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Grain Size and Sedimentary Sorting Characteristics of Atmospheric Dust in the Cele Oasis, Southern Margin of Taklimakan Desert

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Abstract: Grain size is a proxy indicator of airflow intensity and also provides a scientific basis for the prevention of dust hazards. However, the variations in grain size characteristics that occur during transport and deposition processes are seldom discussed. Here, atmospheric dust samples were collected before and after deposition in a sand–dust storm for grain size analysis. The results showed that the grain size distributions of the atmospheric dust were unimodal during transportation but always became bimodal after deposition. This indicates that the bimodal grain size distribution of the aeolian deposits was caused by sedimentary sorting. The coarse-grained component, which was between 20 and 200 µm, was mainly deposited during the sand–dust storm. Grain size may indicate the strength of the airflow field. The fine-grained component, which ranged in size from 0.4 to 20 µm, was mainly deposited after the sand–dust storm. This component can remain suspended in the atmosphere for a long period of time. Oasis shelterbelts can be used to reduce the fine-grained component of the dust aerosol through the interception of particles by foliage. The grain size variation found in this study from before to after sand–dust storm deposition deepens our understanding of the sediment sorting process.

Keywords: atmospheric dust; aeolian activity; oasis; sedimentary sorting; grain size distribution

1. Introduction

The sustainable development of oases is crucial to maintaining social stability and economic development in arid areas, and aeolian processes seriously affect the environmental quality, human health, and sedimentary evolution of oases. Therefore, studying the grain size characteristics of modern atmospheric dust in oasis areas would facilitate the interpretation of a considerable amount of environmental information, such as dust sources, transportation dynamics, and deposition processes, and also help to control the hazards associated with aeolian activities and improve air quality. Such studies have important theoretical and practical significance that could improve the well-being of oasis residents.

Previous studies have focused on dust transport and deposition processes and their grain size characteristics in oasis areas. There are three main ways to restrict sand and dust from an oasis area: windbreaks, sand fixation, and dust retention. The oasis edge protection system and the inner shelter forest grid play important roles as windbreaks and are necessary for sand fixation [1]. In addition, the microclimate effect caused by oasis vegetation can accelerate dust deposition inside the oasis [1,2]. Leaves with different surface characteristics exhibit the selective retention of atmospheric particles [3,4]. In particular, the large leaf area and rough leaf surface of oasis vegetation play a role in the
retention of atmospheric dust and improve air quality [4]. Therefore, analyzing the grain size characteristics of modern atmospheric dust in combination with the leaf dust retention characteristics can enhance our understanding of the role of vegetation in alleviating dust pollution and improving the environmental quality in oases.

Atmospheric dust exhibits specific grain size characteristics after being transported and sorted [5]. These can be characterized by a series of parameters, including the grain size distribution, grain size parameters (mean grain size, sorting, kurtosis, and skewness), and C–M figure (the C value is the grain size corresponding to 1% of the cumulative curve (the coarsest grain size) and M is the grain size corresponding to the 50% value (median size)). These parameters can be used to identify the sources, discriminate the formation environment, and reconstruct the paleoenvironmental change sequence [6–8].

Aeolian deposits are reputed to be excellent geological archives that contain significant environmental information. As an important proxy indicator for the strength of the regional airflow field, the grain size of aeolian deposits, especially loess deposits, is now used widely to obtain regional environmental information [8,9]. A specific size class is usually chosen as a direct proxy indicator [8–12]. Moreover, mathematical models have been used to extract proxy indicators, such as by end-member modeling [13,14], the granularity–standard deviation method [15], etc. Nevertheless, the grain size change characteristics of atmospheric dust from before to after deposition can facilitate a deep understanding of the depositional processes.

In this study, the grain size characteristics of atmospheric dust collected before and after deposition were analyzed to reveal the relationships among aeolian activities and the grain size characteristics of dustfall in an oasis region and provide a theoretical basis for maximizing the effects on preventing dust hazards by oasis shelterbelts.

