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ORIGINAL ARTICLE

Experimental investigation of the height profile of sand-dust fluxes in the 0–50-m layer and the effects of vegetation on dust reduction

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Abstract The height profile of sand-dust flux at 0–2.0-m has been well studied. However, there have been very few experimental studies in the 0–50-m layer. In this study, the height profile of sand-dust flux at 0–50-m was observed by using three sandstorm observation towers (50 m in height) in 2006. The towers were located at three sites with different vegetation conditions (desert, edge of an oasis, and oasis) in the Minqin region, a typical desert-oasis area in China. At the same time, the features of the underlying vegetation were investigated. Results indicated that in the 0–50-m layer, sand-dust flux decreased rapidly as height rose at the desert and the edge of oasis sites, whereas it increased slightly as height rose in the oasis site. At the three sites sand-dust fluxes at each height increased with wind velocity, and there was a fairly good exponential relationship among them. In 2006, a total of 19 sandstorms occurred. The annual sand-dust that passed through a 1-m-wide, 50-m-high section was 9,169 kg at the desert site, 5,318 kg at the edge of oasis site, and 2,345 kg at the oasis site. Compared with the desert site, the annual sand flux was lower by 42% at the edge of oasis site and 74% at the oasis site. Vegetation had a significant effect in reducing the sand-dust flux.

Keywords Sandstorm · Sand-dust flux · Height profile · Minqin · Oasis

Introduction

Sand-dust flux is usually caused by sandstorms, which are some of the most catastrophic weather phenomena occurring in the arid and semiarid regions of the world. Sand-dust flux has profound effects on human settlements. It can carry away substantial amounts of soil in the source region, pollute the air and environment over a huge area, and deposit dust downwind (George et al. 2006; Zhao et al. 2004). As a result of this capacity to cause ecological harm, the occurrence, transportation, and sedimentation of sand-dust flux has attracted much attention worldwide.

Up to now, there have been many studies on sand flux. Field studies of erosion processes have shown that the surface features of the land cover play an important role in dust occurrence and transportation. Lin et al. (1999) showed that sand-dust events are closely related to vegetation cover, soil texture, and the proportion of bare land in the source areas. Shi and Zhao (2003), while presenting a system for forecasting sand-dust events, described soil type, vegetation characteristics, land-use type, and topsoil water content as the most important parameters in building a model of blown sand. Hupy (2004) investigated the influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate and quantified the importance of vegetation cover for reducing wind erosion in semi-arid landscapes. Nilson and Lehmkuhl (2001) concluded that dust flux and dust accumulation are part of a

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complex process and cannot be explained by simple climatic situation and environmental conditions.

The characteristics of the transportation and deposition of sand-dust flux at a height 2.0 m from the ground, especially within 0.2 m, are well documented, as is the fact that the vertical distribution of sand mass flux decreases exponentially with height (Williams 1964; Wu and Lin 1965; Dong et al. 2002; Liu and Dong 2004). Goossens et al. (2001) investigated the seasonal variation of dust flux over 15 months near Gronheim. Results showed that dust flux gradually increased from 30 μg m^{-2} s^{-1} in November 1998 to more than 100 μg m^{-2} s^{-1} in May 1999, and then dropped rapidly to about 30 μg m^{-2} s^{-1} at the end of the experiment.

Dust caused by sandstorms can be transported great distances, and its source area, transportation route, and affected area can be well monitored and predicted by satellite observation. High level dust deposits have been reported frequently in China (Derbyshire et al. 1998; Han et al. 2008), Korea and Japan (Zhang et al. 1997; Chung 1986; Byung-Gon and Soon-Ung 2001) and North America (Pye 1987; Prospero et al. 1989).

However, because ground-based observations are usually within a height of 2 m and satellite observations are usually concentrated on high altitude and large-scale features of sandstorms, there are very few observations of sand-dust flux in the 0–50-m layer. Chen and Fryrear (2002) collected dust samples in the 0–15.67-m layer during a sandstorm and found that the suspended dust in the flow decreased by a power function of height. According to their calculations, the total amount of dust in the 0–15.67-m layer was 84,960 kg km^{-1} h^{-1}. But this kind if observation is still rare.

In order to effectively reduce the frequency and damage caused by sandstorms, an understanding of the height profile in the 0–50-m layer is urgently needed. The objective of this study was to investigate the characteristics of sand-dust fluxes in the 0–50-m layer based on long-term tower observations. Meanwhile, the effects of different kinds of land cover on reducing dust will also be investigated.

