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Characteristics of the lower layer of sandstorms in the Minqin desert-oasis zone

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By measuring the sand-dust flux, vertical deposition, and the wind velocity throughout 19 sandstorms in the Minqin region, we quantitatively analyzed the horizontal distribution and vertical variation in sandstorm characteristics under different land cover conditions. The effect of different land cover on mitigating sandstorms was also investigated. The results indicated that, in the surface layer ranging from 0–50 m, the intensity of sand-dust horizontal flux and concentration of sand-dust decreased with the increase of the height in the desert and the edge of oasis, whereas the two physical quantities increased slightly with the increase of the height in the oasis. The two physical quantities obey power function well under all three cover conditions. Moreover, in the desert and at the edge of oasis, the sand-dust vertical deposition decreased with the increase of the height. But a partial unimodal distribution at the oasis site and the maximum deposition occurred at the height of 9 m, which corresponds to the middle height of farmland protection forest. The annual flux that passed through a section of 1 m in width and 50 m in height was 9169 kg in the desert, 5318 kg at the edge of oasis, and 2345 kg in the oasis. And the annual fluxes at the edge of oasis and in the oasis are 42% and 74% less, respectively, than that in the desert. This implies that the wind break forest significantly reduced the intensity of sandstorms.

Minqin, the lower layer, sand-dust, horizontal flux, vertical deposition

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The occurrence and development of sandstorms are not only a key process in the acceleration of land desertification but also a concrete symptom of this process.

Because of its enormous effects on ecosystems, human health, and industrial and agricultural production, sandstorm, as well as its characteristics, has been the focus of many investigations [1–3]. Those investigations, however, were concerned primarily with the release, transportation, and deposition of sand-dust, more specifically, e.g., the estimation of dust emission from the ground, analysis of the mechanisms and influencing factors of threshold sand, simulations of sand-dust transport and deposition processes. The main methods used were model calculation combined with field experimental verification, principally through radar and satellite monitoring [4–14]. For example, Che et al. [13] using the DPM (Dust Production Mode1) model, calculated the horizontal saltation fluxes, dust emission

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fluxes and sandblasting efficiencies of different kind of soil aggregates in North China deserts under different roughness lengths and different wind friction velocities. Husar et al. [14] monitored two intense sandstorms that occurred on April 15 and 19, 1998 through satellite images and radar, clearly revealing that the North Asian sandstorms exhibit a layered structure.

However, all of these studies tended to focus on the macro-characteristics and influence of sandstorm movement, while the micro-structure of sandstorm, the transport process of sand-dust, and the impact of micro-environmental variation on this process received insufficient attention.

In recent years, great progresses have been made in studying the effects of meteorological elements, such as wind velocity, precipitation, air temperature and so on, and the vegetation coverage and the moisture or texture of land [15–24]. Joseph [24] collected particulates in suspension and saltation at heights of 5, 10, 20, 50, and 100 cm from different surfaces, in which the largest amounts of sediment were collected in the areas of loose sand and at the sites directly downwind from loose sand, in comparison with the sites containing heavy crusting, gravel, or a forb/grass cover. Differences between the sites with gravel surfaces and those with forb/grass cover were insignificant. Their results quantify the importance of surface cover as an agent for reducing the extent of wind erosion on semi-arid landscapes. Wang et al. [16] through analyzing the particle sizes, SEM and element content of surface and dust samples at the source and deposition areas, pointed out that mobile dunes are not major dust contributors.

However, because ground based observations are usually within a height of 2 m and satellite observations are usually concentrated on high altitudes and the large-scale feature of sandstorms, few research has been done on the vertical distribution and horizontal variation of sandstorm elements such as sand-dust horizontal flux, sand-dust concentration and so on at lower layers (especial 0–50 m). Chen and Fryrear [25] collected dust samples from the 0–15.67 m layer of a sandstorm and found that both the suspended dust in the flow and the vertical distributions of sand-dust concentration were decreasing with height by a power function. According to their calculations, the total amount of dust through the 0–15.67 m layer could be 84960 kg km^{-1} h^{-1}. However, this kind observation is still scarce.