2. Study Area

This study was carried out in the Cele Oasis (36°57′–37°5′ N, 80°43′–80°53′ E), southern edge of the Taklimakan Desert, which is located on the piedmont alluvium and diluvial fan of the Kunlun Mountains (Figure 1). The region has a warm temperate continental arid climate. The annual average temperature is 11.9 °C, the extreme maximum temperature is 41.9 °C, and the extreme minimum temperature is −23.9 °C [16,17]. Precipitation is very limited. The average annual precipitation is about 35 mm; the average annual potential evaporation is 2600 mm; and the value of the drought index, defined as the ratio of the possible evaporation from the water surface at a certain time to the precipitation at the same place during the same period, is 20.8 [18,19]. The water is mainly supplied from the ice and snow melt and mountain precipitation in the Kunlun Mountains. Strong westward winds together with frequent sand–dust storms prevail in spring and summer [2,20]. The average annual sand–dust weather accounts for 142.4 days of the year, of which there are 21.2 sand–dust storm days and up to 49 days in the maximum frequency year (1960) [21]. The oasis ecosystem is well developed, but the Cele Oasis is located on the edge of the desert, and regional wind–sand activities are frequent and intense.
3. Study Methods

Dust particles do not complete sedimentary sorting until they settle to the ground. We collected atmospheric dust before and after deposition to understand the sorting of the atmospheric dust in the deposition process. The aeolian deposit samples were collected by dust traps, which were made of polyvinyl chloride pipes with an inner diameter of 15 cm and a height of 30 cm according to the Chinese national standard (GB/T 15265-94). To avoid the impact of local saltating particles, the dust traps were placed on shelves at a height of 3.5 m at eight sites (Figure 1), and all of them were located in an open area without tall trees, buildings, or other obstructions at the edge of an oasis shelterbelt. Atmospheric dust was collected by total suspended particulate sampler (TSP). The TSP was also placed in an open area. We collected sand–dust storm samples at eight locations (WE4–WE11) on 8 May 2011 (T1) and two locations (CB-1–CB-2) in Cele National Station of Observation and Research for Desert-Grassland Ecosystem in the study area on 28 July 2011 (T2) (Figure 1), and also collected one atmospheric dust sample in the area on 28 July 2011 (AD1).

Grain sizes of all samples were measured using a laser grain size analyzer (Mastersizer 2000, manufactured by Malvern Instruments Ltd. in Worcestershire, United Kingdom) installed in the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The test range, which was between 0.02 μm and 2000 μm, was divided into 100 size classes. The residual error was less than 2%. As the atmospheric dust in the study area has not been affected by pedogenesis, the samples were not pretreated to remove organic matter or carbonates.

Calculation method for the grain size parameters and principles of the classification were established according to the Folk and Ward (1957) and mentioned in Blott and Pye (2001) [22].
The polymodal grain size distribution of the deposited dust was fitted and separated using the lognormal function mentioned in detail by Xiao et al., (2009) [23]. Additionally, the formula is expressed as follows:

\[
F(x) = \sum_{i=1}^{n} \left[ \frac{c_i}{\sigma_i \sqrt{2\pi}} \int_{-\infty}^{+\infty} \exp\left( -\frac{(x - a_i)^2}{2\sigma_i^2} \right) dx \right]
\]

(1)

where \( n \) is the number of modes, \( a_i \) is the mean value of the \( i \)th mode’s grain size in \( \mu m \), \( c_i \) is the percentage of the \( i \)th mode, and \( \sigma_i \) is the standard deviation of the \( i \)th mode.

The function of fitting residual is as follows:

\[
dF = \frac{1}{m} \sum_{j=1}^{m} (F(x_j) - G(x_j))^2
\]

(2)

where \( m \) is the number of grain size intervals. \( F(x_j) \) and \( G(x_j) \) are the fitted and measured percentage of the \( j \)th grain size interval, respectively.

