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ORIGINAL PAPER

Oasis microclimate effect on the dust deposition in Cele Oasis at southern Tarim Basin, China

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Abstract Seasonal dustfall was collected in the Cele Oasis at southern Tarim Basin, China, to study the oasis microclimate effect on the spatial distribution of dust deposition. The deposition rates and grain-size parameters were analyzed for each season. In spring, when there is no significant microclimate effect, the deposition rates decreased from the windward margin to the downwind margin. In summer and autumn, when there is a significant microclimate effect, the deposition rates increased slightly from the windward margin to the downwind margin of the oasis, similar with the annual dust deposition pattern. The differences in the dust deposition pattern between seasons indicate that dust deposition is greatly enhanced in the center and downwind directions of the oasis during floating dust days in summer and autumn when there is a significant oasis microclimate effect. Therefore, it can be inferred that the background wind blowing the cold-wet center away from the geometric center of the oasis may be a key factor affecting the dust deposition pattern. The natural dust deposition pattern during winter is uncertain due to deposition from anthropogenic sources. Our results suggest that the dust deposition in the Cele Oasis is affected by a mechanical obstruction effect due to rough surfaces and by an oasis microclimate effect.

Keywords Dustfall · Oasis microclimate effect · Grain size · Tarim Basin

Introduction

A significant change in surface roughness can enhance dust deposition; rough patches can be regarded as dust-sink areas that can turn into dust sources if vegetation coverage changes (Field et al. 2012; Funk et al. 2012; Hoffmann et al. 2008; Tsoar and Pye 1987). Oases act as sinks for dust, and there have been some theories regarding the factors that increase dust deposition in oasis (Chen et al. 1999; Liu et al. 1994). In general, mechanical obstruction by rough surfaces, oasis microclimate effect (cold-wet island effect), and the influence of human activities can promote dust deposition inside oases (Chen et al. 1999; Liu et al. 1994; Wan et al. 2013). The influence of mechanical obstruction by the rough surfaces on the spatial distribution of dust deposition has been previously studied (Wan et al. 2009; Xu et al. in print.). However, an understanding of the effects of the oasis microclimate on dust deposition is still lacking.

The Tarim Basin is situated in the mid-latitude westerlies zone. This area has an extremely dry climate with scarce precipitation, intense evaporation, and great temperature variation. Annually, there were more than 30 days with dust storms and 200 days with dust weather (Qian et al. 2002). The mean annual number of days with floating dust in Hotan is 232 with a maximum of 304 days observed in 1985 (He and Zhao 1997). The Taklimakan Desert, located in the center of the basin, is not only a major dust source for Asia, but also the North Pacific Ocean and Greenland (Bory et al. 2002; Gong et al. 2003; Sun et al. 2001; Xuan et al. 2004; Zhang et al. 2003a, 2003b). The dustfall in the Tarim Basin mainly occurs in spring and summer, with little dustfall in

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autumn and winter (Liu et al. 1994, 2010). Therefore, the Cele Oasis in the southern Tarim Basin, Xinjiang Province of West China, was used as a case study. The purpose of this study was to investigate and characterize the spatial and temporal distribution of dust deposition in the Cele Oasis and reveal the effects of the oasis microclimate on dust deposition.

Materials 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 Tarim Basin and the northern foot plain of the Kunlun Mountains (Fig. 1). It stretches about 14 km from east to west and occupies 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 2600 mm (Ma et al. 2009). The annual average temperature is 11.9 °C, with a maximum of 41.9 °C and minimum −23.9 °C (Guo et al. 2008). The dominant wind is from the W, with an occurrence frequency of 62.3–76.23 %, followed by NNW, with an occurrence of 17.8 %. Westerly dust-raising winds (>6 m s^{-1}) account for 94.6 % of the total (Wan et al. 2013; Xing et al. 2008). The average annual numbers of dust and dust storm days are 142.4 and 21.2, respectively. Dust events occur predominantly in spring and summer, with dust storms from March to September accounting for approximately 90 % of the annual total and correlating well with the monthly percentage of dust-raising wind (Wan et al. 2013). Besides, the surface soil around the oasis contains a substantial amount of dry and loose sand-dust materials, which can easily be raised in windy conditions (Qian et al. 1995), resulting in a large amount of aeolian deposition in the oasis.

