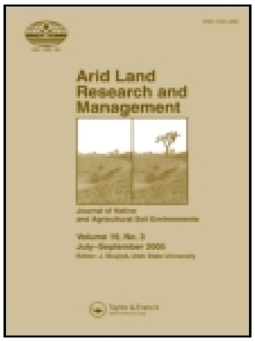

Arid Land Research and Management

ISSN: 1532-4982 (Print) 1532-4990 (Online) Journal homepage: http://www.tandfonline.com/loi/uasr20

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To cite this article: Lishuai Xu, Guijin Mu, Xiao Ren, Lin Sun, Yongchong Lin & Dejun Wan (2016) Spatial distribution of dust deposition during dust storms in Cele Oasis, on the southern margin of the Tarim Basin, Arid Land Research and Management, 30:1, 25-36

To link to this article: http://dx.doi.org/10.1080/15324982.2015.1053630

Published online: 08 Feb 2016.

ARID LAND RESEARCH AND MANAGEMENT
2016, VOL. 30, NO. 1, 25–36
http://dx.doi.org/10.1080/15324982.2015.1053630

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Spatial distribution of dust deposition during dust storms in Cele Oasis, on the southern margin of the Tarim Basin

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ABSTRACT

The Cele Oasis, located in the southern margin of the Tarim Basin and in the northern foot plain of the Kunlun Mountains, has suffered serious dust storm disasters. To identify the spatial distribution of dust deposition in the oasis, dust samples were collected at eight sites using passive dry samplers, and dust deposition rates and particle sizes were measured. Results indicated that with wind blowing in a single direction, dust deposition rates increased windward from the outside of the oasis to the margin, and decreased gradually leeward; with wind blowing in a single directions, the windward margins had higher deposition rates than the other regions. Fine particles of $<70\,\mu m$ were deposited preferentially inside the oasis, where the mean grain size is larger than outside the oasis. The oasis protection system at the margin had a mechanical obstruction effect extending about 2 km from the oasis edge to its exterior, enhancing dust deposition through reducing wind speed. The wind speed recovery, due to the decrease in roughness on the leeward side of the oasis, suppressed deposition of fine particles, resulting in minimum deposition rates and larger mean grain sizes on that side. Although a small amount of harmful dust (such as $PM_{2.5}$ and PM_{10}) was deposited during the dust storms, these particles are thought remain in the environment for long periods and prove harmful to human health.

ARTICLE HISTORY
Received 14 September 2014
Accepted 18 May 2015

KEYWORDS
Dust deposition; oasis; particle size; Tarim Basin

Introduction

In arid northwestern China, oases represent social and economic activity centers, and effective protections systems have been established to protect them from wind and sand. However, the floating dust during dust storms invading the oasis can still affect the oasis ecosystems in several ways, such as causing damage to human health (Wang et al. 2010; Wang et al. 2013) and crops (Li et al. 2012; Zia-Khan et al. 2015), and depositing of fine particles and nutrients in the soil (Wen, Guan, and Cui 2002). A preliminary observation in the Tarim Basin revealed that dustfall in the Cele Oasis was three times higher compared to that in the adjacent Gobi region (Liu et al. 1994). However, little is known about dust entry into the oasis and the spatial distribution of its deposition.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uasr.

Oasis protection systems play an important role in maintaining the stability and sustainability of oases, attracting international attentions from the scientific communities and the public. The systems not only prevent invasion by wind-blown sand, but can also significantly reduce near-ground wind velocity (Zhao et al. 2008; Zhao et al. 2011a; Mao et al. 2014), thus affecting the transportation and deposition of suspended dust (Li et al. 2006; Zhao et al. 2011b). Previous research with limited data proposed that the rough surfaces of oases enhance dust deposition by reducing wind speed (Liu et al. 1994; Wan, Mu, and Lei 2009; Wan et al. 2013). However, an understanding of the spatial distribution of dust deposition and the effect of oasis protection systems on deposition is still lacking.