In view of this scarcity of research, we systematically observed 19 sandstorm processions at three towers, which were 50 m high and constructed at three typical sites with different land covers in order to quantify: (1) the vertical distribution and horizontal variation of sand-dust horizontal flux, variation in sand-dust concentration, and vertical deposition between typical areas, (2) the law of development and variation of these elements when they pass by the typical area; the effects of different land covers on reducing sandstorms.

1 Study location

The experiment was conducted in Minqin County, Gansu Province, China. The area is located at the lower reaches of the Shiyang River Basin, in a warm arid climate zone. From 1961 to 2008, mean annual precipitation has been 116.36 mm; mean annual evaporation has been 2383.7 mm, which is 20.5 times higher than precipitation, aridity 5.8; prevailing wind direction is north-west; mean gale (velocity $\geqslant$17 m s^{-1}) occurrence is 27.4 d yr^{-1}; and sand-dust events occur 25 d yr^{-1}, mean annual wind velocity 2.4 m s^{-1}, wind velocity of threshold sand 5 m s^{-1}. Water shortages lead to inhospitable natural conditions in this area, such as dry climate, unstable air conditions, sparse vegetation, and abundant sources of sand and loose surface material. Therefore, this region has become one of the main sources of sandstorms in China.

2 Experimental methods and data sources

2.1 Sandstorm Monitoring System

The Sandstorm Monitoring System included three 50 m high observation towers. Selected for this study were three typical sites with different land covers: desert, edge of oasis, and oasis. The three observation towers were constructed at these three sites, along the main wind direction in the Minqin area. The distance between the tower in the oasis and that at the edge of oasis was 3.5 km, and the distance between the tower at the edge of oasis and that in the desert was 4.8 km. Each tower measured wind velocity, quantity of horizontal flux and vertical flux of sand-dust at 19 different heights (1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 29, 33, 37, 41, 45, and 49 m). The locations of the three observation towers are shown in Figure 1.

2.2 Description of land cover characteristics of the three sites

When sandstorms occurred, they passed sequentially through the desert site, the edge of oasis site, and the oasis site. Over this 8.3 km route, the species of vegetation changes significantly. The height and coverage of vegetation, as well as surface roughness length increase gradually. Landform and soil characteristics also changes along the route. Detailed characteristics of the three sites are listed in Table 1.

2.3 The observation facility and observation items

The sand-dust horizontal flux was sampled by horizontal sand-dust flux sampler systems (Figure 2(a)), which were developed by the Gansu Desert Control Research Institute. The resistance of the filter bags to flow is less than 1.0% atmospheric pressure under the conditions of wind velocity