Sampling sites and dust traps

To investigate the spatial and temporal distribution of dust deposition in the Cele Oasis, we established eight sampling sites (Fig. 2). Site 0 (S0) and site 1 (S1) were located in the transition zone, about 100 and 35 m from the western boundary of the oasis, respectively. The dominant plant species were *Alhagi sparsifolia* Shap, *Karelinia caspia*, and *Calligonum caput-medusae* with 67 % vegetation coverage (Mu et al. 2013). Site 1–1 (S1-1) was located in the shelterbelt, 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. These four sites (S1-1, S2, S3, and S4) represented the interior of the oasis. The oasis farmland protection systems are composed of *Populus alba* with a narrow forest shelterbelt and a small grid. Sites 5 and 6 (S5 and S6) were located in newly reclaimed farmland that had been nearly abandoned because of salinization. Vegetation coverage at these two sites was sparse. S5 represented the eastern edge of the oasis, whereas S6 was outside of the oasis. The dust traps were plastic cylindrical pipes (15.5 cm in diameter and 30 cm long), with plastic bags attached to the outside of each container. The traps were placed about 4 m above the ground to avoid the influence of local dust, and three traps were set at each site, as described previously (Xu et al. in print). At each site, two traps were used to collect seasonal dustfall and one for annual dustfall.

Sampling and analytical procedures

Dust samples were collected through four seasons, as determined by local plant phenology and the seasonal variations in dust weather. From March 7 to April 5, 2013, the dust representing the spring dustfall was collected. The dustfall data from two dust storms that occurred during early and mid-April 2013 have already been published (Xu et al. in print). The dustfall from two consecutive sampling periods (April 18–June 5, June 6–September 4) was used to represent summer dustfall, although only samples collected during the later period were analyzed for the grain size. Samples September 5–November 17 were used to represent autumn dustfall. Winter dustfall was collected from November 18,

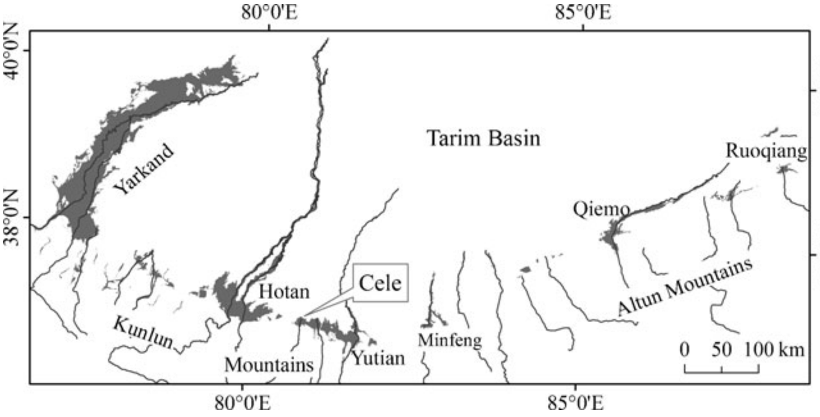


Fig. 1 Location of the Cele Oasis in southern Tarim Basin, adjacent to the Kunlun Mountains

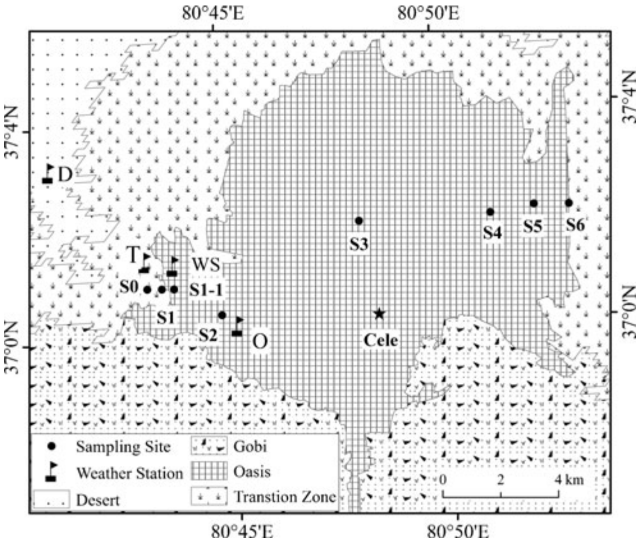


Fig. 2 Location of eight sampling sites and four weather stations in the Cele Oasis

