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Impact of utility-scale solar photovoltaic array on the aeolian sediment transport in Hobq Desert, China (Postprint)

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Abstract

Deserts are ideal places to develop ground-mounted large-scale solar photovoltaic (PV) power station. Unfortunately, solar energy production, operation, and maintenance are affected by geomorphological changes caused by surface erosion that may occur after the construction of the solar PV power station. In order to avoid damage to a solar PV power station in sandy areas, it is necessary to investigate the characteristics of wind-sand movement under the interference of solar PV array. The study was undertaken by measuring sediment transport of different wind directions above shifting dunes and three observation sites around the PV panels in the Hobq Desert, China. The results showed that the two-parameter exponential function provides better fit for the measured flux density profiles to the near-surface of solar PV array. However, the saltation height of sand particles changes with the intersection angle between the solar PV array and wind direction exceed 45°. The sediment transport rate above shifting dunes was always the greatest, while that around the test PV panels varied accordingly to the wind direction. Moreover, the aeolian sediment transport on the solar PV array was significantly affected by wind direction. The value of sand inhibition rate ranged from 35.46% to 88.51% at different wind directions. When the intersection angle exceeds 45°, the mean value of sediment transport rate above the solar PV array reduces to 82.58% compared with the shifting dunes. The results of our study expand our understanding of the formation and evolution of aeolian geomorphology at the solar PV footprint. This will facilitate the design and control engineering plans for solar PV array in sandy areas that operate according to the wind regime.

Full Text

Abstract

Deserts are ideal locations for developing ground-mounted, utility-scale solar photovoltaic (PV) power stations. However, solar energy production, operation, and maintenance are affected by geomorphological changes caused by surface erosion that may occur after construction. To avoid damage to solar PV power stations in sandy areas, it is necessary to investigate the characteristics of wind-sand movement under the interference of solar PV arrays. This study measured sediment transport at different wind directions above shifting dunes and at three observation sites around PV panels in the Hobq Desert, China. The results showed that a two-parameter exponential function provides a better fit for the measured flux density profiles near the surface of the solar PV array. However, the saltation height of sand particles changes when the intersection angle between the solar PV array and wind direction exceeds 45°. The sediment transport rate above shifting dunes was always the greatest, while that around the test PV panels varied according to wind direction. Moreover, aeolian sediment transport on the solar PV array was significantly affected by wind direction. The sand inhibition rate ranged from 35.46% to 88.51% at different wind directions. When the intersection angle exceeds 45°, the mean sediment transport rate above the solar PV array reduced by 82.58% compared with shifting dunes. These results expand our understanding of the formation and evolution of aeolian geomorphology at solar PV footprints and will facilitate the design and implementation of engineering plans for solar PV arrays in sandy areas according to the wind regime.

Keywords: aeolian sediment transport; mass flux density profiles; sand-fixation; shelter efficacy; solar photovoltaic array

1 Introduction

Solar photovoltaic (PV) technology is one of the most important means used by many countries to reduce dependence on conventional fossil fuel-based energy sources and decrease greenhouse gas emissions [**?**, **?**]. China' s desert area is approximately 7$×10^{5}$ km^2, of which sandy land area is about 5$×10^{5}$ km^2, accounting for 13% of the country' s total land area [**?**, **?**]. Most deserts are distributed in arid and semi-arid regions of Northwest China, which have abundant solar and thermal resources [**?**, **?**, **?**, **?**]. These desert areas are largely unsuitable for activities such as agriculture [**?**, **?**], and the cost of land use is very low. Thus, deserts are ideal locations for building ground-mounted, utility-scale solar PV power stations in China [**?**, **?**], with potential to improve land utilization rates and generate economic benefits. In 2018, global solar power generation reached 2480.4 TWh, with China' s contribution being 634.2 TWh.

However, deserts are characterized by strong winds, sand activity, and surface mobility. Solar energy production, operation, and maintenance are severely affected by geomorphological changes caused by surface erosion processes after construction of large-scale solar PV power stations. Most previous studies have focused on designing efficient structures to withstand aerodynamic forces [?, ?, ?, ?, ?, ?, ?, ?, ?] and on how dust deposition on PV panels influences power generation efficiency [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Yet, limited information exists about aeolian sand transport processes and surface erosion of PV facilities in desert areas.