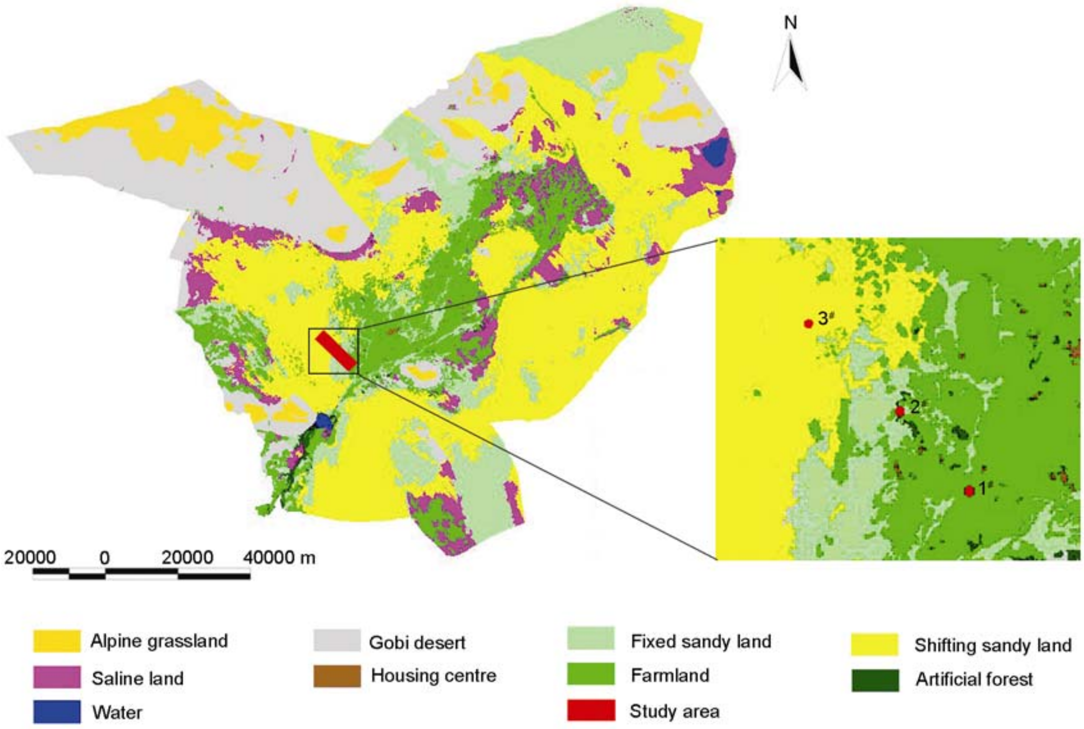

Figure 1 Land types of Minqin County and the three observation tower locations.

Table 1 Characteristics of the three sites' underlying surface features

	Soil characteristics	Vegetation characteristics				Landform characteristics
		Vegetation species	Height (m)	Coverage (%)	Surface roughness length (cm)	
Desert	Aeolian sandy soil and gravel aeolian sandy soil	*Nitraria tangutorum*	0.34	6.25	0.0178	Shifting sand dunes of 3–8 m high and semi-stable *Nitraria tangutorum* shrub sand dunes about 1 m in height. The flat land between dunes was covered by loose, sandy soil as well as gravel.
Edge of oasis	Aeolian sandy soil and clay	*Nitraria tangutorum*	0.44	14.0	0.0681	Stable and semi-stable sand dunes of 1–3 m high. The flat areas between the dunes were covered by clay soil with a smooth, compacted surface. There was wind-break forest left in this small area, which mainly consisted of *Haloxylon*, the preserving rate is 570 ha^{-1}.
		Calligonum mongolicum	0.50	1.4		
		Haloxylon	0.95	4.1		
		forbs	0.35	0.7		
Oasis	Sandy loam and loam	Crop	0.6–2.0	About 90 during the growing season, 5 in the non-growing season	1.9974	Flat, and consisting mainly of farmland and farmland shelter forest network. The average height of the farmland shelter forest network was 18–20 m, the average forest belt width was 7–10 m, the average space between belts was 300 m, and the clear bole height was 1–2 m, sparse degree 85%.
		Populus gansuensis	18–20			
		Populus bolleana Lauche	15–20			

at 25 m s^{-1} and area of the filter bags/area of sampler nozzle ratio of 60:1. The sample efficiency is more than 93% when the diameter of sample particle is within 3–100 μm, more efficient than the BSNE recommended by Goossens and Offer [26]. The sand-dust vertical deposition was sampled by wick-type vertical sand-dust deposition wet sampler systems developed by the Gansu Desert Control Research Institute (Figure 2(b)). The sample period was from Jan. 1st to Dec. 31st, 2006, totaling 1 year and 19 sandstorm processions.

2.4 Sample collection and data acquisition

The samples of horizontal flux and vertical flux were collected after every sandstorm event. If no sandstorm occurred over the course of a month, the samples were collected at the end of the month as the background value. The collected samples were dried in an oven at 85°C for 24 h.