2013 to March 10, 2014. The annual dustfall (April 6, 2013 to March 10, 2014) was also collected but the grain sizes were not analyzed. The deposition rates (g m^{-2}) were calculated at each site for each season, and the annual deposition rate of each site was also calculated. In addition, the seasonal dustfall samples were analyzed for grain sizes using a Malvern Mastersizer 2000 without any pretreatment. The measurement range is 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). The maximum wind speed and direction were recorded every hour at a height of 10 m. The location of the weather station (marked as WS) is shown in Fig. 2.

Results

Spatial-temporal distribution of deposition rates

Figure 3 shows the directions and duration (in hour) of winds with speed higher than the threshold friction velocity necessary for dust entrainment, the dust deposition rates in the four seasons, and the annual total dust deposit. During spring, dust entrainment winds mainly blow from the northeast, and dust entrainment wind from the west are the next-most common. The time of the winds with speeds higher than the threshold wind speed amounted to 19.47 % of the springtime. Spring deposition rates ranged from 43.3 to 127.42 g m^{-2}, with a mean of 79.09 g m^{-2}. The interior of the oasis had higher deposition rates than the exterior. Within the interior of the oasis, the deposition rates decreased gradually from the upwind side (east) to the downwind side (west; Fig. 3a). During summer, the dusty weather was mainly affected by westerly winds, and wind with speeds higher than the threshold wind speed represents 29.32 %. The deposition rates ranged from 514.6 to 1552.89 g m^{-2}, with a mean of 1065.21 g m^{-2}. The interior of the oasis had higher deposition rates than exterior, and the deposition rates gradually increased downwind (from the western margin to the east; Fig. 3b). During autumn, the occurrence of dusty weather decreased and was mainly linked to the westerlies. The time of the wind with speed higher than the threshold wind speed occupied 8.0 %. The deposition rates ranged from 59.29 to 140.2 g m^{-2}, with a mean of 98.51 g m^{-2}. The interior of the oasis had higher deposition rates than the exterior, and the highest deposition rate was found at site S4, in the downwind region of the oasis (Fig. 3c). During winter, dusty weather was scare and was affected by northwesterly winds. Winds with speeds higher than the threshold wind speed blew for 4.2 %. The deposition rates increased from the western outside to the east margin of the oasis and then decreased from the east margin of the oasis to the eastern outside. The deposition rates ranged from 21.88 to 65.31 g m^{-2}, with a mean of 39.49 g m^{-2} (Fig. 3d). The annual dustfall was mainly affected by westerlies, and the frequency of dust entrainment winds was 16.2 %. The deposition rates ranged from 761.75 to 1911.53 g m^{-2}, with a mean of 1350.45 g m^{-2}. The overall annual dust deposition pattern was similar to that in the summer: the interior of the oasis had higher deposition rates than the exterior, and the deposition rates gradually increased in the downwind direction (from the west margin to the east) in the interior of the oasis (Fig. 3e).

Characteristics of grain-size parameters

Most of the dust samples collected had bimodal distributions, with peaks clustered at 30–150 and 5–20 μm (Fig. 4). The grain-size parameters for each of the four seasons are shown in Fig. 5. The mean grain size in spring was 80.9 μm, and the mean grain sizes in the interior of the oasis were smaller than those outside the oasis, which is similar to the pattern found during dust storms (Xu et al. in print). The dustfall was well sorted except at site S2 and had a symmetrical bias and a mesokurtic peak. During summer, the mean grain sizes decreased toward the downwind side of the oasis with a mean of 65.3 μm. In summer, the dustfall was moderately or poorly sorted, the size distribution was skewed toward fine or very fine dust and the kurtosis was leptokurtic. During autumn, the mean grain size was 57.2 μm. The smallest mean grain sizes were found western outside the oasis; however, mean grain sizes changed little from the west margin of the oasis to the eastern outside. The dustfall was poorly sorted, the dustfall size distribution was skewed toward fine or very fine particles, and the kurtosis was leptokurtic. During winter, the mean grain sizes decreased toward the downwind side of the oasis with a mean of 53.4 μm. The dustfall was poorly sorted, and the size distribution of particles was skewed toward very fine particles and the kurtosis was leptokurtic.