Study area and experimental methods

Study area

The experiment was conducted at the Gansu Minqin National Studies Station for Desert Steppe Ecosystems (MSDSE), which belongs to the Chinese Ecosystem Research Network. The station is located in Minqin County, Gansu Province, China (102°59′05″E, 38°34′28″N, Fig. 1), an area positioned at the lower reaches of the Shiyang River Basin, a typical desert and oasis area in China. This area is surrounded by the Badain Jaran Desert in the west and north, and by the Tengger Desert in the east. The climate is arid. Mean annual precipitation is 113.6 mm, mean annual pan-evaporation is 2,643.3 mm, and the prevailing wind direction is northwest. The mean gale (velocity ≥17 ms^{-1}) occurrence is 26.3 days $year^{-1}$, and sand-dust events occur 25 days $year^{-1}$. 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. Because of this, the region has become one of the main sources of sand storms in China.

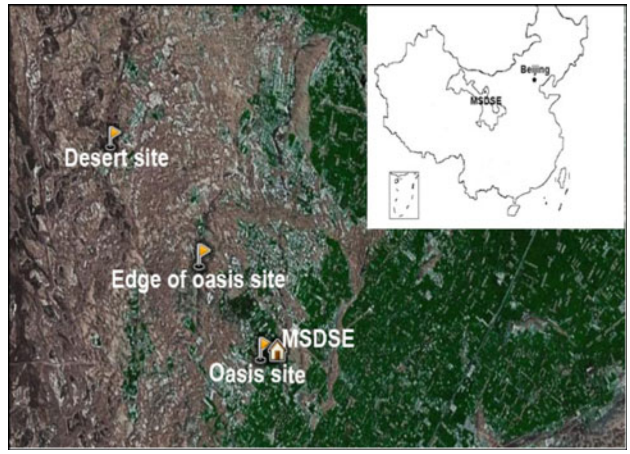

Fig. 1 Location of Minqin National Station for Desert Steppe Ecosystem Studies (MSDSE) and the three observation sites

Experimental methods

Three typical sites with different kinds of land cover were selected for this study: desert, edge of oasis, and oasis. Three observation towers (50 m in height) were constructed at these three sites along the main wind direction in Minqin area. The distance between the towers at the oasis and edge of oasis sites was 3.5 km; the distance between the towers at the edge of oasis and the desert sites was 4.8 km. At each tower, wind velocity and quantity of sand-dust flux were observed 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). Three-cup anemometers and horizontal sand-dust flux sampler systems (developed by Gansu Desert Control Research Institute, patent no.: 200610104691.5) were used for wind velocity and sand-dust flux measurements. Sand-dust fluxes were collected by using a sand-dust flux sampler (Fig. 2). The sampler had a 30-mm-diameter sampler nozzle designed to self-orient and always face into the wind, with an outlet in a bag sealed with a microporous membrane. The sampler automatically gathered sand-dust samples in the bag. The bag was replaced after every sandstorm event. If no sandstorm occurred over the course of a month, the bag was

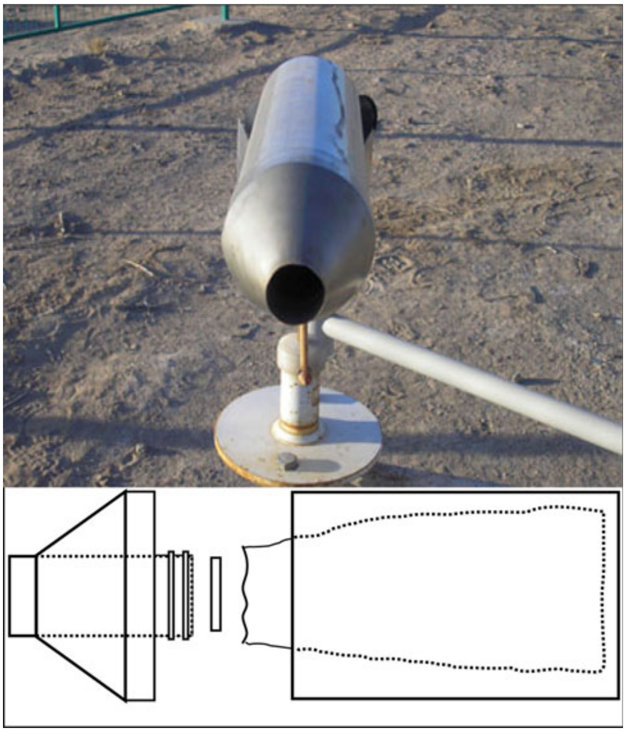

Fig. 2 Photograph and construction scheme of the sand-dust flux sampler

replaced at the end of the month. The sample period was from 1 January to 31 December 2006.