Many desert surfaces, especially those with high silt and clay contents, are much more prone to wind erosion when mechanically disturbed [?, ?, ?]. Lands are disturbed when utility-scale solar facilities are built. The field surface airflow characteristics can be altered by PV installations, resulting in further soil loss under the surface of PV panels and formation of sand ridge landforms between panels. The geomorphological changes of PV power stations caused by surface erosion processes can aggravate the release rate of surface dust and increase dust deposition on PV panels. In addition, erosion can expose panel column bases and lead to instability of the PV panel infrastructure.

Thus, it is necessary to investigate the characteristics of wind-sand movement under the interference of solar PV arrays to avoid further damage to solar PV power stations and plan engineering measures for sand control. Aeolian transport is the basic process that defines the evolution of aeolian geomorphology [?, ?]. To understand sediment transport characteristics under PV array interference, more effective measures should be taken to control and improve sand flow movement to eliminate hazards. Significant efforts have been made in sediment transport theory, with mathematical models for mass-flux-density profiles over different underlying surfaces. Different methods have also been established for wind-tunnel tests and field observations. Although no consensus exists on the best mathematical model for horizontal sediment flux, it is now widely accepted that the mass-flux-density of suspended sediment decaying with increasing height follows a power function [?, ?, ?], while the mass flux density of saltating sediment decaying with increasing height follows an exponential decay function [?, ?, ?, ?, ?, ?, ?, ?]. However, establishing solar PV arrays can disrupt this relationship.

Most previous research focusing on wind tunnel and numerical simulation tests has shown that the height of solar panels above the ground and the aspect ratio (width/breadth) did not significantly affect the aerodynamic coefficients of panels, while row spacing for ground-mounted solar panel arrays and wind direction had significant effects on wind load and wind flow field characteristics [?, ?, ?, ?, ?, ?]. However, little work has compared sand transport with different wind directions in solar PV power stations in sandy areas. Likewise, field experience has shown that erosion and deposition intensities differ across solar PV power stations, with the windward edge area being stronger than the hinterland area [?, ?]. This study systematically analyzes the mass-flux-density profile and aeolian transport rate of sediment transport around PV panels in the hinterland of solar PV arrays with different wind directions. Our overall goal was to provide information that could be used to determine technical schemes for wind-sand hazard prevention and control in solar PV power stations to ensure safe and stable plant operation.

2.1 Study Area and Test PV Power Station

The study area was located in the middle part of the Hobq Desert in China (37°20 -39°50 N, 107°10 -111°45 E; Fig. 1 [Figure 1: see original paper]). The region has a typical temperate continental climate, with mean annual precipitation of 227 mm and mean annual potential evaporation of 2400 mm. Mean annual solar radiation is 597.9 kJ/cm^2 and annual mean wind velocity is 3.5 m/s. Wind direction is primarily from the west or northwest, with strongest winds occurring from March to May. Long-term surface aeolian sand activity processes have led to formation of aeolian landforms including crescent dunes, crescent dune chains, and lattice dune chains.

Our test solar PV power station was built at the end of 2018. Relative mechanical leveling work was carried out before PV panel installation. The station capacity was 200 MWp and covered an area of 5.9 km^2. The size of a single PV panel group was 18 m × 4 m, consisting of 2 rows and 18 columns of basic panel cells (1 m × 2 m). The upper edge of panels was 2.70 m and the lower edge was 0.35 m above ground. Each panel had a projection width of 3.2 m. The PV panels faced south with an inclination of 36°. The north-south spacing between panels was 8 m. Our observation field was 300 m from the west edge of the solar PV power station. During testing, the power station surface had no protective measures such as sand-binding plants or sand barriers.

2.2 Observation Methods

Aeolian sand activity was strongest in the study area during March–May due to frequent strong winds, extended drought, and limited rainfall (Fig. 2 [Figure 2: see original paper]). Thus, field observations were conducted from 20 March to 13 April 2019. To investigate wind direction influence on wind-sand movement characteristics of solar PV arrays, we collected sediment transport data at eight wind directions (Fig. 3 [Figure 3: see original paper]; Table 1).