4. Results

The atmospheric dust and deposited dust exhibit different grain parameters (Table 1). The deposited dust has a mean size between 70 and 77 \( \mu m \), and it is either moderately sorted or moderately well sorted; the skewness is between fine skewed and symmetrical, and the kurtosis is between leptokurtic and mesokurtic. The atmospheric dust has a mean grain size is 19.5 \( \mu m \), and it is very poorly sorted. The skewness is fine skewed, and the kurtosis is mesokurtic.

Table 1. Grain size parameters of the atmospheric dust and deposited dust.

| Samples | Mean (\( \mu m \)) | Sorting | Skewness | Kurtosis |
|---------|-------------------|---------|----------|----------|
| T1      |                   |         |          |          |
| WE04    | 73.1              | 1.52    | -0.05    | 0.98     |
| WE05    | 72.5              | 1.62    | -0.05    | 0.98     |
| WE06    | 73.0              | 1.62    | -0.07    | 0.98     |
| WE07    | 71.8              | 1.63    | -0.05    | 0.98     |
| WE08    | 76.6              | 1.54    | -0.04    | 0.98     |
| WE09    | 76.1              | 1.52    | -0.04    | 0.97     |
| WE10    | 72.2              | 1.58    | -0.04    | 0.96     |
| WE11    | 73.6              | 1.58    | -0.05    | 0.96     |
| Mean value | 73.6          | 1.58    | -0.05    | 0.97     |
| T2      |                   |         |          |          |
| CB-1    | 69.8              | 1.74    | -0.22    | 1.41     |
| CB-2    | 72.8              | 1.61    | -0.1     | 1.08     |
| Mean value | 71.3          | 1.68    | -0.16    | 1.25     |
| AD1     | 19.5              | 4.08    | -0.23    | 1.047    |

The grain size distribution curves of the deposited dust and atmospheric dust are shown in Figure 2. They exhibit obviously different grain size characteristics. The deposited dust shows the typical bimodal grain size distribution of the aeolian deposits (with a tail in the size class of <2 \( \mu m \)) [6,7]. The grain size characteristics of samples from different locations in the same dust fall event are very consistent with each other. For the coarse-grained component (peak 1), the grain size distribution curve is mainly between 20 and 200 \( \mu m \), with a modal grain size of ~70 \( \mu m \) (Figure 2). The mean size is between 72 and 80 \( \mu m \), and according to Folk and Ward (1957) as mentioned in Blott and Pye (2001), the component is moderately to well sorted. For peak 2, the mean size is between 13 and 20 \( \mu m \), and the dust is poorly sorted. The content of peak 2 is sometimes small because the samples were collected during a dust storm with a strong airflow field [7,24]. In all, this result is consistent with the bimodal grain size distribution curve typical of aeolian deposits collected near the source area (Figure 2) [7].
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The atmospheric dust collected in the study region exhibits unimodal grain size distribution characteristics (with a fine tail in the size class of <2 μm; Figure 2). The modal grain size is ~45 μm, which is smaller than the modal size of peak 1 of the deposited dust. The mean size is 19.5 μm, and the dust is very poorly sorted (σ = 4.1), finely skewed (Sk = −0.23), and mesokurtic (K = 1.01). Thus, the atmospheric dust exhibits a different grain size distribution curve than the deposited dust collected at the same time.

Figure 2. Grain size distribution curves of the atmospheric dust and deposited dust (a1,b1). (a2,b2): Peaks 1 and 2 were fitted and separated according to the lognormal function mentioned by Xiao et al. [23].