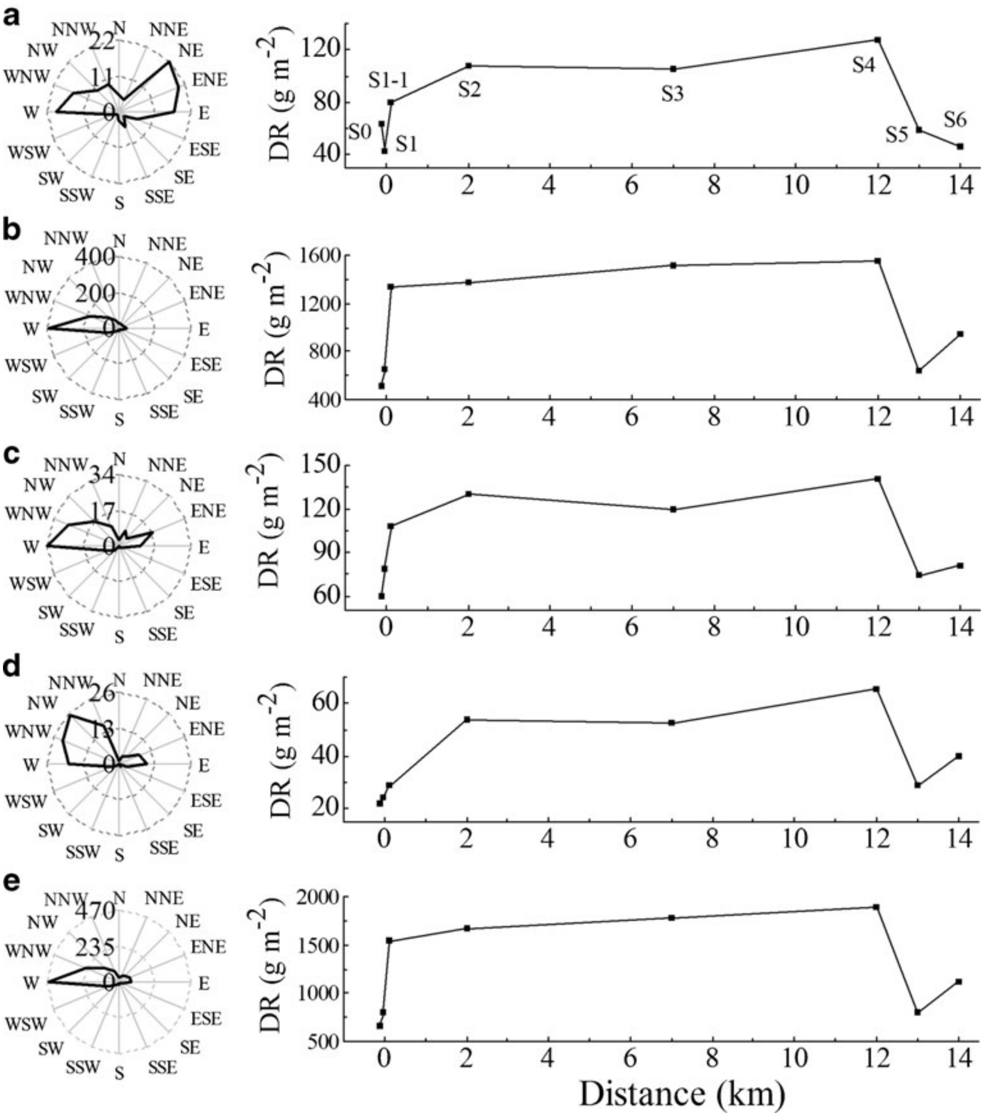


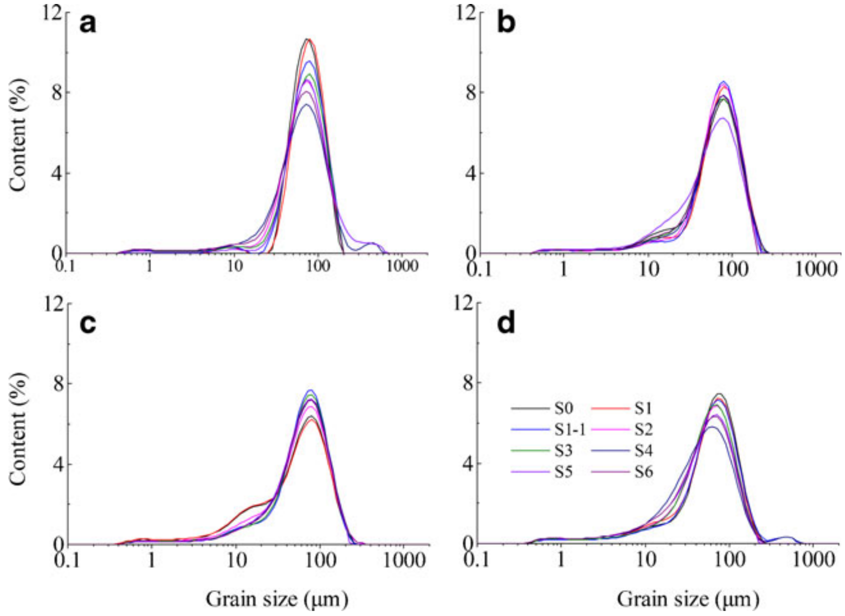
Fig. 3 Directions of dust entrainment winds and distribution of dust deposition rates in each of the four seasons and annually. **a**, **b**, **c d**, and **e** represent spring, summer, autumn, winter, and annual dustfall, respectively

Discussion

The wind speed, temperature, and relative humidity are different in the Cele Oasis and its surrounding desert (Fig. 6, modified from Mao et al. 2013). Three weather stations were placed in the desert, oasis-desert transitional zone, and the interior of Cele Oasis, marked in Fig. 2 with D, T, and O, respectively. Wind speeds measured at 2 and 10 m above the ground was lower in the interior of the oasis than in the desert and transitional zone throughout the year (Fig. 6a, b). This suggests that the mechanical obstruction effect of rough surfaces could affect dust deposition over the entire year. In contrast, the oasis cold-wet island effect showed seasonal variation. The oasis had a lower temperature than the surrounding desert from May to October, but no significant difference was found in the other months. From April to October, the oasis had a significantly higher relative humidity than the surrounding desert, but in other months, relative humidity was only