After each observation, changes in underlying surface shape were noted. Wind erosion led to trench formation in the immediate downwind vicinity of panels and sand ripples between adjacent north-south panels (Fig. 4a [Figure 4: see original paper]). These micro-topographic changes likely influenced wind speed characteristics and sand transport. Therefore, we smoothed the surface surrounding test PV panels and flattened the underlying surface before arranging experimental instruments (Fig. 4b–c) to enable comparison of experimental results.

The configuration of specific measurement instruments is shown in Figure 4d. We established four observation sites: three around PV panels (between panels, before panels, and behind panels) and one on shifting dunes free of solar PV arrays to the west, 300 m from the power station.

With one sediment sampler at each observation site, the sampler was about 0.3 m tall and divided into 15 vertical openings (0.02 m × 0.02 m each) that collected horizontally transported, wind-eroded sediment above the surface (Fig. 4e). Individual observation durations were 20 to 60 min, determined by sediment transport rate magnitude—greater transport rates corresponded to shorter observation periods. For each measurement period, we measured sand transport simultaneously at all four locations from the beginning to the end of the sand transport period. We used an electronic balance with 0.01-g precision to weigh transported sediments collected at each height. Wind speed and direction were recorded using a HOBO sensor (Onset Computer Corp., USA) at observation sites on shifting dunes and between panels, synchronized with aeolian sediment transport observations. Cup anemometers were arranged at heights of 20, 50, 100, and 200 cm, with a wind vane installed at 200 cm height. The acquisition interval was 3 s.

2.3.1 Calculation of Mass Flux Density Profiles

The mass-flux-density profile describes how the sand transport rate (mass per unit time and per unit area) changes with increasing height above ground. Although no consensus exists on the best mathematical model for horizontal sediment flux, exponential, power, and modified multi-parameter functions usually produce better results. Thus, we selected three commonly used models to investigate mass flux density profiles above solar PV power station surfaces:

$$q(z) = az^{-b} \tag{1}$$

$$q(z) = ae^{-bz} \tag{2}$$

$$q(z) = a_1e^{-b_1z} + a_2e^{-b_2z} \tag{3}$$

where height z represents the arithmetic mean of the top and bottom of each chamber in the sampler (cm); $q(z)$ represents the flux at height z (g/(cm^2·min)); and a and b represent regression coefficients.

2.3.2 Calculation of Aeolian Environment Effect

Average wind speeds varied during observation periods for eight wind directions (Fig. 3), ranging from 7.37 to 11.57 m/s. To eliminate differences in sediment transport caused by varying wind speeds, the interception effect of solar PV arrays on sediment transport is expressed by the sand inhibition rate:

$$R_q = \frac{q_{st} - q_{PV}}{q_{st}} \times 100\% \tag{4}$$

where R_q represents the sand inhibition rate, q_{st} represents the aeolian sediment flux above shifting dunes, and q_{PV} represents the average aeolian sediment flux ($g/(cm^2 \cdot min)$) of three observation sites around PV panels.

Similarly, we used the relative acceleration rate to show the effect of solar PV arrays on near-surface wind speed [?, ?]:

$$R_u = \frac{u_{PV} - u_{st}}{u_{st}} \times 100\% \tag{5}$$

where R_u represents the relative acceleration rate, u_{st} represents the measured velocity (m/s) at height z above shifting dunes, and u_{PV} represents the measured velocity (m/s) at height z of the solar PV array.

3.1 Mass-Flux-Density Profiles

The relationship between sand transport rate and height under eight wind direction conditions is shown in Figure 5 [Figure 5: see original paper]. Sand transport rate decays with increasing height. Table 2 shows regression analysis results for mass-flux-density profiles above shifting dunes and three observation sites around PV panels at eight wind directions. We found that the three-parameter modified exponential function in Equation 3 provides the best fit to observed mass density profiles. However, this improvement was very limited compared with the two-parameter exponential function in Equation 2. The regression goodness of fit (R^2) in Equation 2 was greater than 0.97 in all cases, and in more than 84% of cases, the correlation coefficient (R^2) exceeded 0.99. Therefore, we prefer Equation 2 because it contains fewer coefficients to define. In other words, the existence of solar PV arrays does not change the sediment transport rate model around PV panels (between, before, and behind panels). The two-parameter exponential function provides an adequate description of aeolian flux density profiles under solar PV array interference in the sandy area investigated.