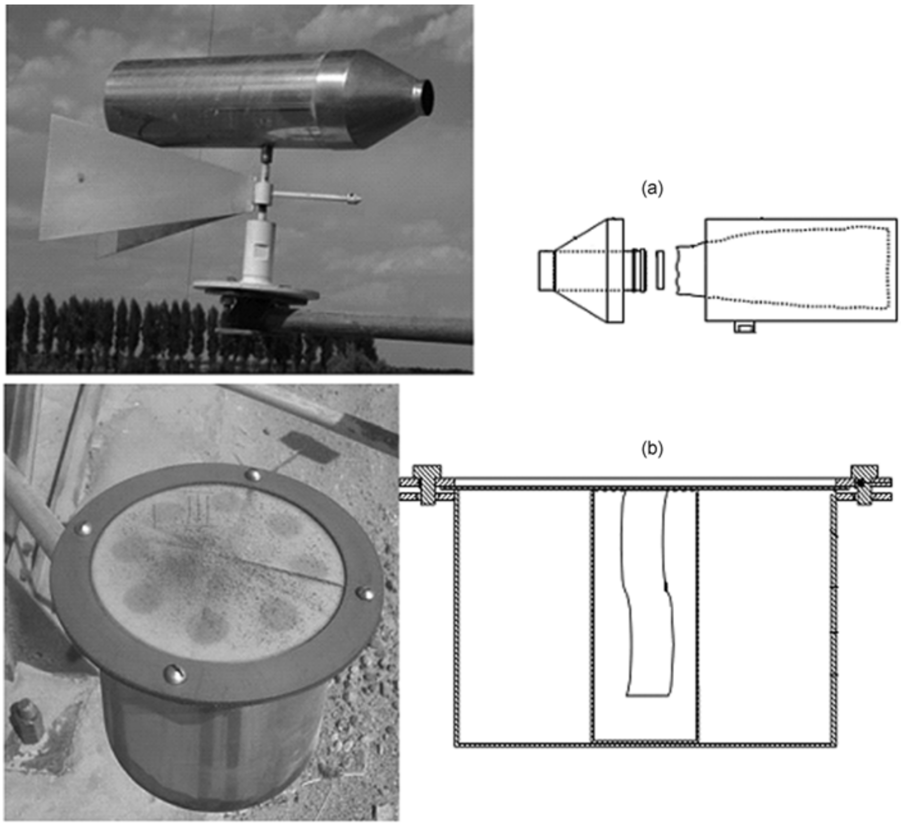

Figure 2 Photograph and structural plan of the horizontal sand-dust flux sampler systems (a) and wick-type vertical sand-dust deposition wet sampler systems (b).

The dried samples were weighed using an electronic scale with 0.0001 g precision. Wind velocity was measured by three-cup anemometers every 5 min.

3 Results

3.1 The distribution features of wind velocity

At the 0–50 m layer, the wind velocity increased by a power function with height at all three sites, which is in agreement with the conclusion of established research that the wind velocity increases with height. Regression equations between the wind velocity (V) and height (x) at the 0–50 m layer for the three sites: $V=ax^b$, a and b are constants (Table 2).

Along the horizontal gradient, as sandstorms progressed through the desert into the oasis, wind velocity decreased dramatically (Figure 3). From the desert into the wind-break forest shelter belt at the edge of oasis, the average wind velocity reduction was 4.11%; continuing to the oasis site, the average wind velocity reduction was 30.45%. Viewed from the vertical gradient, the wind velocity decreased obviously with height, and the main reduction of wind velocity was concentrated at the 0–25 m layer. Compared with the desert site, the wind velocity reduction within the oasis was 25.44%–53.91%, with the maximum wind velocity reduction occurring at 5 m above the ground surface. The wind velocity reduction passing from the desert to the oasis was 3.14%–11.65%, with the maximum reduction at 1 m. Thus, the reduction of wind velocity was concentrated mainly near ground layer, and the effect of the farmland shelter forest network on the wind velocity reduction was more significant than that of the wind-break forest.

3.2 The distribution features of sand-dust horizontal flux

Figure 4 shows that sand-dust horizontal flux decreased by a power function with height at the desert and the edge of oasis sites, but increased slightly by a power function in the oasis site. Regression equations between the sand-dust flux (F) and height (x) at the 0–50 m layer for the three sites: $F=ax^b$, a and b are constants (Table 3).