The Tarim Basin has the highest frequency of dust storms in China (>30 days per year) where dust weather events (i.e., dust haze and blowing dust) occur on more than 200 days per year, with the maximum exceeding 260 days (Qian, Quan, and Shi 2002). The Taklimakan Desert, in the center of the basin, has a significant dust emission rate and is the major source of dust of Asia (Sun, Zhang, and Liu 2001; Xuan and Sokolik 2002; Gong et al. 2003; Liu et al. 2004). During dust events, fine particles can reach altitudes >5000 m, transported over long distances by westerly winds. These particles can settle out in downwind regions, but most of them are deposited near the source region. Consequently, the Taklimakan Desert is not only a dust source but also a deposition region (Zhang et al. 1998; Sun, Zhang, and Liu 2001). The high frequency of dust events causes the southern margin of the Tarim Basin to have a very large amount of dust deposition. As an example, annual dust deposition in the Cele Oasis can reach 2646.2 $g\,m^{-2}$ (Wan et al. 2013).

Previous studies suggested that the rough surface of an oasis induces inhomogeneous distribution of dust deposition during dust storms. The purpose of this study is to observe the spatial distribution of dust deposition in the Cele Oasis and to explain the spatial changes with the deposition rate and the grain size during dust storms.

Material and methods

Study area

The Cele Oasis (80°43′E—80°53′E, 36°57′N–37°05′N) is located in the southern margin of the Taklimakan Desert, in the northern foot plain of the Kunlun Mountains. It stretches about 14 km east-west with an area of about 157 km^2. The climate is extremely arid, with a mean annual precipitation of 35 mm and an annual potential evaporation of 2,600 mm (Ma et al. 2009). The annual average temperature is 11.9°C, with maximum and minimum temperatures of 41.9°C and −23.9°C, respectively (Guo et al. 2008). According to meteorological data from 2005–06 from Cele Station, the dominant wind is from the west, with an occurrence frequency of 62.3–76.23%, followed by north-northwest winds, with an occurrence of 17.8%. Westerly sand-driving winds (>6 $m\,s^{-1}$) accounted for 94.6% of the total (Xing et al. 2008; Wan et al. 2013). In 1960–2007, the average annual number of dusty and dust storm days were 142.4 and 21.2, respectively. Dust events occurred predominantly in the spring and summer, with dust storms in March-September accounting for approximately 90% of the annual total, and correlating well with the monthly percentage of dust-raising wind (Wan et al. 2013). Because of serious sand and dust invasion, Cele County has been relocated eastward three times (Tian and Song 1997).

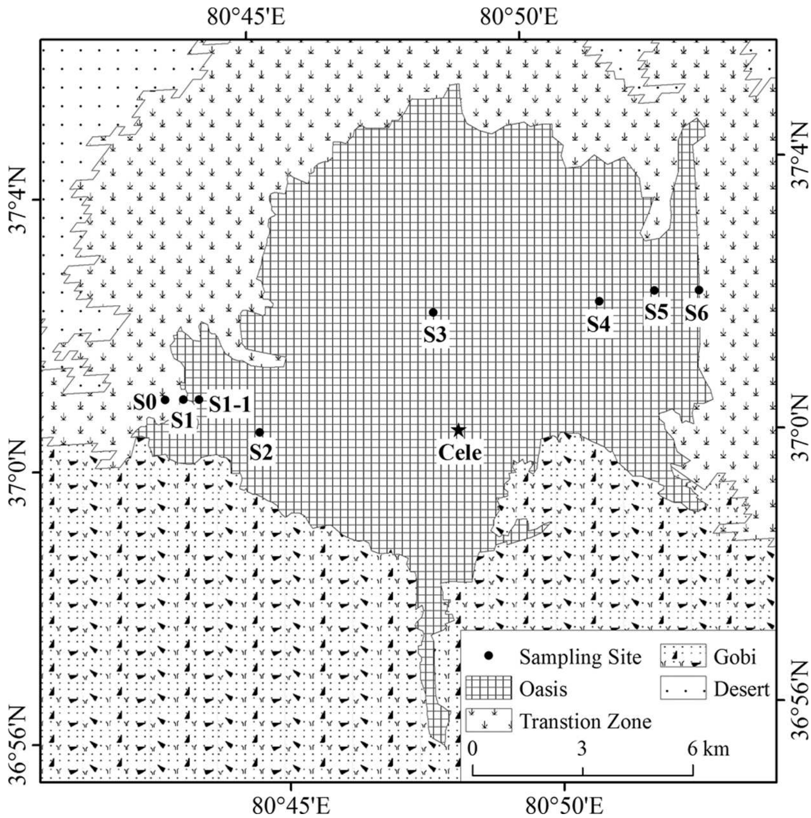

Figure 1. Location of the eight sampling sites in Cele Oasis.