Most previous studies show that parameter a in Equation 2 represents the maximum flux density value, while other studies suggest that parameter a represents creeping in sediment transport [?, ?]. Relationships between regression coefficient a and wind direction are shown in Figure 6a [Figure 6: see original paper]. Coefficient a decreases as wind direction changes from W (west) to N (north). Parameter b in Equation 2 represents the decay rate of sediment transport as a function of height [?, ?]. The greater the value of b, the more slowly the flux density decays with height. From Figure 6b [Figure 6: see original paper], we can see that the value of b shows a slow decreasing trend as wind direction changes from WSW (west-southwest) to N, except for the observation site between panels.

3.2 Sediment Transport Rate and Thickness of the Saltation Layer

Figure 7 [Figure 7: see original paper] shows sediment transport rates above four observation sites at eight wind directions. Sediment transport rate above shifting dunes was always larger than that in the solar PV array, with large gaps among different wind directions. The amount above shifting dunes was 1.55 times the mean value of the solar PV array with prevailing WNW wind direction, while it was 8.70 times with prevailing N wind direction. This indicates that the kinetic energy obtained by the near-surface of solar PV arrays is strongly related to wind direction. With wind direction changing from W to N, less kinetic energy was transmitted to the near-surface, and the role of solar PV arrays in intercepting wind-sand flow became more pronounced.

In the solar PV array, sediment transport rates at three observation sites were also related to wind direction. The rate was highest at the observation site between panels and lowest at sites before and behind panels when prevailing wind direction was almost parallel to the arrangement direction of solar PV arrays (Fig. 7b and c). As the positional relationship between wind direction and solar PV array changed from parallel to vertical, sediment transport rate increased for the observation site before panels and decreased for the site between panels. Then, the sediment transport rate increased to its highest point at the observation site before panels (Fig. 7a, e–h), followed by sites between and behind panels.

To further understand the relationship between sand transport and height under solar PV array interference, we plotted cumulative histograms for four observation sites at eight wind directions (Fig. 8 [Figure 8: see original paper]). Most sand was transported very close to the ground in all cases with prevailing WSW, W, or WNW wind directions (Fig. 8a–e). It is also shown that 75% and 90% of total transport was concentrated below 0.05 m and 0.1 m, respectively. The vertical distribution of sand transport was not impacted by solar PV arrays under these conditions. Wind-sand flow for sites between and behind panels tended to move toward higher layers evidently with prevailing NW, NNW, or N wind directions (Fig. 8f–h), with 75% and 90% of total transported particles concentrated below 0.10 m and 0.20 m, respectively. However, saltation height at the observation site before panels tended to move toward lower layers, with 75% and 90% of total transported particles concentrated below 0.03 m and 0.06 m, respectively.

3.3 Sand Inhibition Rate of Utility-Scale Solar PV Array

The relationship between sand inhibition rate and wind direction is shown in Figure 9 [Figure 9: see original paper]. Sand inhibition rate was significantly affected by wind direction, ranging from 35.46% to 88.51% at different wind directions. It was lowest for prevailing WNW wind direction and highest for prevailing N wind direction. The sand inhibition rate initially decreased before increasing when prevailing wind direction changed from W to N (Fig. 9b–h), showing a downward trend from W to WNW (Fig. 9b–d) and increasing quickly with addition of NW wind direction. It increased further when prevailing wind direction was NW (northwest), NNW (north-northwest), or N, with a mean value of up to 82.58%. In contrast, we found that sand inhibition rate varied when wind direction changed from W to WSW and WNW. It was 56.01% with prevailing WSW and W wind directions (Fig. 9a), and only 43.88% and 35.46% with prevailing WNW and W wind directions, respectively (Fig. 9c and d). These differences are caused by structural characteristics of PV facilities: PV panels face south, are high in the north and low in the south, and incline at 36°. Airflow was more directed to the surface after being blocked by solar PV arrays when wind direction was WNW, while it was more directed to the upper atmosphere with WSW wind direction. Thus, sand inhibition rate for WSW wind direction is better than for WNW wind direction due to differences in kinetic energy obtained by the near-surface of solar PV arrays.