The collected samples were dried in an oven at 85°C for 24 h. The dried samples were weighed using an electronic scale with 0.0001-g precision. Mass flux of sand-dust at a given height was calculated with Eq. (1) (Chen and Fryrear 2002):

$$F_m(z) = Q(z)/TA \quad (1)$$

where $F_m(z)$ is the horizontal mass flux of sand-dust at height z, kg m^{-2} h^{-1}; $Q(z)$ is the total measured quantities of sand-dust we collected at height z, kg; T is the duration of sampling, *h*; A is the intake area of the samplers, m^2.

Description of land cover characteristics at the different sites

There were three observation sites with different kinds of land cover in this study: desert, edge of oasis, and oasis (Fig. 3).

At the desert site (right photograph in Fig. 3), the land types were shifting sand dunes 3–8 m in height 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. The ratio of shifting sand area was more than 20%. The dominant vegetation was a *Nitraria tangutorum* community with a mean height of 0.34 m, while the total coverage of vegetation was 6.25%.

Fig. 3 Photograph of the three observation towers and their corresponding land covers. *Left* oasis site; *middle* edge of oasis site; *right* desert site

The edge of oasis site (middle photo in Fig. 3) was the transition region from desert to oasis where stable and semi-stable sand dunes with a soil crust were the dominant land covers. The flat area between the dunes was covered by clay soil with a smooth, compact surface. In this site, the main vegetation types were a native *Nitraria tangutorum* community, a native *Calligonum mongolicum* community, a planted *Haloxylon* community, and some forbs. Their vegetation coverage was 14.0, 1.4, 4.1, and 0.7%, and their mean height was 0.44, 0.50, 0.95, and 0.35 m, respectively. This vegetation comprised the majority of the windbreak and sand-fixation forest in this area.

The oasis site (left photograph in Fig. 3), which was located downwind of the desert site and the edge of oasis site, is predominantly flat and consists mainly of farmland and a windbreak forest shelterbelt. The land is used primarily for farming (wheat, maize, alfalfa, and cotton) and tree nurseries. The arable land is tilled by farmers in spring (April) for seeding. The windbreak forest shelterbelt mainly consists of *poplar* and several other tree species. The height of the shelterbelt averages 18–20 m, and the clear bole height is 1–2 m.

Results and discussions

Height profiles of sand-dust flux at different land cover conditions

Figure 4 shows the height profiles of the average sand-dust flux for 19 sandstorm processes that occurred in 2006. It shows that sand-dust flux decreased by a power function

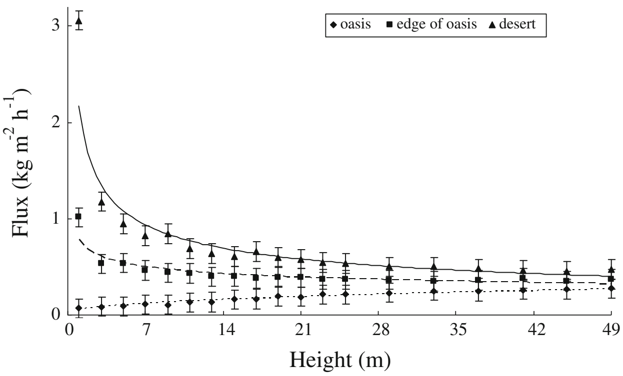

Fig. 4 Height profiles of sand-dust flux in the 0–50-m layer for the three different land covers. Data are the average of 19 sandstorm processes in 2006. The *bars* represent 1 SD

Table 1 Regression equations for the sand-dust flux and height for the three sites, where F is the flux of sand-dust (kg m^{-2} h^{-1}), z is the height from ground surface to 50 m, a and b are constants, and R^2 is the determination coefficient ($F = az^b$)

	a	b	R^2
Oasis site	0.0539	0.4113	0.94
Edge of oasis site	0.7804	−0.2273	0.85
Desert site	2.1751	−0.4334	0.93

with height at the desert and edge of oasis sites, which agrees with the results of Chen and Fryrear (2002). However, sand-dust flux increased slightly by a power function in the oasis site (Fig. 4). Regression equations for the sand-dust flux and height in the 0–50-m layer for the three sites are summarized in Table 1.