From desert to oasis, the sand-dust horizontal flux decreased gradually. The average horizontal flux of once procession from 0–49 m was 1.04 g cm^{-2} in the desert zone, 0.59 g cm^{-2} in the edge of oasis zone, and 0.24 g cm^{-2} in the oasis. With the increase in height, differences in sand-dust horizontal flux among sites became gradually smaller and the regression lines had a tendency to overlap, clearly indicating that the effect of land cover on sand-dust horizontal flux gradually decreases as height increases. Moreover, it

Table 2 Regression equations between the wind velocity and height for the three sites

	a	*b*	R^2
Oasis site	3.48	0.33	0.925
Edge of oasis site	7.85	0.16	0.982
Desert site	8.89	0.13	0.994

Table 3 Regression equations between the sand-dust flux and height for the three sites

	a	*b*	R^2
Oasis site	0.07	0.41	0.941
Edge of oasis site	1.07	–0.23	0.846
Desert site	2.96	–0.43	0.941

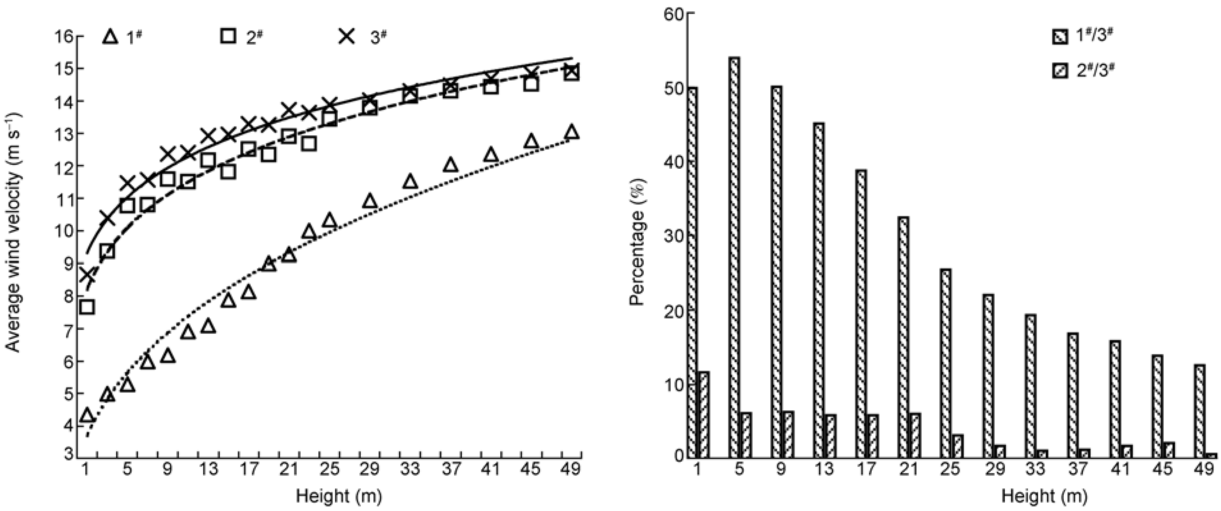

Figure 3 Height profiles and characteristics of wind velocity at 0–50 m layer for the three different land covers.

