(z)}{c_r} = a \ln \left(\frac{z}{z_r} \right) + 1$$

where a is the regression coefficient, which can be expressed as $a = -\Phi/(ku_*c_r)$ following Equation 3. According to Equation 3 and by setting $z_r = 1.00$ m, we further transformed Equation 9 as follows:

$$\ln(c(z)) = b \ln(z) + \ln(c(1))$$

where $c(1)$ (mg/m^3) is the PM10 concentration at a height of 1.00 m; and b is the regression coefficient, which can be expressed as $b = -\Phi/(ku_*)$. If $u_{*pt} < u_* < u_{*t}$ (where u_{*t} (m/s) is the threshold friction velocity for sand movement), we can use Equation 9 to describe the vertical concentration profiles of PM10 on a bare, flat surface.

When wind speed was below u_{*t} , almost no dust emissions resulted from saltation. Although convective dust might occur due to atmospheric instability under weak wind conditions, it was expected to be negligible since fine particles on the Gobi surface were situated between coarse particles and protected by them, making them difficult to lift by weak winds. Suspensions above the ground surface were therefore considered to be entirely transported from upwind directions. At this point, the vertical concentration profiles of suspensions were closely associated with upwind conditions. Although the absolute suspension concentration is difficult to predict, the gradient of the vertical concentration profile can be predicted through its relationship with u_* . According to Equation 9, b is clearly a function of u_* . We illustrated the relationship between b and u_* (Fig. 3 [Figure 3: see original paper]), where b was obtained by regressing Equation 9 to the aforementioned 10-minute average concentration data.

A linear correlation between b and u_* is evident in Figure 3, which is consistent with field observation results from Gillies and Berkofsky (2004). Thus, Equation 9 can be further expressed as follows:

$$\ln(c(z)) = b(u_*) \ln(z) + \ln(c(1))$$

where $b(u_*)$ is the linear function of u_* ; and p and f are empirical parameters with values of -0.1259 and 0.0044, respectively, in this study, according to Figure 3. From Equation 10, we can estimate the vertical concentration profiles of suspensions near the surface if we measure $c(z)$ at 1.00 m height and u_* . Moreover, due to the close link of parameter b with u_* rather than surface conditions, the linear function $b(u_*)$ is expected to be generally applicable over extended areas.

3.2 Vertical Concentration Profiles of PM10 With Saltation

A wind erosion event occurred in the study area on 5 April 2017 under persistent, steady northeasterly winds from 15:00 through the nighttime hours. The 240-minute observation period began at 14:08, and u_* reached a steady state and

remained above u_{*t} (approximately 0.230 m/s at the measurement site) after approximately 60 minutes (Fig. 4a [Figure 4: see original paper]).

During the first 60 minutes, u_* exhibited an overall increasing trend. Specifically, u_* fluctuated significantly, and the maximum instantaneous u_* exceeded u_{*t} , but no continuous, obvious sand flow occurred above the ground surface. At this stage, significant fluctuations in PM10 concentrations at heights of 0.10 and 0.50 m were primarily caused by aerodynamic lifting of loose dust particles on the surface (Fig. 4b and c). From 60 to 180 minutes, u_* experienced a slight increasing trend, and sand transport became active (Fig. 4d); nonetheless, PM10 concentrations at heights of 0.10 and 0.50 m decreased slightly with increasing u_* before showing a slight increase, while fluctuating significantly. After 180 minutes, u_* remained steadily fluctuating, and sand transport gradually weakened before ceasing altogether. During this period, PM10 concentrations at heights of 0.10 and 0.50 m gradually decreased to stable values but did not reach zero. PM10 concentrations at heights of 1.00 and 2.00 m remained relatively stable throughout the observation period, making it difficult to directly identify their links with u_* or sand flux (Fig. 4e and f).

Figure 4 demonstrates that when sand transport occurred, PM10 concentrations in the lower layer (heights of 0.10–0.50 m) were greatly affected. PM10 concentrations fluctuated significantly and showed no obvious regularity, making it impossible to describe the vertical concentration profiles of PM10 suspensions during wind erosion periods with a single logarithmic function. In the upper layer (heights of 1.00 and 2.00 m), PM10 concentrations changed little and were minimally affected by sand transport. In an earlier field study, Gillies and Berkofsky (2004) found that the logarithmic function could still express the vertical concentration profiles of suspensions above the saltation layer (i.e., heights of 1.70–9.00 m in their study). Such evidence suggests that the vertical concentration profiles of PM10 suspensions above the saltation-affected layer are not directly affected by dust emissions during erosion periods under transport conditions similar to those without saltation; namely, they remain solely controlled by wind conditions. Equation 10 was used to describe the vertical profile in this study, which was further verified using 10-minute average suspension concentrations above the saltation-affected layer (heights of 1.00 and 2.00 m) (Fig. 5 [Figure 5: see original paper]).