The differences in sand-dust flux among sites were larger in the layers closest to the ground, and they gradually decreased with height. At a height of 1 m, sand-dust flux was 3.06 kg m^{-2} h^{-1} at the desert site, 1.02 kg m^{-2} h^{-1} at the edge of oasis site, and 0.07 kg m^{-2} h^{-1} at the oasis site, respectively. The sand-dust flux at the desert site was 44 times that at the oasis site. At a height of 49 m, sand-dust flux was 0.47 kg m^{-2} h^{-1} at the desert site, 0.37 kg m^{-2} h^{-1} at the edge of oasis site, and 0.27 kg m^{-2} h^{-1} at the oasis site. The sand-dust mass flux at the desert site was only 1.7 times that at the oasis site.

An important explanation for this result is the difference in land cover at each site, especially the difference in land cover between the desert and the oasis sites. The land covers at the desert and at the edge of oasis sites were similar, characterized by dunes and bare soil, and there were no high trees or windbreak shelterbelts. Therefore, the height profiles of sand-dust flux at these two sites were similar. At the oasis site, because there was farmland and a windbreak shelterbelt of tall trees, sand-dust flux near the ground was very small. Because there was a large difference in vegetation cover between the desert and the oasis sites, the height profile patterns of these two sites were almost opposite to each other.

These results clearly indicate that vegetation, particularly the windbreak shelterbelt, plays an important role in reducing sand-dust flux, especially in the near-ground layer. However, the effect of land cover on sand-dust flux gradually decreases as height increases. There was still a difference at a height of 50 m, but it was much smaller than that at the near-ground level.

Effects of wind velocity on sand-dust flux

In order to analyze the effect of wind velocity on sand-dust flux under different land cover conditions, we selected three sandstorm processes that occurred on 12 February, 2 May, and 23 May. Table 2 summarizes the wind velocities of each sandstorm and the corresponding regression equation for sand-dust flux and height at each site.

The height profiles during these three sandstorms are shown in Fig. 5 and generally agrees with the annual average (Fig. 4). Results showed that although wind velocity significantly affected the sand-dust transportation capacity of the atmosphere, it did not change the height profile. It only had some influence on the shape of the regression line.

By using the results from Table 2 and Fig. 5, we calculated the amount of sand-dust transported through a 1-m-wide, 10-m-high area at heights of 0–10, 10–20, 20–30, 30–40, and 40–50 m. The following equation was used for the calculation:

$$Q = \int_{\mathrm{bottom}H}^{\mathrm{top}H} y\,dx \qquad (2)$$

where Q is the amount of sand-dust transported through a 1-m-wide, 10-m-high area, kg h^{-1}; x is height, m; y is the regression equation for each site in Table 2.

Based on these calculations, the ratio of the sand-dust passing through any given layer to the total amount in the 0–50-m layer is shown in Fig. 6.

It was shown that there was very little difference in the distribution pattern of the relative percent of sand-dust that passed through under different wind velocity conditions. However, the difference between sites was large. At the desert site and the edge of oasis site, the percentage of sand-dust that passed through decreased with height. At the oasis site, however, the percentage of sand-dust passing through increased with height. For example, in the 0–10-m layer, the percentage of sand-dust that passed through was 7–8, 20–40, and 35–55% for the oasis site, the edge of oasis site, and the desert site, respectively. However, the corresponding percentages were 30, 12–20, and 10–12% in

Table 2 Wind velocity of each sandstorm and the regression equations for the sand-dust flux and height during three dust storm processes

Date	Wind velocity (m/s)	Regression equations		
		Oasis site	Edge of oasis site	Desert site
12 February	Max. 12.4	$y = 0.0601x^{0.5522}$	$y = 0.3986x^{-0.0334}$	$y = 1.0235x^{-0.2994}$
	Ave. 7.0	$R^2 = 0.9638$	$R^2 = 0.8040$	$R^2 = 0.7430$
2 May	Max. 19.5	$y = 0.1432x^{0.5489}$	$y = 3.1249x^{-0.4319}$	$y = 7.291x^{-0.6368}$
	Ave. 7.4	$R^2 = 0.9700$	$R^2 = 0.9507$	$R^2 = 0.9696$
23 May	Max. 13	$y = 0.1176x^{0.6038}$	$y = 1.6168x^{-0.2157}$	$y = 3.9875x^{-0.4582}$
	Ave. 7.1	$R^2 = 0.9567$	$R^2 = 0.8787$	$R^2 = 0.8909$