Sampling sites

To investigate the spatial distribution of dust deposition in the Cele Oasis, we established eight sampling sites (Figure 1). Site 0 (S0) was located in the transition zone, about 100 m from the western boundary of the oasis. At S0 (Figure 2a), the dominant plant species were

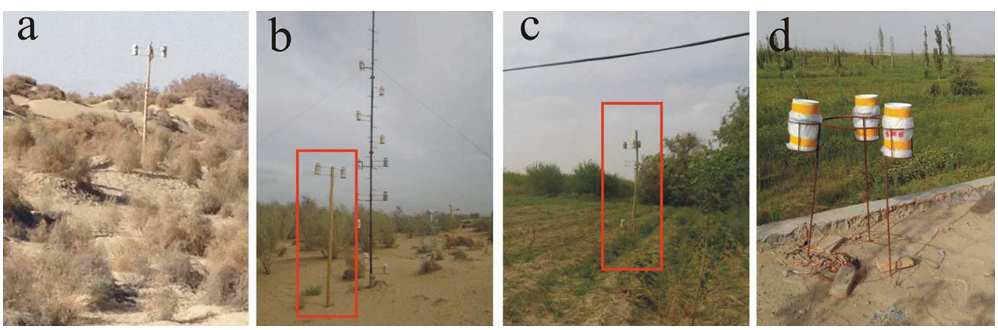

Figure 2. Landscapes of four sampling sites and their dust traps. (a) and (b) correspond to S0 and S1, located in the west transitional zone of the oasis. (c) corresponds to S1-1, located in the west shelterbelt of the oasis. In (b) and (c), the setups denoted by rectangles were used for sampling. (d) corresponds to S6, located in the east, outside of the oasis, and the trap was fixed to a roof about 4 m above the ground.

Alhagi sparsifolia Shap and *Karelinia caspia* (Pall.) Less., with an average heights of 0.5–1.2 m and a vegetation coverage of more than 40% (Yang et al. 2012; Mao et al. 2014). Site 1 (S1) was located about 35 m away from the oasis western boundary, in an area covered by *A. sparsifolia* and *Calligonum caput-medusae* Schrenk (Figure 2b). Site 1–1 (S1-1) was located in the shelterbelt (Figure 2c), Site 2 (S2) about 2 km away from the oasis western edge, and Site 3 (S3) in the oasis center, about 7 km from the western edge. Site 4 (S4) was located on the eastern margin of the oasis, about 12 km from the oasis' western edge. Sites 5 and 6 (S5 and S6) were located in newly reclaimed farmland and farmlands that have almost been abandoned because of salinization, with sparse vegetation coverage. S5 represented the eastern margin of the oasis, while S6 was outside of the oasis (Figure 2d).

Sampling and analytical procedures

The samplers were plastic cylinder pipes (15.5 cm in diameter and 30 cm long), with plastic bags attached to the outside of each container (Figure 2), similar to passive traps used by other researchers (Pye 1992; McGowan, Sturman, and Owens 1996; Sun, Liu, and Lei 2000; Singer et al. 2003; Li et al. 2008). The samplers were placed about 4 m above ground to avoid the influence of local dust. To collect enough dust, we set two samplers at each site. In April 2013, we collected dust samples after the strong wind during two dust storms had died out (DS1 in April 3–5 and DS2 in April 16–17). The samples were carefully transferred from the traps to bags using a small brush and stored in zip lock bags.

In the laboratory, we removed plant branches and leaves, and weighed the samples on an electric balance with a precision of 0.1 mg to calculate the deposition rates ($g\,m^{-2}$) at each site from each dust storm. Finally, the samples were analyzed for grain size using a Malvern Mastersizer 2000 without any pretreatment. The measurement range was 0.02–2000 μm, split into 100 size classes. Grain size parameters were determined using the Folk and Ward graphical measures in GRADISTAT (Blott and Pye 2001). Wind speeds and directions were provided by the Cele National Field Observation and Research Station, Chinese Academy of Sciences (Cele Station). The wind speed was recorded every 2 min at a height of 10 m, while maximum wind speeds were recorded hourly.