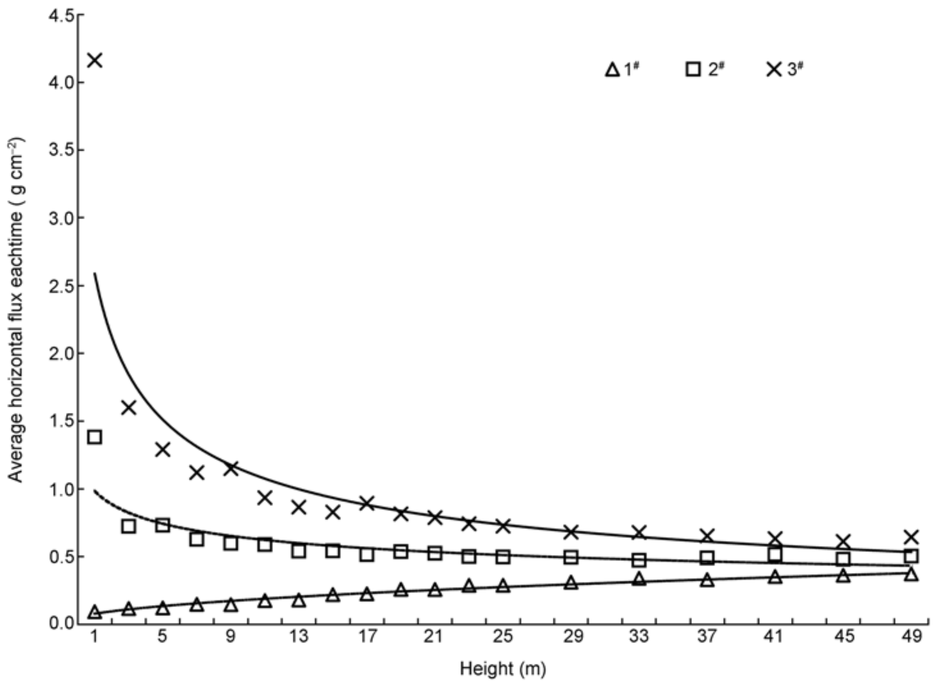

Figure 4 Height profiles of sand-dust horizontal flux at 0–50 m layer for the three different land covers.

was concluded that the transportation of sand-dust at the desert and the edge of oasis sites was concentrated mainly near ground layer. In contrast, the vegetation in the oasis, particularly the farmland shelter forest network, changed the vertical distribution pattern of the sand-dust horizontal flux, and the horizontal flux thus increased with height and concentrated in the upper layers at the oasis site.

3.3 The distribution features of sand-dust concentration

Sand-dust concentration was obtained by

$$C_{(x)} = \frac{Q_{(x)}}{V_{(x)}TA}, \tag{1}$$

where $C_{(x)}$ is the concentration at height x, g m^{-3}; $Q_{(x)}$ is the total measured quantities of sand-dust we collected at height x, kg; $V_{(x)}$ is the mean wind velocity at height x, m s^{-1}; T is duration of sampling, h; A is the intake area of the samplers, m^2.

During the sandstorms, the variation of sand-dust concentration with height was similar to the variation in horizontal flux. At the 0–50 m layer, the sand-dust concentration decreased with height at the desert and the edge of oasis sites, and increased slightly at the oasis site (Figure 5), all following a correlative power relationship: $C=ax^b$, a and b are constants (Table 4).

The sand-dust concentration decreased with height at the desert site, with a maximum value of 104.54 mg m^{-3} obtained at 1 m decreasing rapidly to 32.41 mg m^{-3} at 3 m, 24.12–10.09 mg m^{-3} at the 5–25 m layer, and decreasing slightly at the 29–49 m layer. The sand-dust concentration also decreased with height at the edge of oasis site, the maximum value of 43.41 mg m^{-3}, also at 1 m, decreased rapidly to 18.93 mg m^{-3} at 3 m, 16.55–9.00 mg m^{-3} at 5–25 m, and decreasing slightly at the 29–49 m layer. But at the oasis site, sand-dust concentration increased slightly with height; the regression line did not have an obvious turning point, and the change in the sand-dust concentration was small.

Viewed from the horizontal gradient, the sand-dust concentration decreased gradually from desert to oasis; the mean sand-dust concentration was 18.49 mg m^{-3} at the desert site, 12.58 mg m^{-3} at the oasis border site, and 6.02 mg m^{-3} at the oasis site. As the sand-dust concentration decreased with height at the desert and the edge of oasis and

Table 4 Regression equations between the sand-dust concentration and height for the three sites

	a	*b*	R^2
Oasis site	4.85	0.10	0.878
Edge of oasis site	30.17	−0.48	0.914
Desert site	58.44	−0.67	0.901