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5. Discussion
5.1. Sorting Effect during Deposition

This study found different grain size distribution characteristics between atmospheric dust and deposited dust (Figure 2). The atmospheric dust showed a unimodal grain size distribution, small mode size, and a relatively low coarse particle content. However, the coarse particle content was significantly higher in the deposited dust, which exhibited a bimodal grain size distribution (Figure 2). This variation in the grain size distribution characteristic was observed in different areas and was universal. This result indicates that the atmospheric dust was sorted during deposition and that this sedimentary sorting is stable.

Detrital particles in air should undergo sorting during deposition, which is influenced by the airflow field and gravity and thus form a specific type of grain size distribution [25–27]. During transportation, different sedimentary sorting occurs for different size classes [7,26,28]. This can be explained by the ratio $U_f/u^*$, where $U_f$ is the settling velocity of the particle, and $u^*$ is the drag velocity of the airflow, which is always used to describe the state of motion of...
particles in a strong airflow field [29–32]. Generally, particles larger than 20 μm can settle to the surface relatively easily, even in a sand–dust storm, because of their larger gravitational forces [26,29]. However, particles smaller than 20 μm (U_f/ν < 0.1) do not deposit easily in a sand–dust storm (ν between 0.2 and 0.6 m/s) because of their smaller gravitational forces [25,28]. They are mainly deposited in stable airflow field after the sand–dust storm.

In a sand–dust storm, the coarser particles are generally sorted first according to the ratio U_f/ν (Figure 2), forming a coarse-grained component (peak 1), and the content of the fine-grained component (peak 2) is small or even absent (Figures 2 and 3) [7,24] because these sizes are not conducive to deposition in a strong airflow field [25,28].

![Figure 3](image-url)

**Figure 3.** Grain size distribution curves of the deposited dust collected during sand–dust storms in the Cele Oasis [24]. The samples in (a) were collected during 3–5 April 2013, and those in (b) were collected during 16–17 April 2013.

During the post-dust storm period, the fine-grained component is more conducive to being deposited in the stable airflow field. Therefore, these grains can be sorted gradually after the sand–dust storm, forming the fine-grained component (peak 2). The content of the fine-grained component increases with extension of the settling time [7]. Some coarser particles also continue to be deposited. Ultimately, the aeolian deposits exhibit a bimodal particle size distribution.

This phenomenon has also been observed elsewhere. For example, deposited dust and atmospheric dust collected in Mali region, West Africa, showed different grain size distribution characteristics between deposited dust and atmospheric dust (Figure 4) [33]. The deposited dust has a typical bimodal grain size distribution, but the atmospheric dust has a unimodal grain size distribution (Figures 2, 4 and 5). Additionally, similar grain size variation characteristics between atmospheric dust and deposited dust were found in Harbin City, Heilongjiang Province, and Shantou City, Guangdong Province, China (Figure 5) [34,35]. The dry dust fall (deposited dust) observed in Harbin City (Figure 5A) exhibited a typical bimodal grain size distribution (with a fine tail at the size of less than 2 μm) [34], and very different grain size distributions featuring a unimodal distribution were observed from atmospheric dust collected by TSP and wet dust fall collected from “slurry rain” in Harbin City and Shantou City (Figure 5A,B). “Slurry rain” particles are dust particles that are leached from the atmosphere and settle to the surface via precipitation in the form of condensation particles. Such wet dust falls do not undergo sedimentary sorting during the leaching process, which is similar to the case of samples collected by an active sampler (Figure 5B).
Figure 4. Grain size distributions of atmospheric dust and deposited dust collected at the town of Sevare, Mali [33]. (a). Samples collected at 2.5 m, 25 April 1990; (b). Samples collected at 2.5 m, 26–27 April 1990.

Figure 5. Grain size distributions of atmospheric dust and deposited dust. Data for part (A) are from Xie and Chi, whose samples were collected in Harbin, China, on 13 May 2011 [34]. Data of part (B) are atmospheric dust collected in the winter monsoon ((a) 12 December 2016) and summer monsoon ((b) August 2016) Shantou City, Guangdong Province, China [35], and atmospheric dust collected in Nanjing City, Jiangsu Province, China ((c) 11 March 2006) [36].