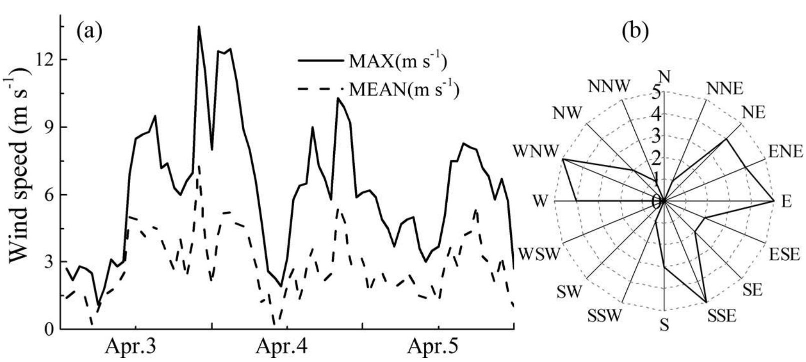

Figure 3. (a) Wind speeds and (b) frequency of sand-driving wind directions on April 3–5. Solid and dashed lines in (a) represent the maximum and 2-min average wind speed, respectively.

Results

Wind speed and direction

Figure 3 presents the changes in wind speed and frequency of sand-driving wind directions during DS1, a light dust storm that lasted for about 60 h. The wind speed reached a maximum of 13.5 m s^{-1}, and visibility was less than 1000 m. The storm involved three stages of wind speed and direction: initially, the sand-driving wind blow from the west at a relatively high speed, later slowing and changing to an easterly wind, and finishing at minimum speed from the south. Because of changes in wind direction, the dust plumes invaded the oasis from the west, east, and south. Figure 4 shows the changes in wind speed and the frequency of sand-driving wind direction during DS2, a strong dust storm, with a maximum wind speed of 20.5 m s^{-1}. The storm lasted for about 20 h, with visibility less than 150 m. Given the westerly wind, the dust plume invaded the oasis from the west.

Spatial distribution of dust deposition rates

The spatial distribution of deposition differed between the two dust storms (Figure 5). In DS1, the deposition rates increased from outside the oasis to the margin (S0–S2, S6–S4) and had a decreasing trend from the western margin to eastern margin. The deposition rates ranged from 16.33–49.52 g m^{-2}, with a mean of 29.69 g m^{-2}. S2 had the largest deposition rate, followed by S4, meaning that the windward margin had higher deposition rates. The center of the oasis had a higher deposition rate than the outside, but lower than for S2 and S4. DS2 had highly variable deposition rates, ranging 15.14–190.71 g m^{-2}, with a mean of 66.24 g m^{-2}. The deposition rate was highest at S1-1, decreasing gradually downwind. From S0 to S1-1, the deposition rates had a sharp increase and reached the maximum, gradually decreasing toward the leeward side of the oasis. The inner oasis had small fluctuations in deposition rates, and the leeward side had the lowest rates. In summary, the deposition rates increased windward from outside the oasis toward the margin, and decreased from the margin to the leeward side.

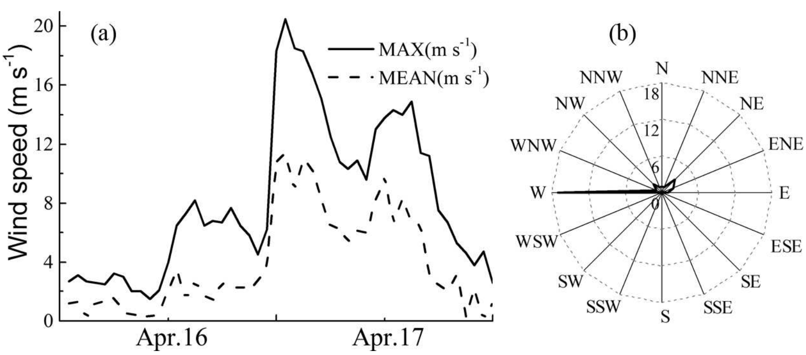

Figure 4. (a) Wind speeds and (b) frequency of sand-driving wind directions on April 16–17. Solid and dashed lines in (a) represent the maximum and 2-min average wind speed, respectively.