slightly higher in the oasis than in the desert. Therefore, it can be inferred that the Cele Oasis had a significant microclimate effect (cold-wet island effect) in summer and autumn, especially in summer; however, this effect can be ignored in spring and winter. In addition, the wet-cold island effect in Cele Oasis is sustained during periods of blowing sand and floating dust days, but is destroyed during dust storms (Mao et al. 2013, 2014). The faint downdrift induced by the cold island effect and the particle moisture absorption induced by the wet island effect combined with gravity probably enhance dust deposition in the oasis (Liu et al. 1994; Wan et al. 2013).

In a period without significant microclimate effect, the deposition pattern during dusty weather events is likely to be similar to that of dust storms. Dust storm deposition patterns are controlled by the mechanical obstruction effect due to rough surfaces and the directions of the dust entrainment winds. The combined influence of these factors results in deposition rates that decrease toward the downwind side of the oasis (Wan et al.

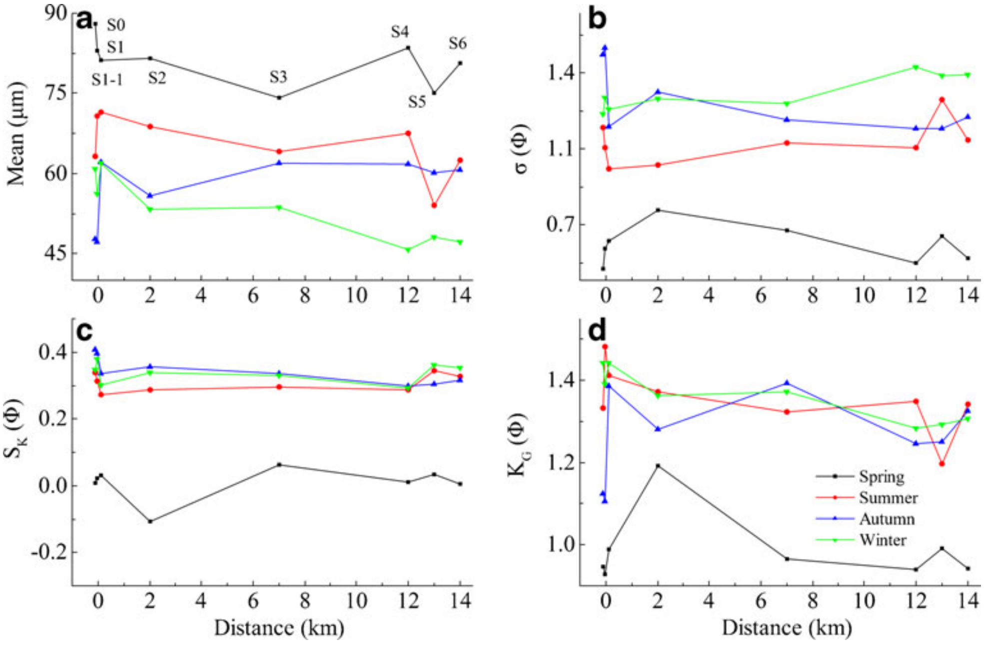
Fig. 4 Seasonal variations of grain size distribution. **a**, **b**, **c**, and **d** represent spring, summer, autumn, and winter, respectively