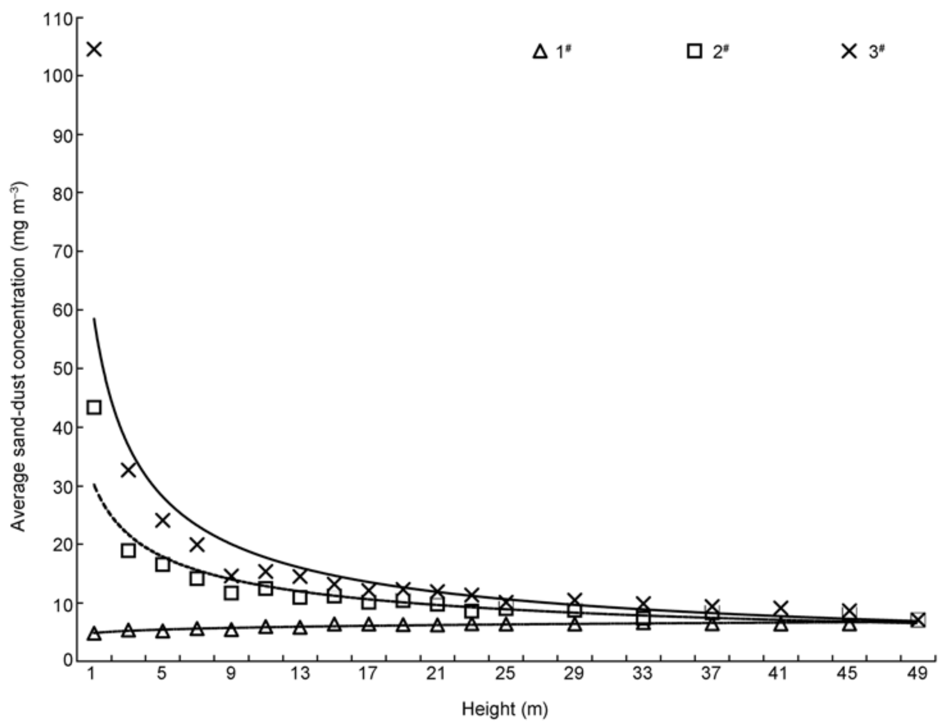

Figure 5 Height profiles of sand-dust concentration at 0–50 m layer for the three different land covers.

increased at the oasis, the three regression lines almost coincided at 41 m, indicating that the sand-dust concentration was influenced little by the underlying surface at 41 m and above.

3.4 The distribution features of sand-dust vertical deposition

Figure 6 shows that at the desert site, the sand-dust vertical deposition decreased with height, the change in sand-dust vertical deposition was relatively large at 0–25 m, but was smaller at higher layers. The variation of the sand-dust vertical deposition at the edge of oasis was similarly to that at the desert site, obviously decreasing at 0–25 m; but exhibited significant difference from the oasis site, although the peak range was still under 25 m; the maximum value was obtained at 9 m, and the regression line showed a single partial peak shape. Viewed from the horizontal gradient, the sand-dust vertical deposition decreased generally from desert to the oasis, especially at 1 m, where it decreased from 5.96 mg m^{-2} at the desert site to 3.53 mg m^{-2} at the edge of oasis and 2.34 mg m^{-2} at the oasis site. The sand-dust vertical deposition was almost identical at all three sites at 29 m and above, and the result shows that the motion of the sandstorm airflow and the stability of the aerosols were similar in this scope.

3.5 The horizontal distribution feature of total transported sand-dust flux in a year

For this study, we calculated the total amount of the sand-dust horizontal flux of all 19 sandstorm processions in 2006, which transported through a section 1m in width and 50 m in height. The results showed that the total amount of sand-dust horizontal flux transported through was 9169 kg at the desert site, 5318 kg at the edge of oasis site, and 2345 kg at the oasis site. Compared with the desert site, the edge of oasis site had 42.00% less sand-dust, and the oasis site had 74.40% less. The result of this study reflects the effects of wind-break forest and farmland shelter forest network on reducing sandstorms.

4 Discussion

The sand-dust horizontal flux and vertical deposition of sandstorms were closely related to the underlying conditions. Soil type, terrain features, vegetation characteristics and roughness influenced the characteristics of wind velocity height profiles, the emission from the ground and the deposit procession of sand-dust particles [17, 23]. Then will finally influence the vertical distribution of sand-dust horizontal flux and vertical deposition. The results of our study show that among the three different surfaces types in the Minqin region, the vertical distribution of sand-dust horizontal flux and the vertical deposition were significantly different, but many distinctive factors influence the surface characteristics, such as vegetation, soil type, terrain features. Here we mainly considered the integrated effects of these characteristics on the sandstorm; the weight of the effects of each factor on sandstorm will be the subject of future