In other words, Equation 10 can accurately describe the vertical concentration profiles of PM10 suspensions above the saltation-affected layer during aeolian processes.

The above analysis confirmed that, first, the heights of 0.10 and 0.50 m were within the saltation-affected layer, where PM10 concentration was greatly affected by saltation, whereas the heights of 1.00 and 2.00 m were beyond the saltation-affected layer, where PM10 concentration was determined by airflow transport. Second, a concentration transition height (TSA) existed between the saltation-affected layer and the airflow-transport layer: the layer above the TSA was closely related to wind conditions, and Equation 9 can be used to express

the relative concentration profile of PM10. Although PM10 concentration in the saltation-affected layer below the TSA was directly influenced by local dust emissions, no definitive conclusion exists regarding its relative concentration profile. The exponential function [?, ?], power function [?, ?, ?], and logarithmic function [?, ?] have all been used to express PM10 vertical concentration profiles in the saltation-affected layer in previous studies. In this study, we selected the exponential function. Thus, the vertical concentration profile of PM10 suspensions is expressed in a piecewise manner as follows:

$$c(z) = \begin{cases} me^{nz} & \text{if } z \leq \text{TSA} \\ b \ln(z) + c(1) & \text{if } z > \text{TSA} \end{cases}$$

where m and n are regression coefficients.

Since we confirmed that the heights of 0.10 and 0.50 m are in the saltation-affected layer and the heights of 1.00 and 2.00 m are in the TSA, we obtained the regression coefficients in Equation 11 by fitting $c(z) = me^{nz}$ to every 10-minute average PM10 concentration at heights of 0.10 and 0.50 m, and $c(z) = b \ln(z) + c(1)$ to every 10-minute average suspension concentration at heights of 1.00 and 2.00 m. The height of the intersection point between the two functions should then be the TSA.

Table 1 shows the results and corresponding observation data from 91 to 240 minutes. During the period of 91-140 minutes, the TSA fluctuated around 0.60 m. From 141 to 170 minutes, the TSA increased to a maximum of 0.77 m. Because PM10 concentration data at the three upper heights could be expressed as a logarithmic function, the TSA was less than 0.50 m from 171 to 240 minutes.

According to Table 1, a strong correlation existed between u_* and TSA from 91 to 170 minutes ($r = 0.70$, $P < 0.001$), while this was not the case after 171 minutes. This suggests that u_* is not critically important in affecting the TSA. Therefore, the TSA is only related to u_* under certain conditions. This agrees with the consensus that saltation of soil particles and aggregates during aeolian processes represents the most crucial physical mechanism of dust emissions. In addition, the TSA indicates the upper limit of influence of local dust emissions, with its value directly reflecting dust emission intensity. During wind erosion, the trend in dust emission intensity generally progressed from weak to strong and then weakened until dust emissions nearly ceased, as shown in the TSA column in Table 1.

4.1 Dust Emission Rate (f_v) During Wind Erosion

The key issue and most practical problem associated with wind erosion are the rate and quantity of soil loss [?, ?]. For short-distance movement (i.e., saltation and “creep”) of large particles during wind erosion, both surface erosion and deposition occur simultaneously. Thus, soil loss by wind transport should equal

the difference between erosion quantity and deposition quantity [?, ?]. For suspensions, once small dust particles are blown off the surface, deposition can be considered negligible. Therefore, the quantity of dust emissions equals the dust loss by wind erosion. Consequently, studying dust loss during erosion processes is more feasible and convincing than studying soil transport in saltation and creep.