2009; Xu et al. in print.). This hypothesis was supported by the distribution of dust deposition during spring in the Cele Oasis. During spring, when the oasis microclimate effect can be ignored, the dust entrainment winds mainly blow from the northeast. At that time, the deposition rate was greatest along the east margin of the oasis (S4, windward margin), then decreased toward the downwind margin (west margin).

During periods with significant microclimate effect, dust deposition during dust weather events is likely controlled by the mechanical obstruction effect combined with the microclimate effect. Therefore, the deposition rates may not decrease from the windward margin toward downwind margin of the oasis. This hypothesis was supported by the distribution of dust deposition during summer and autumn in the Cele Oasis. During summer and autumn, the dust entrainment winds mainly blow from the west, while the deposition rates increase slightly from the windward margin to the downwind margin (west margin to east margin), a trend opposite to the deposition pattern of dust storms and spring. Clearly, some factors greatly enhanced dust deposition in the center and the downwind part of the oasis. This pattern was similar to the annual dust deposition. Previous studies revealed that background wind can affect the oasis cold-wet island effect, as they can blow the cold-wet center away from the geometric center of the oasis,

Fig. 5 Grain-size parameters of dustfall for spring (**a**), summer (**b**), autumn (**c**), and winter (**d**)



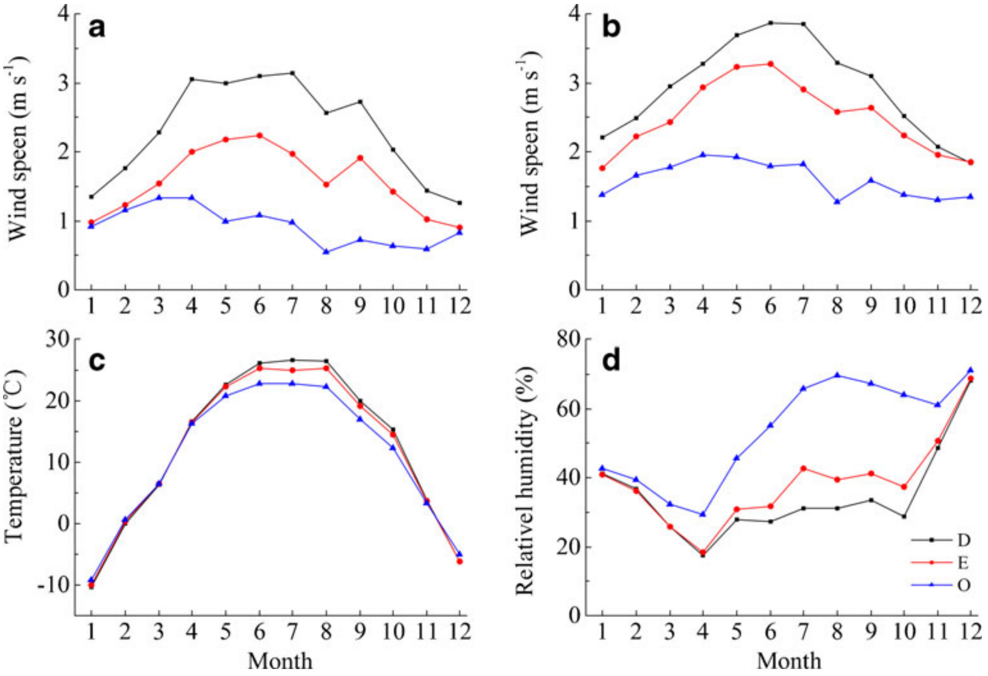


Fig. 6 Difference in the wind speed, temperature, and relative humidity between the Cele Oasis and its surrounding desert. **a**, **b** Wind speed at the heights of 2 and 10 m, respectively. **c**, **d** Temperature and relative humidity, respectively (modified from Mao et al. 2013)

thereby destroying the oasis effect (Chen et al. 2005, 2006; Potchter et al. 2008; Wen et al. 2006, 2007), which had been observed in the Cele Oasis (Mao et al. 2014). Therefore, deviation of the cold-wet center from the geometrical center of the oasis may be the key factor contributing to the relatively high dust deposition in the center and the downwind areas of the oasis. From spring to autumn, the mean grain size of trapped dust decreased, the sorting became poor, particle size distribution became skewed toward finer particles, and the kurtosis became leptokurtic, indicating that the oasis microclimate effect can promote the deposition of finer particles.

In winter, dusty weather occurred infrequently and wind speeds faster than the threshold wind speed were observed 4.2 % of the time. Chen et al. (1999) proposed that from late autumn through the following spring, anthropogenic influences, such as the removal of land cover and extensive grazing add dust to the atmosphere. Yabuki et al. (2005) found that the size-distribution of aerosols is unimodal in spring and summer and bimodal in winter, indicating that the anthropogenic particles during winter may contaminate the dustfall. During such a long time, the mean deposition