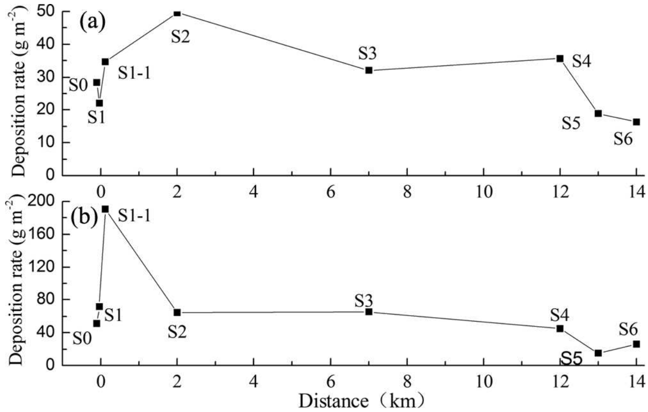

Figure 5. Spatial distribution of deposition rates for the two dust storms at eight oasis sites: DS1 (a) and DS2 (b). S0 and S1 were located in the west-outside the oasis; S1-1, S2, S3, and S4 were located inside the oasis; S5 and S6 were located on the east side.

Particle size distribution and characteristics

The mean grain size was smaller inside the oasis than outside and edges of the oasis (Figure 6). The mean grain size was largest for S0 and S1, slightly smaller for S5 and S6, and smallest for S3. During the two dust storms, the sorting coefficient, skewness, and kurtosis ranged from 0.50–0.68, 0.0–0.05, and 0.93–0.977, respectively. The dust was then moderately well sorted with a nearly symmetrical skewness and mesokurtic. During moderate windstorms, particles with diameters <20 μm can stay in suspension for long periods of time, while particles in the range of 20–70 μm are transported by suspension for short periods, and deposited when the wind speed decreases. Coarser particles (70–100 μm) are transported by modified saltation and deposited near the source region (Pye 1987). After DS1, there were no particles <20 μm on the west or east side of oasis (S0, S1, S5, and S6), and the inner oasis had more particles in the 20–70 μm range than the outside (Table 1). However, the content of particles in

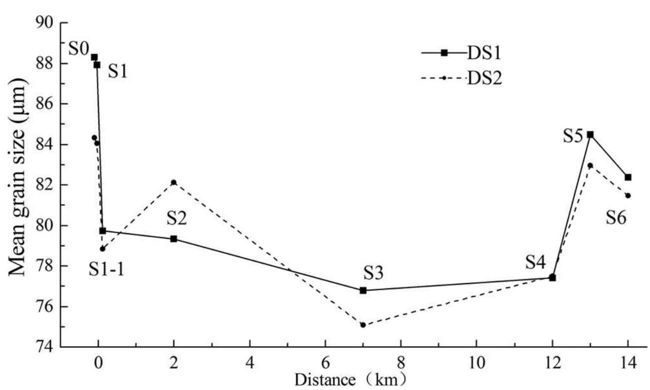

Figure 6. Spatial distribution of mean grain size for the two dust storms at eight oasis sites: (S0–S6), representing different locations in the oasis. The solid and dashed lines represent the mean grain sizes for DS1 (April 3–5, 2013) and, DS2 (April 16–17, 2013), respectively.

Table 1. Comparison of particle sizes between the two dust storms.

	<20 μm (vol.%)		20–70 μm (vol.%)		70–100 μm (vol.%)		>100 μm (vol.%)	
Sites	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2
S0	0.00	0.00	38.62	43.63	36.21	35.31	25.16	21.06
S1	0.00	0.00	39.02	43.98	36.20	35.26	24.79	20.76
S1-1	1.73	1.88	47.49	48.52	29.77	32.51	21.01	17.09
S2	1.80	1.86	47.91	44.66	27.27	30.71	23.02	22.78
S3	2.01	1.91	49.96	52.21	26.91	25.98	21.12	19.90
S4	2.12	1.87	49.09	49.55	27.17	27.02	21.63	21.56
S5	0.00	1.64	43.85	43.77	32.57	31.68	23.59	22.90
S6	0.00	2.07	46.83	45.05	30.35	31.17	22.82	21.70

the range 70–100 μm and >100 μm was highest in the west outside the oasis, and the minimum occurred inside. After DS2, no particles <20 μm were found on the west side of the oasis either, while the interior and the leeward regions had about 2% of the particles <20 μm. The inner oasis had a higher content of particles in the 20–70 μm range than the outer region, and a lower content of particles in the range 70–100 μm and >100 μm (Table 1). The oasis is thus advantageous for fine particle deposition. During the two dust storms, the dust particle sizes clustered between 40 and 140 μm, and the particle size distribution curves had unimodal and bimodal distributions (Figure 7). For DS1, the particle size distribution curves were unimodal outside the oasis, changing to bimodal inside the oasis. For DS2, the windward side of the oasis had unimodal curves, whereas the interior and leeward areas had bimodal particle size distribution curves.