Currently, two main model designs are used to estimate dust emissions caused by wind erosion. One is based on microscopic mechanisms of emission processes, represented by the dust production model [?, ?, ?, ?]. This model design incorporates sophisticated parameters for surface features (e.g., soil texture, moisture, etc.) as well as physical mechanisms. Due to the complexity of natural conditions compared to wind tunnels, this model design is currently more applicable to theoretical estimation of dust emissions across expansive areas and large timescales. However, it does not provide an accurate description of dynamic changes in dust emissions during aeolian processes in the field. The other model design is based on turbulent and molecular diffusion and draws analogy to scalar fluxes, as represented by Gillette (1978). This approach is simpler and more frequently used in wind tunnel and field experiments [?, ?]. However, in practical application, this model generally simplifies the vertical concentration profile as a single linear form derived from concentrations measured at two specific heights, ignoring the influence of dust emission on the profile (i.e., below the TSA) during wind erosion.

Among the three widely accepted mechanisms of dust emissions, direct aerodynamic lifting represents a substantially less important source of dust aerosols compared to the ejection of dust aerosols from soil aggregates by impacting saltating particles and the ejection of dust aerosols from disintegrating soil aggregates during saltation processes [?, ?, ?, ?]. Moreover, this latter source typically occurs at the onset of wind speed increase and is greatly restricted by the supply of wind-erodible sediment [?, ?, ?]. Thus, dust emissions caused by direct aerodynamic lifting have little influence on near-surface suspended PM10 concentrations during aeolian processes [?, ?, ?]. Under ideal conditions, suspensions above the TSA are composed entirely of suspended PM10 particles transported from upwind directions, while suspensions below the TSA consist of PM10 particles emitted from both local and upwind areas.

Therefore, the local dust emission rate (f_v) equals the difference between the horizontal total suspension transport rate and the suspension transported from upwind directions [?, ?]. Assuming that the vertical concentration profile of suspensions transported from upwind directions below the TSA is not affected by sand saltation or local dust emissions, we can still use Equation 10 to describe the vertical concentration profile outside the saltation-affected layer. Therefore, f_v (mg/(m · s)) can be expressed as the difference between the total horizontal suspension transport rate (q_d ; mg/(m · s)) and the horizontal suspension transport rate from upwind directions (q_{d0} ; mg/(m · s)) in the saltation-affected layer:

$$f_v = q_d - q_{d0} = \int_{z_0}^{\text{TSA}} [c(z) - c'(z)]u(z) dz$$

where $c'(z)$ (mg/m^3) is the concentration of suspensions transported from upwind directions at height z below the TSA, which can be deduced from $c(z)$ above the TSA and expressed by Equation 10. Parameters b and $c(1)$ were acquired by fitting measured suspension concentrations above the TSA, while m and n were acquired from fitting below the TSA. The f_v values from 91 to 140 minutes and from 141 to 170 minutes, calculated using Equation 12, were 0.238 and 0.440 $\text{mg}/(\text{m} \cdot \text{s})$, respectively. After 170 minutes, f_v decreased to nearly zero. Therefore, the dust loss (i.e., the quantity lost through dust emissions) at the study site during the 180-minute wind erosion event, calculated using Equation 7, was approximately 1.44 g/m .

This computational method for f_v , based on changes in dust emissions during wind erosion, truly links horizontal suspension transport to vertical dust emissions. Compared to previous methods [?, ?, ?, ?, ?, ?], this computational method demonstrates the influence of saltation intensity on dust emissions through the TSA and regression coefficients in Equation 11. Most importantly, this method can separate local dust emissions from aeolian suspension originating from upwind sources, enabling quantitative expression of dynamic changes in both local dust emissions and aeolian suspension transport.

4.2 Influence of Surface Renewal on Dust Emissions

Currently, dust emission models are generally transport-limited, meaning emissions are solely governed by wind forces. However, natural arid environments are dominated by supply-limited surfaces, which means emissions are controlled by the availability of erodible grains [?, ?, ?, ?, ?]. Consequently, the practicality of such models is significantly limited, and determining mechanisms that limit surface dust availability is key to solving this problem. As shown in Section 3.2, saltation intensity and dust emissions were significantly correlated with u_* during the first 170 minutes of the wind erosion event, while saltation intensity and f_v decreased significantly after 170 minutes even though u_* did not decrease substantially. In Table 2, we compared soil texture in the 0-1 cm soil layer at a location 2.00 m upwind from the measurement site before and after the erosion event. The results showed that particles finer than 10 μm in the surface sediments decreased after the wind erosion event; however, a considerable amount remained available to supply dust emissions.