rate is slightly higher than that of a weak dust storm (Xu et al. in print). The frequency of the dust entrainment wind was lower in winter than in other seasons, with frequencies in spring and summer that were 4.64 and 6.98 times than in winter, respectively. In autumn, the dust entrainment winds were infrequent, but the maximum wind speed was 17 m s^{-1} and the wind speeds >12 m s^{-1} blew for a total of 4 h. In winter, the maximum wind speed was only 11.9 m s^{-1}. The wind dynamics indicated that the dust weather in winter was mainly composed of blowing sand and floating dust days. Figure 6a, b also indicates that the average wind speed in winter was significantly lower than in other seasons. The weak wind dynamic and low dust entrainment wind frequency resulted in the transport of very little dust into the oasis. Therefore, small amounts of anthropogenic dust could change the dust deposition pattern during winter. Besides, the mode of dustfall changed with location just in winter, which also indicated anthropogenic influences in winter. So the natural dust deposition pattern in winter was changed by anthropogenic sources.

Conclusions

To characterize the oasis microclimate effect on the spatial distribution of dust deposition, seasonal dustfall samples were collected in the Cele Oasis, southern Tarim Basin. The deposition rates and grain size parameters were analyzed. During spring, when there was no significant oasis microclimate effect, the deposition rates decreased from the windward margin to the downwind margin, similar to the dust deposition pattern during dust storms. During summer and autumn, with a significant oasis microclimate effect, the deposition rates increased slightly from the windward margin to the downwind margin of the oasis, a trend opposite to that observed in spring. The difference in the dust deposition patterns between spring and summer, in addition to the annual dust deposition pattern, indicates that dust deposition was greatly enhanced in the center and downwind of oasis during floating dust days when there was a significant oasis microclimate effect. Therefore, it can be inferred that the background wind blowing the cold-wet center away from the geometric center of the oasis is likely the key factor. The grain size characteristics indicated that the oasis microclimate effect caused a greater deposition of fine particles during summer and autumn than in spring. The downdraft induced by the oasis cold island effect and the particle moisture absorption induced by the oasis wet island effect may play an important role in dust deposition during floating dust days. In winter, the dust samples may have been contaminated by anthropogenic sources. Therefore, winter dust deposition pattern for non-anthropogenic dust remains uncertain. In conclusion, the dust deposition in the Cele Oasis was not only affected by the mechanical obstruction effect of rough surfaces but also by the oasis microclimate effect, which greatly enhanced dust deposition in the center and downwind part of the oasis.

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