Wind velocity was measured at 10 m height (measured by the weather station of Gansu Minqin National Studies Station for Desert Steppe Ecosystems)

the 40–50-m layer. This result agrees with the annual average (Fig. 4). Therefore, it was concluded that the transportation of sand-dust at the desert and edge of oasis sites was mainly concentrated in the near-ground layer. However, it was concentrated in the upper layer at the oasis site. It was also shown that, at the desert site and the edge of oasis site, as wind velocity increased, the percentage of passed sand-dust in the near ground layer also increased. For example, at edge of oasis site, when mean wind velocity was 7.1 m s^{-1} (22 May), the percentage of sand-dust passing through was 21.10 and 19.40% in the 0–10- and 40–50-m layers, respectively. The corresponding values were 40.08 and 11.91% when the mean wind velocity was 7.4 m s^{-1} (2 May). However, wind velocity had little influence on the relative percentage of sand-dust at the oasis site.

Relationship between sand-dust flux and wind velocity at different heights

Based on the tower observations, we found that sand-dust flux was fairly well correlated with wind velocity at different heights. To show it more clearly, data measured at 1, 9, 17, 25, 33, 41, and 49 m were analyzed and are shown in Fig. 7.

It was shown that sand-dust fluxes increased with the enhancement of wind velocity, and there was a correlative exponential relationship between them. Effect of wind velocity on the change rate of sand-dust flux decreased gradually with height. This was especially obvious at a height of 1 m at the desert and the edge of oasis sites, where the sand-dust flux increased dramatically with increasing wind velocity and the curve was the steepest. At heights of 9, 17, 25, 33, 41, and 49 m, this response was much slower. The height profile of sand-dust flux in Fig. 5 also supports this finding. This point was important for the study and application of sand-dust movement, because previous observations have been limited mostly to a height of 2 m.

Figure 7 shows that the distribution of these curves at the oasis site was fairly uniform. The reason may be that at this site sources of sand-dust were limited. If there were abundant sources of sand-dust, flux intensity would be expected to increase.

Total transported sand-dust in a year

By using the equation below, the total amount of sand-dust transported through a 1-m-wide, 50-m-high section (Y, kg m^{-2} y^{-1}) was calculated:

$$Y = \int_0^{50} aydx \tag{3}$$

x is the height in m, a is the storms occurrence time in 2006, and y is the regression equation for the sand-dust flux and height in Table 1. Results showed that for a 1-m-wide, 50-m-high section, the total amount of sand-dust transported through was 9,169 kg in the desert site, 5,318 kg in the edge of oasis site, and 2,345 kg at the oasis site.

These results indicated that large amounts of sand-dust could be transported by the wind in 1 year. Though only 1 year of data is represented here, because the wind velocity and times of the sandstorms were near the long-term average, this result should represent the average yearly level of transported sand-dust. The results also indicated that the differences between sites were very significant. Compared with the desert site, the edge of oasis site had 42.0% less sand-dust, and the oasis site had 74.4% less. To the best of our knowledge, these are the first results based on field experiments, in which case they should be very important for future study and prevention of sandstorms.

Influence of vegetation conditions on the characteristics of sand-dust flux

In 2006, 19 sandstorms occurred during the year. During each sandstorm, although the meteorological conditions,