Moreover, the proportion of coarse sand increased significantly, and coarsening of the surface soil texture was evident. The reason for decreasing dust emissions after 170 minutes is the gradual limitation of erodible grain supply resulting from surface renewal as erosion progresses, which changes the surface transition type from transport-limited to supply-limited. Under this level of u_* , soil texture coarsening forms a protective layer over erodible particles that acts against the

corresponding u_* by weakening saltation and dust emissions. It is clear that if subsequent u_* increases to a degree where shear force against the surface exceeds such protection, saltation processes and dust emissions will continue. This trend occurred from 90 to 240 minutes. Such evidence suggests that the surface supply of erodible grains is the determining factor for saltation intensity. When a sufficient supply of erodible grains exists, significant correlations occur among u_* , saltation intensity, and f_v . When supply is limited by factors such as surface renewal or increased soil moisture, u_* will not necessarily correlate with the other two factors. Although this study did not further examine the relationship between saltation intensity and f_v , we plan to investigate abrasion efficiency (the ratio of f_v to saltation flux) in aeolian processes in future research.

In arid regions, sustained high wind speeds on the ground surface do not necessarily result in suspensions when dust supply is limited. A known property is that when surface renewal occurs as erosion progresses, surface soil texture coarsening will reach a point where a protective layer of erodible particles forms at a corresponding u_* , causing sand transport and dust emissions to cease [?, ?, ?]. Therefore, future soil loss models designed for both saltation particles and dust emissions should be based on all wind erosion events, and dynamic changes in various parameters during aeolian processes should also be considered, especially detailed responses of surface soil texture and erodible grain supplies to relative wind speeds at all levels and their overall duration [?, ?]. Although our field investigation results are much simpler than those found in actual environments, they are typical of dust emission processes on Gobi surfaces during aeolian processes.

From the calculations in Section 3.1, we found that during the most intense period of wind erosion (i.e., 90–170 minutes), f_v accounted for only approximately one-quarter of the total horizontal suspension transport rate below the TSA. After 170 minutes, the horizontal transport rate of suspended particles introduced from upwind directions accounted for nearly 100.0%. For near-surface suspension concentrations during wind erosion, contributions from other sources of suspended transport were much greater than local dust emissions. Therefore, the contribution of the Gobi surface to atmospheric dust was limited [?, ?, ?]. Moreover, observed suspended particles transported from upwind directions were mainly derived from erodible surfaces around the Gobi desert and its interior (e.g., sand dunes, playas, alluvial fans, etc.). However, observed results would differ when upwind surface and local surface conditions change. For instance, if the upwind surface has lower dust emission ability than the local surface, local dust emissions would exceed upwind suspension. Additionally, gravel coverage of the local surface significantly affects calculation results [?, ?, ?]. Therefore, if gravel coverage of the local surface is higher than in the present study, dust emissions constitute a smaller proportion of total horizontal suspension. Additional observations under other surface conditions should be conducted. This paper proposes a method that can separate dust emissions from total suspension in airflow regardless of upwind or local surface conditions.

5 Conclusions

This study analyzed measured data of wind profiles, PM10 concentrations at different heights, and sand transport on a Gobi surface. On Gobi surfaces with sufficient dust supply, the vertical concentration profiles of PM10 matched the logarithmic model better without aeolian saltation ($u_{*pt} < u_* < u_{*t}$). For aeolian processes with saltation ($u_* > u_{*t}$), we divided the profile into the saltation-affected layer and the airflow-transport layer according to the two different sources of suspensions (i.e., locally emitted dust and upwind transported dust). The profile was expressed in a piecewise manner with the TSA as the boundary between the saltation-affected layer and the airflow-transport layer. Based on the vertical concentration profiles, we used a mathematical method to separate emitted dust from total suspension in airflow and proposed a computational method from a new perspective to calculate f_v to directly describe changes in dust emissions during aeolian processes. The calculated dust loss on the Gobi surface during a 180-minute wind erosion event was approximately 1.44 g/m. In the present study, only one type of surface condition was investigated. Future research should include additional observations under other surface conditions.