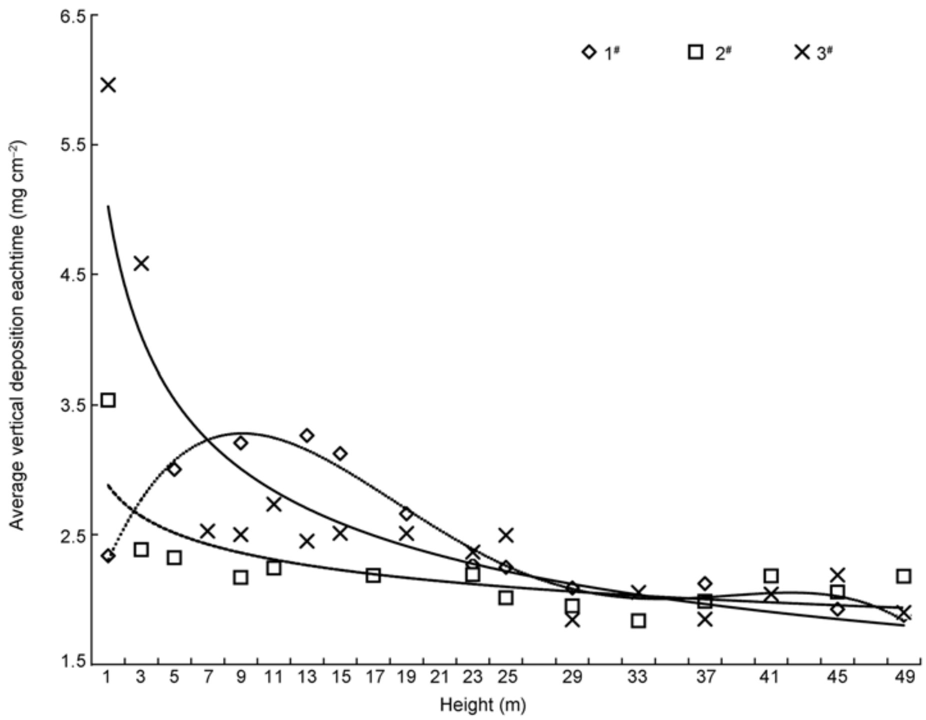

Figure 6 Height profiles of sand-dust vertical deposition at 0–50 m layer for the three different land covers.

investigations.

5 Conclusions

Having viewed over an 8.3 km horizontal gradient, from desert to the edge of oasis and from edge of oasis to oasis, with the three observation towers (50 m in height), we systematically analyzed the observational data of 19 sandstorm processions, and reached following conclusions. In the 0–50 m layer:

(1) The vertical distribution features of wind velocity during the sandstorms at each site agreed with the results of classic research that wind velocity increases by a power function with height. Viewed from the horizontal gradient, as the sandstorms progressed from desert to oasis, the wind velocity decreased dramatically. The effect of underlying surface conditions, especially vegetation, on wind velocity was quite obvious; the closer to the land surface the lower wind velocity.

(2) The intensity of sand-dust horizontal flux decreased with the increase in height at the desert and the edge of oasis sites, and the transportation of sand-dust horizontal flux was mainly concentrated in the lower layers, with a more pronounced trend as the height and coverage of vegetation increased. In contrast, at the oasis site the horizontal flux increased with height and was concentrated in the upper layers.

(3) The sand-dust concentration decreased with elevation at the desert and the edge of oasis sites, while it increased slightly with elevation at the oasis site. Viewed from the horizontal gradient, the sand-dust concentration decreased gradually from desert to oasis, following the increase of surface roughness. From 41 m and above, the concentrations at all three sites were almost the same, indicating that the sand-dust concentrations at these heights were influenced little by the underlying surface conditions.

(4) In the desert and at the edge of oasis, the sand-dust vertical deposition decreased with height, especially at the 0–25 m layer. Due to the influence of the farmland shelter forest network, the maximum deposition occurred at 9 m in the oasis site, which corresponds to the middle height of forest bands.

(5) Our analysis shows that the total amount of the sand-dust horizontal flux of all 19 sandstorm processions in 2006 through a section 1 m in width and 50 m in height was 9169 kg in the desert, 5318 kg at the edge of oasis, and 2345 kg at the oasis, respectively. The wind break forest had a significant effect on reducing the intensity of sand-dust storms.

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