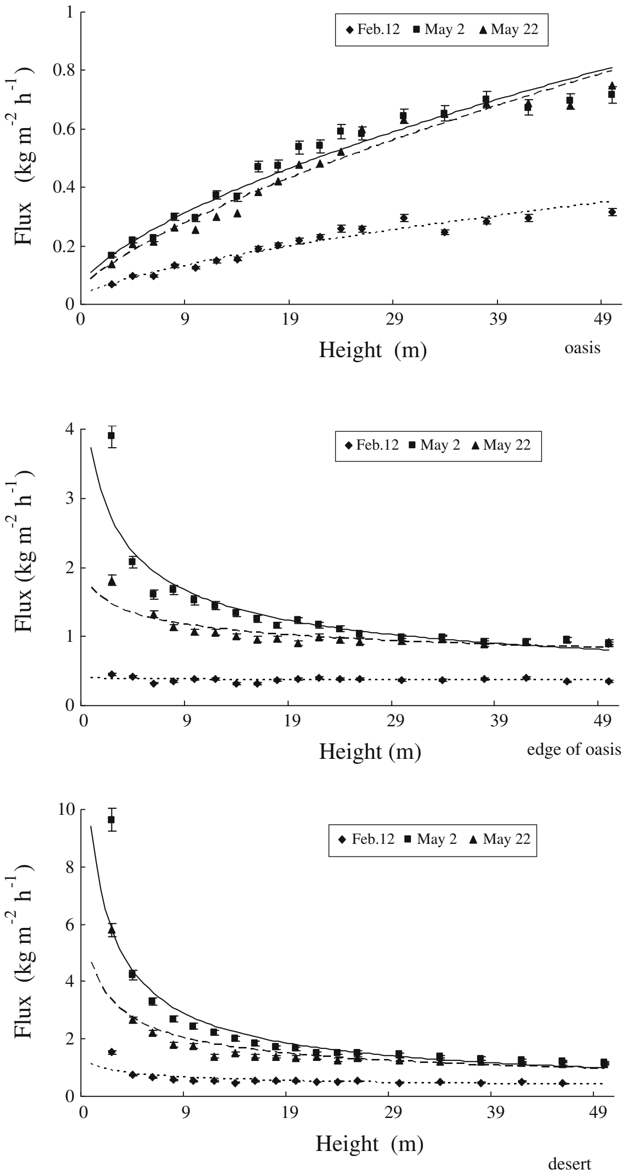

Fig. 5 Height profile of sand-dust fluxes during three sandstorms in 2006 with different wind velocities. The *bars* represent 1 SD. Average wind velocity was 7.0, 7.4, and 7.1 m s^{-1} on 12 February, 2 May, and 23 May, respectively