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References

- Alfaro S C, Gomes L. 2001. Modeling mineral aerosol production by wind erosion: Emission intensities and aerosol size distributions in source areas. *Journal of Geophysical Research: Atmospheres*, 106(D16): 18075-18084.
- Anderson R S, Hallet B. 1986. Sediment transport by wind: Toward a general model. *Geological Society of America Bulletin*, 97(5): 523-535.
- Bagnold R A. 1941. *The Physics of Blown Sand and Desert Dunes*. Dordrecht: Springer, 1-265.
- Budd W F. 1965. The drifting of non-uniform snow particles. *Studies in Antarctic Meteorology*, 9: 59-70.
- Dong Z B, Man D Q, Luo W Y, et al. 2010. Horizontal aeolian sediment flux in the Minqin area, a major source of Chinese dust storms. *Geomorphology*, 116(1): 58-66.
- Freire L S, Chamecki M, Gillies J A. 2016. Flux-profile relationship for dust concentration in the stratified atmospheric surface layer. *Boundary-Layer Meteorology*, 160(2): 249-267.
- Fryrear D W, Saleh A. 1993. Field wind erosion: vertical distribution. *Soil Science*, 155(4): 294-300.

- Gillette D A. 1974. On the production of soil wind erosion having the potential for long range transport. *Journal of Geophysical Research Atmospheres*, 8: 734-744.
- Gillette D A, Walker T R. 1977. Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of West Texas. *Soil Science*, 123(2): 97-110.
- Gillette D A. 1978. A wind tunnel simulation of the erosion of soil: Effect of soil texture, sandblasting, wind speed, and soil consolidation on dust production. *Atmospheric Environment*, 12(8): 1735-1743.
- Gillette D A, Fryrear D W, Gill T E, et al. 1997. Relation of vertical flux of particles smaller than 10 μ m to total aeolian horizontal mass flux at Owens Lake. *Journal of Geophysical Research: Atmospheres*, 102(D22): 26009-26015.
- Gillies J A, Berkofsky L. 2004. Eolian suspension above the saltation layer, the concentration profile. *Journal of Sedimentary Research*, 74(2): 176-183.
- Hagen L J, Van Pelt S, Sharratt B. 2010. Estimating the saltation and suspension components from field wind erosion. *Aeolian Research*, 1(3): 147-153.
- Hinds W C. 2000. *Aerosol technology: Properties, behavior, and measurement of airborne particles*. New York: John Wiley & Sons, 1121-1122.
- Houser C A, Nickling W G. 2001. The emission and vertical flux of particulate matter <10 μ m from a disturbed clay-crust surface. *Sedimentology*, 48(2): 255-267.
- Kind R J. 1992. One-dimensional aeolian suspension above beds of loose particles: A new concentration profile equation. *Atmospheric Environment*, 26(5): 927-931.
- Kjelgaard J, Sharratt B, Sundram I, et al. 2004. PM10 emission from agricultural soils on the Columbia Plateau: Comparison of dynamic and time-integrated field-scale measurements and entrainment mechanisms. *Agricultural and Forest Meteorology*, 125(3-4): 259-277.
- Kok J F, Parteli E J R, Michaels T I, et al. 2012. The physics of wind-blown sand and dust. *Reports on Progress in Physics*, 75(10): 10690, doi: 10.1016/j.aeolia.2015.02.003.
- Leys J F, Mctainsh G H. 1996. Sediment fluxes and particle grain-size characteristics of wind-eroded sediments in southeastern Australia. *Earth Surface Processes and Landforms*, 21(7): 661-671.
- Loosmore G A, Hunt J R. 2000. Dust resuspension without saltation. *Journal of Geophysical Research: Atmospheres*, 105(D16):
- López M V. 1998. Wind erosion in agricultural soils: An example of limited supply of particles available for erosion. *CATENA*, 33(1): 17-28.