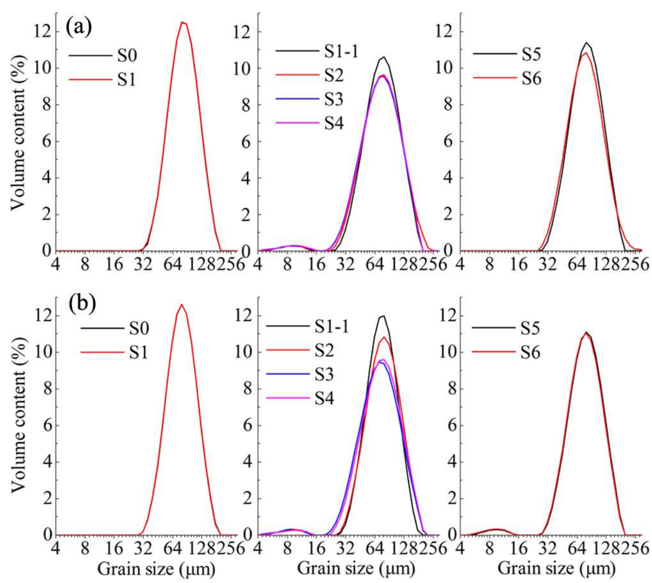

Figure 7. Curves of particle size distribution for the two dust storms: DS1 (a) and DS2 (b). S0 and S1 were located in the western outer region of the oasis; S1-1, S2, S3, and S4 were located inside the oasis; S5 and S6 were located on the east side.

Discussion

Inhomogeneous distribution of dust deposition in oasis

Oasis protection system can reduce wind speed and sand transportation rate through the rough surface (Zhao et al. 2008; Mao et al. 2014), and the vertical distributions of the horizontal sand-dust flux and dust deposition in the oasis were found to be different from those in the desert and on the edge of the oasis (Zhao et al. 2011a; Zhao et al. 2011b), indicating that the rough surface of the oasis influence the spatial distribution of dust deposition inside and outside the oasis. Our results indicate that with wind blowing in a single direction, the deposition rates increased windward from outside of the oasis to the inner margin and decreased gradually toward the leeward side, similar to results published earlier (Wan, Mu, and Lei 2009; Wan et al. 2013). However, the highest deposition rates appeared in the inner margin of the oasis rather than outside. Therefore, we conclude that the oasis protection system on the windward margin had a mechanical obstruction effect, enhancing dust deposition during the storms by reducing the wind speed. Tsoar and Pye (1987) pointed out that a large change in surface roughness leads to a rapid increase in net deposition to the roughness boundary, with the deposition rate decreasing toward the inside of the rough region. Additionally, observation of sand deposition around the shelterbelt revealed that the main deposition of sand occurred in a narrow zone limited to 20 m in front and about 20 m inside the belt, with most of the deposition occurring 10 m inwards (Mohammed, Stigter, and Adam 1996). These aforementioned observation results confirm the reliability of our results.

However, variation in the direction of sand-driving winds ten to change the spatial distribution of dust deposition. During DS1, the wind blow form three directions, and the western and eastern margins of the oasis (S2 and S4) had higher deposition rates than others sites because of these changes in wind direction. The first stage of the storm saw the highest wind speed and a westerly direction, so the dust plumes invaded the oasis from the west, with the mechanical obstruction effect from the oasis protection system enhancing dust deposition on the western margin. During the second stage, the wind showed a decreased in speed and changed to an easterly direction, resulting in a high dust deposition rate on the eastern margin. Finally, the wind dropped to a minimum speed and changed to a southerly direction. S2 was a short distance away from the western and southern edges of the oasis, which meant that it was more vulnerable to dust invasion; this was confirmed by the higher amount of deposition at S2 than at S1-1. The spatial distribution of dust deposition during the two dust storms revealed that the oasis protection system caused a mechanical obstruction effect that extended about 2 km from the edge of the oasis to its interior, resulting in a large capture of dust in the windward margin. The sand-driving wind directions, combined with the mechanical obstruction effect, controlled the spatial distribution of dust deposition rates. In addition, the wind speed recovery on the leeward side due to the lower vegetation coverage compared to the inner oasis suppressed dust deposition, as confirmed by the minimum deposition rate observed in this area.