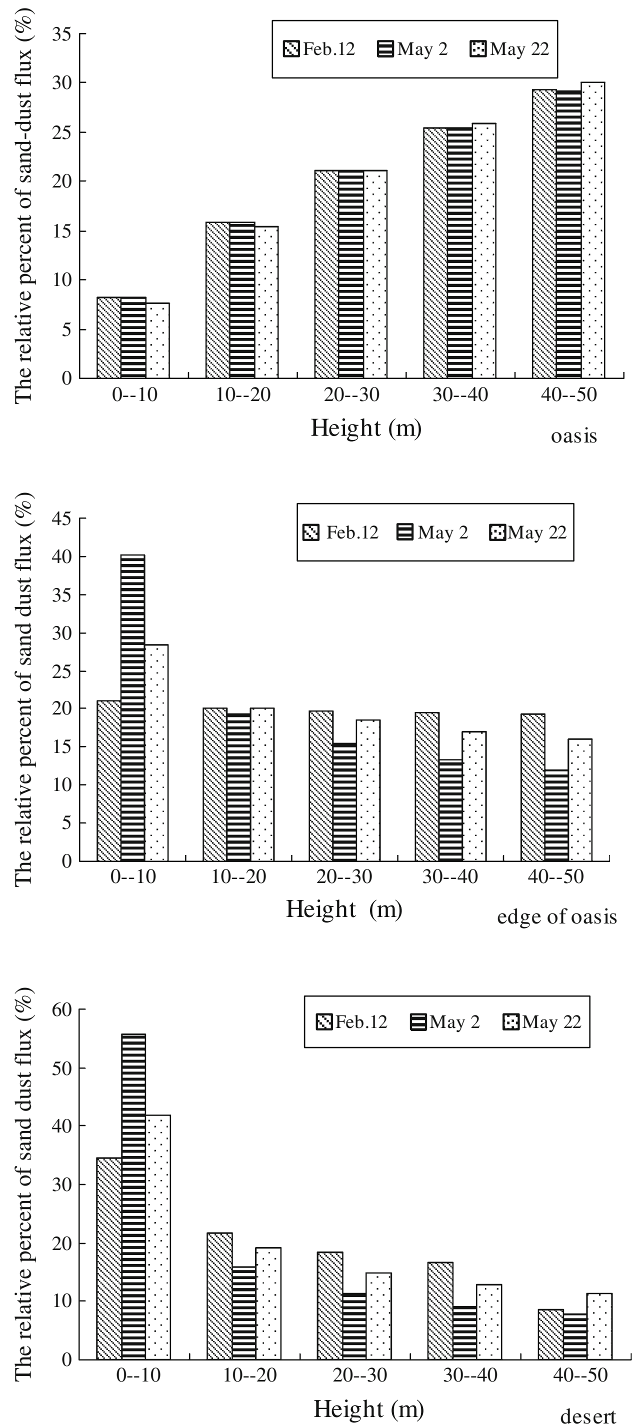

Fig. 6 Ratio of sand-dust passing through a given layer (10 m thick) to the total amount passing through a 0–50-m layer. Average wind velocity was 7.0, 7.4, and 7.1 m s^{-1} on 12 February, 2 May, and 23 May, respectively

such as wind velocity, temperature, and air pressure, were obviously very different, the difference in the height profiles was small. Therefore, it could be concluded that the differing meteorological conditions present in different sandstorm processes had little influence on the height profile of the sand-dust flux.

As discussed before, the difference in height profiles at the three sites was remarkable. Figure 8a shows a comparison of sand-dust flux for the three sites at the same height. It was clearly shown that the amount of flux in the three sites could be ranked as: the desert > the edge of oasis > the oasis. The ratio of sand-dust flux between the oasis site and the desert site, the oasis site and the edge of oasis site, and the edge of oasis site and the desert site is shown in Fig. 8b. Generally, the ratio gradually decreased

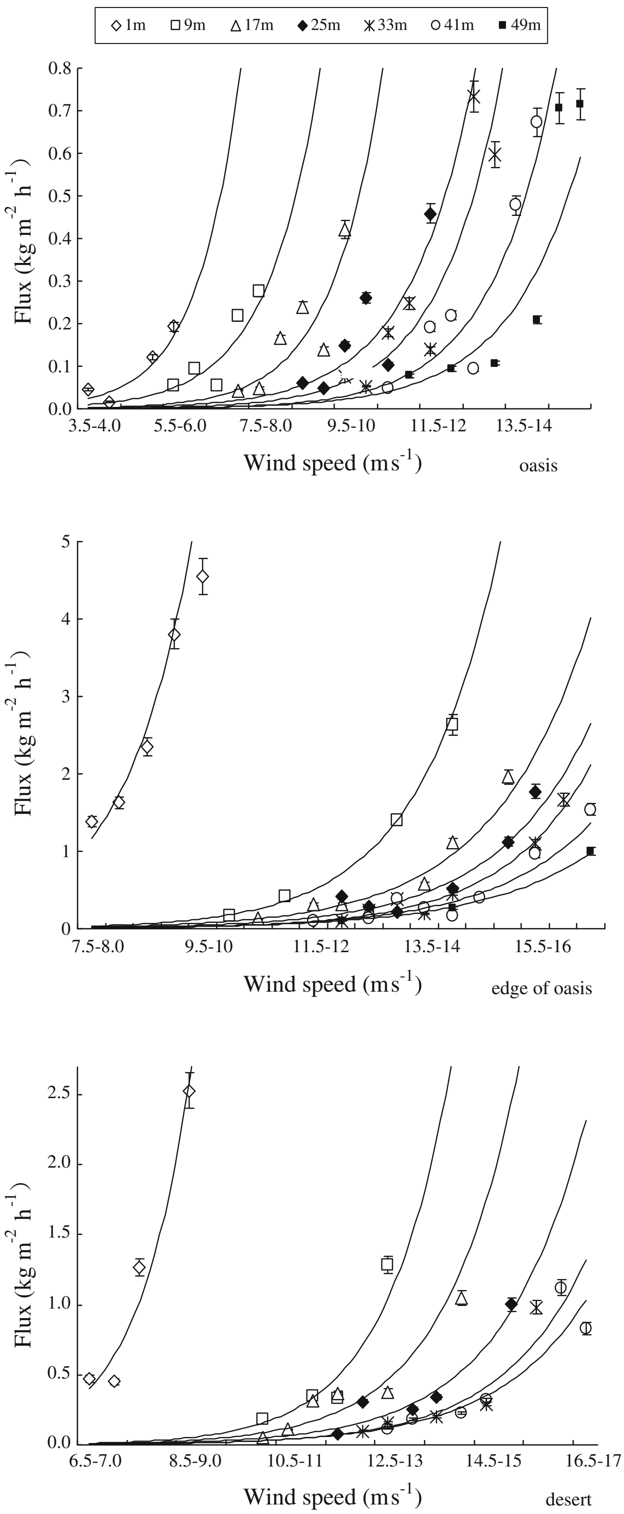

Fig. 7 Relationship between sand-dust flux and wind velocity at different heights

with height. For example, the ratio between the oasis site and the desert site gradually decreased from 98% at 1 m to 41% at 49 m.