- Macpherson T, Nickling W G, Gillies J A, et al. 2008. Dust emissions from undisturbed and disturbed supply-limited desert surfaces. *Journal of Geophysical Research*, 113(F2), doi: 10.1029/2007JF000800.
- Nickling W G. 1978. Eolian sediment transport during dust storms: Slims River Valley, Yukon Territory. *Canadian Journal of Earth Sciences*, 15(7): 1069-1084.
- Nickling W G, Gillies J A. 1993. Dust emission and transport in Mali, West Africa. *Sedimentology*, 40(5): 859-868.
- Prandtl L. 1953. *Essentials of Fluid Dynamics with Applications to Hydraulics, Aeronautics, Meteorology and other Subjects*. London: Blackie & Son, 1-99.
- Pye K, Tsoar H. 2009. *Aeolian Sand and Sand Dunes*. Berlin: Springer, 1-106.
- Qiu X F, Zeng Y, Miao Q L. 2001. Temporal-spatial distribution as well as tracks and source areas of sand-dust storms in China. *Acta Geographica Sinica*, 56(3): 316-322.
- Shao Y P, Lu H. 2000. A simple expression for wind erosion threshold friction velocity. *Journal of Geophysical Research*, 105(D17): 22437-22443.
- Shao Y P. 2008. *Physics and Modelling of Wind Erosion*. Heidelberg: Springer, 1-278.
- Shao Y P, Wyrwoll K, Chappell A, et al. 2011. Dust cycle: An emerging core theme in Earth system science. *Aeolian Research*, 2(4): 181-204.
- Shao Y P, Zhang J, Ishizuka M, et al. 2020. Dependency of particle size distribution at dust emission on friction velocity and atmospheric boundary-layer stability. *Atmospheric Chemistry and Physics*, 20: 12939-12953.
- Sharratt B, Pi H. 2018. Field and laboratory comparison of PM10 instruments in high winds. *Aeolian Research*, 32: 42-52.
- Sweeney M, Etyemezian V, Macpherson T, et al. 2008. Comparison of PI-SWERL with dust emission measurements from a straight-line field wind tunnel. *Journal of Geophysical Research: Atmospheres*, 113(F1): 228-236.
- Vories E D, Fryrear D W. 1991. Vertical distribution of wind-eroded soil over a smooth, bare field. *Transactions of the Asae*, 34(4): 1763-1768.
- Wagenbrenner N S, Germino M J, Lamb B K, et al. 2013. Wind erosion from a sagebrush steppe burned by wildfire: Measurements of PM10 and total horizontal sediment flux. *Aeolian Research*, 10: 25-36.
- Wang R D, Li Q, Zhou N, et al. 2019. Effect of wind speed on aggregate size distribution of windblown sediment. *Aeolian Research*, 36: 1-8.
- Wang R D, Li Q, Wang R J, et al. 2021. Influence of wind velocity and soil size distribution on emitted dust size distribution: A wind tunnel study. *Journal of Geophysical Research: Atmospheres*, 126, e2020JD033768, doi: doi.org/10.1029/2020JD033768.

Wang X S, Zhang, C L. 2021. Field observations of sand flux and dust emission above a gobi desert surface. *Journal of Soils and Sediments*, 21: 1815–1825.

Wang X S, Zhang C L, Zou X Y. 2021. A model of the sand transport rate that accounts for temporal evolution of the bed. *Geomorphology*, 378, 107616, doi: 10.1016/j.geomorph.2021.107616.

Whicker J, Breshears D D, Field J P. 2014. Progress on relationships between horizontal and vertical dust flux: Mathematical, empirical and risk-based perspectives. *Aeolian Research*, 14: 105–111.

Wu W, Yan P, Wang Y, et al. 2018. Wind tunnel experiments on dust emissions from different landform types. *Journal of Arid Land*, 10(4): 1–13.

Zender C S, Bian H, Newman D. 2003. Mineral Dust Entrainment and Deposition (DEAD) model: Description and 1990s dust climatology. *Journal of Geophysical Research*, 108(D14): 4416, doi: 10.1029/2002JD002775.

Zhang C L, Song C Q, Wang Z T, et al. 2018. Review and prospect of the study on soil wind erosion process. *Advances in Earth Science*, 33(1): 27–41. (in Chinese)

Zhang C L, Wei G R, Zou X Y, et al. 2022. The varying fetch effect of aeolian sand transport above a gobi surface and its implication for gobi development process. *International Soil and Water Conservation Research*, doi: 10.1016/j.iswcr.

Zhang J, Teng Z J, Huang N, et al. 2016. Surface renewal as a significant mechanism for dust emission. *Atmospheric Chemistry and Physics*, 16(24): 15517–15528.

Zhang Y Y, Hu R F, Zheng X J. 2018. Large-scale coherent structures of suspended dust concentration in the neutral atmospheric surface layer: A large-eddy simulation study. *Physics of Fluids*, 30(4): 046601, doi: 10.1063/1.5022089.

Zobeck T M, Pelt R. 2006. Wind-induced dust generation and transport mechanics on a bare agricultural field. *Journal of Hazardous Materials*, 132(1): 26–38.

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