In short, the atmospheric dust, which has a unimodal grain size distribution, exhibits a bimodal grain size distribution after sedimentary sorting.

5.2. Implications from the Grain Size Characteristics

The origin of the bimodal grain size distribution of aeolian sediment has been widely discussed, but some controversies remain. Some scholars have considered that different grain size sub-peaks indicate different material sources [6, 33, 37, 38]. The peak 1 component is transported at a low altitude and deposited proximally due to its coarser grain size during a sand–dust storm [25, 28]. The peak 2 component (<20 μm) can be transported a longer distance and hence over a larger spatial scale once the particles are lifted into the atmosphere [6, 28]. Therefore, this component is considered to be sourced from a more distant region [37] or to be atmospheric background dust [6].
However, in this study, a higher proportion of the fine-grained component (<20 μm) was found in the atmosphere during dusty days (Figures 2–4). This supply was sufficient for the deposition of the peak 2 component, even without the material from distant regions. Moreover, many previous studies have found that both the coarse and the fine components of aeolian deposits came from the same source region [34,39,40]. The coarse- and fine-grained particle components of the loess on the Chinese Loess Plateau were shown to come from the same source area using the geochemical tracing method [39–41].

The unimodal grain size distribution of atmospheric dust indicates that detrital particles of various size classes are fully mixed during transportation once they are lifted into the atmosphere (Figure 2a). Even if the dust is supplied from different material sources, it is mixed thoroughly during transportation (would not show specific peaks in the grain size distribution (Figure 2a)). Thus, the atmospheric dust would not retain grain size sub-peaks corresponding to material sources. Subsequently, these mixed particles are sorted during deposition, forming a multi-modal grain size distribution. Therefore, the bimodal grain size distribution characteristics of aeolian deposits are mainly attributable to sedimentary sorting.

Studying the deposition processes and grain size characteristics of atmospheric dust in oasis areas before and after deposition is important for preventing dust hazards and for alleviating dust pollution. Oases are located at the edges of particle source regions and are important dust sinks [1,42]. The dust deposited in oases is mainly transported by suspension and saltation. Therefore, these two aspects should be considered to prevent dust pollution. Several strategies can be used. First, the shelterbelts around the oasis margin should be strengthened to prevent wind and sand invasion through the mechanical obstruction effect [1,43]. Second, for the portion of atmospheric dust that invades the interior of the oasis, plants with a strong retention capacity can be used to intercept the dust. The different grain size characteristics of atmospheric dust and foliar dust shown in previous studies further demonstrate that various plants can selectively retain different grain size fractions [3,4,44,45], resulting in a different grain size distribution of foliar dust (Figure 6) [4,43]. Consequently, analyzing the grain size characteristics of aeolian dust in oases has important implications for selecting greening tree species for intercepting the main size component of the atmospheric dust (Figure 6) and can help to maximize the wind-breaking, sand-fixing, and dust-intercepting effects of shelterbelts in oases.

Figure 6. Grain size distribution curves of foliar dust, atmospheric dust, and deposited dust [3].
6. Conclusions

A comparison of the grain size distribution characteristics between atmospheric dust and deposited dust collected before and after sedimentary sorting, respectively, produced some important results:

1. Atmospheric dust exhibited a unimodal grain size distribution that was significantly different from the bimodal distribution of the deposited dust. This difference was mainly caused by sedimentary sorting.

2. The main size class of the deposited dust in the Cele Oasis was 20–200 µm, which was larger than the mean grain size (19.5 µm) of the atmospheric dust. The mechanical blocking effect of an oasis protection system at the margins can help reduce the wind speed and accelerate the sedimentation of coarse particles during a sand–dust storm. Meanwhile, the foliage of oasis shelterbelts can intercept fine particles, which is significant for alleviating dust aerosol pollution.

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