Particle size distribution inside and outside the oasis

Owing to the effect caused by the oasis protection system, the particles deposited were mainly composed of suspended dust, whose deposition may involve gravitational settling of individual particles, the formation and gravitational settling of grain aggregates, and/or downward turbulent diffusion (Pye 1995). According to our results, the long-term suspended dust (<20 μm) was only deposited inside and leeward of the oasis at reduced wind speed. Particles <20 μm corresponded to about 2% of the total content, leading to bimodal curves of particle size distribution. Fine particles can be transported and deposited as attachment to larger grains or as aggregates (Pye 1987), such as in the North African Desert (Pye 1995), Mali (McTainsh, Nickling, and Lynch 1997), Israel (Falkovich et al. 2001), China's Gansu province (Derbyshire, Meng, and Kemp 1998), Beijing (Shi et al. 2005), and the Qaidam Basin (Qiang, Lang, and Wang 2010). However, particles <20 μm were only deposited inside and leeward under reduced wind speed, indicating that no fine particles deposited as aggregates in the Cele Oasis during the dust storms. Besides, dry deposition of aerosol particles on vegetation canopies is controlled by different mechanisms (Petroff et al. 2008a, 2008b). Therefore, secondary dust fallout from the vegetation canopies may result in the deposition of fine particles. However, we cannot confirm the secondary fallout of dust from the vegetation canopies.

The inner oasis had a higher content of short-term suspended dust particles (20–70 μm) than the outside. Nevertheless, the content of particles >70 μm was lower than outside the oasis. That is, the region with relatively slower wind speed had a higher content of fine particles (<70 μm) than the region with a relatively fast wind speed. We can thus conclude that the reduction in wind speed due to the rough surface of the oasis enhanced the deposition of fine particles (<70 μm), explaining why the inner oasis had a larger mean grain size than the outside. During DS2, the leeward side of the oasis also had a larger mean grain sizes than the interior of oasis, but had the minimum dust deposition rate; this is because the wind speed recovery due to the leeward decrease in roughness suppressed the deposition of fine particles (<70 μm). Through field observations in the Cele Oasis, it was found that there were several sudden increases in the number concentration of fine particles (0.3–1 μm), but the same did not apply for coarser particles (>1 μm); Mikami et al. (2005) proposed that such fine particles (0.3–1 μm) are anthropogenic. Our samples did not contain such fine particles, and were moderately well sorted with a nearly symmetrical bias and a mesokurtic peak. The height of the dust traps and their remote location ruled out the influence of local dust, so we can ignore potential contamination by anthropogenic/local particles.

Conclusions

Aeolian dust was collected during two dust storms at eight sites in the Cele Oasis, in April 2013. DS1 was a light dust storm that consisted of sand-driving winds blowing from three directions (west, south, and east), occurring on April 3–5, while DS2 was a strong dust storm of westerly winds on April 16–17. The dust deposition rates and particle size distributions were examined, and several conclusions were reached. During the dust storms, the dust deposition rates increased windward from outside the oasis to the margin, and decreased gradually toward the leeward side indicating the direction of sand-driving winds. Under multiple wind directions, all windward margins had higher deposition rates. More fine particles (<70 μm) were deposited inside the oasis than outside, and the inner region of the oasis had a larger mean grain size than the outside. The oasis protection system on the margin had a mechanical obstruction effect, reaching about 2 km from the edge to the inner oasis, enhancing dust deposition by reducing the wind speed. However, the recovery of the wind speed because of the decrease in roughness in the leeward direction suppressed the deposition of fine particles, resulting in the leeward side having minimum deposition rates and larger mean grain sizes. Only a small amount of harmful dust (such as $PM_{2.5}$ and PM_{10}) was deposited during the dust storms, however, it is considered that the particles that remain in suspension will continue to be harmful to human health long after the dust storms.

Acknowledgments

The authors are grateful to Prof. Lei Jiaqiang, Zeng Fanjiang, and Dr. Yu Zhitong for the constructive comments, and thank Zhou Jie and Li Lei for their assistance with samplings.

Funding

This work was supported by a fund from the Major Special Projects in Xinjiang Uygur Autonomous Region, China (201130106-1).

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