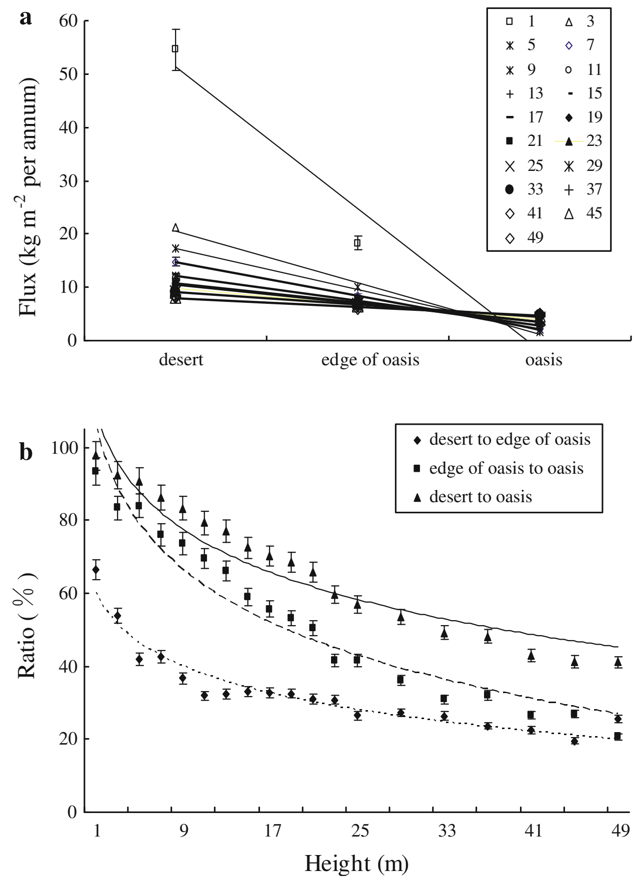

Fig. 8 Comparison of sand-dust flux at different heights and different sites. **a** Changes in annual fluxes at three sites. **b** Ratio of sand-dust flux of the oasis site to the desert site, the oasis site to the edge of oasis site, and the edge of oasis site to the desert site

These differences were caused by the difference in land cover, especially the difference in vegetation (Bilbro and Fryrear 1994). In this study, vegetation coverage and mean height were 7.4% and 0.31 m at the desert site, 12.1% and 0.52 m at the edge of oasis site, and 53.0% and 1.08 m at the oasis site. Our results indicated that the influence of land cover on sand-dust flux decreased linearly with height, and most of the sand-dust that originated in the desert area could travel only a short distance. This was especially true in the near-ground layer. For example, at the desert site only 2.23% of the sand-dust at a height of 1 m and 7.66% of that at 3 m could be transported to the oasis site. Vegetation could significantly affect the height profile in the 0–50-m layer.

Conclusions

In this study, the following conclusions were reached. In the 0–50-m layer, sand-dust flux decreased by a power function with height at the desert and the edge of oasis sites, while it increased slightly with height in the oasis site. Transportation of sand-dust at the desert and the edge of oasis sites was mainly concentrated in the near-ground layers; at the oasis site, however, the transportation of sand-dust was mainly concentrated in the upper layer.

Sand-dust flux increased with increases in wind velocity, and there was a fairly good exponential relationship between them. However, though wind velocity had a significant affect on the sand-dust transportation capacity, it did not change the pattern of the height profile of sand-dust flux.

Large amounts of sand-dust can be carried away by the wind in 1 year. The total annual amount of sand-dust flux transported through a 1-m-wide, 50-m-high section was 9,169 kg in the desert site, 5,318 kg in the edge of oasis site, and 2,345 kg in the oasis site, respectively.

Vegetation, especially the windbreak shelterbelt, had an important role in reducing sand-dust flux. Its effect was stronger at levels near the ground and gradually decreased with an increase in height. Although it was much smaller, its effect on sand-dust reduction could still be observed at a height of 50 m.

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