4 Discussion

Field studies are crucial for improving our understanding of sediment transport under solar PV array interference, supporting theoretical analyses and verifying numerical simulation results. Previous studies [**?**, **?**, **?**, **?**, **?**] have suggested that exponential, power, or modified functions are most suitable for expressing horizontal sand flux. In this study, we found that the two-parameter exponential function provides an adequate description of aeolian flux density profiles for shifting dunes and three observation sites around PV panels in all cases. That is, the existence of solar PV arrays does not change the sediment transport rate model. However, saltation height of sand particles was affected by solar PV arrays and was related to the intersection angle. Saltation height did not change significantly when the intersection angle was less than 45°, but increased significantly for sites between and behind panels and decreased at the observation site before panels when the intersection angle exceeded 45°. These differences may have resulted from wind regime characteristics such as turbulence and vortices. Numerical simulation tests [**?**, **?**] show almost no vortex in solar PV arrays when prevailing wind direction was NW or NS, but vortices occurred when prevailing wind direction was N or S (especially N). Meanwhile, saltation height declined at sites before panels (outside the lower edge of PV panels) due to oblique downward flow guide action becoming stronger as intersection angle increased.

Further, mean wind speeds during observation periods for eight prevailing wind directions ranged from 7.73 to 11.57 m/s due to uncontrollable field conditions. We attempted to investigate wind speed effects on saltation height. When saltation height changed obviously, corresponding wind speeds were 7.92, 8.71, and 9.75 m/s for Figures 8f–h, respectively. Conversely, before saltation height changed, wind speeds were 7.37, 7.73, 10.46, 11.07, and 11.55 m/s for Figures 8e, d, c, b, and a, respectively. Consequently, wind speed did not play a decisive role in saltation height of sand particles.

Sediment transport rate, sand transport height, and regression coefficient a were affected by wind speed [?, ?, ?, ?]. It has been established that the value of a increases with wind speed, while the value of b has no obvious relationship with wind speed [?, ?]. Our observations above shifting dunes support this finding (Fig. 10 [Figure 10: see original paper]). In Figure 6a, wind speeds corresponding to regression coefficient a under different wind directions differ. The value of a for wind directions A–C should be lower than current measured values, and that for directions D–E should be higher than current values in Figure 6a. If we consider wind speed effects on a and modify it by the relationship between coefficient a and wind speed, this does not break the overall tendency of regression coefficient a with wind direction change. It can be seen that creeping sediment transport decreases as intersection angle increases above the surface in solar PV arrays.

Our field observations confirmed that sediment transport rate for solar PV arrays was influenced by intersection angle. It was 48.42% of that above shifting dunes when intersection angle was less than 45°, and 17.42% when intersection angle exceeded 45°. Obviously, the intersection angle between solar PV array and wind direction is a key factor impacting sediment transport in solar PV arrays.

Wind provides the power that entrains sediments and creates aeolian geomorphology, shaping its subsequent development [?, ?]. Recently, numerical simulation [?, ?] and field observation [?, ?] studies have shown that wind attenuation is maximal as intersection angle approaches 90° regardless of forward or reverse winds, consistent with our results. We used relative acceleration rate of wind speed to evaluate airflow changes at heights of 20, 50, 100, and 200 cm above the surface under solar PV array disturbance. Table 3 shows relative acceleration rates in the hinterland region at eight wind directions. The rate ranged from 0.11 to 0.23 when the angle between wind direction and solar PV array was less than 45°, and from 0.62 to 0.65 when the angle exceeded 45°. Linear regression analysis of the relationship between sand inhibition rate and relative acceleration rate at heights of 20, 50, 100, and 200 cm (Fig. 11 [Figure 11: see original paper]) revealed strong, significant relationships at each height, with regression goodness of fit (R^2) greater than 0.82 in all cases. This better explains differences in sediment transport under different wind directions.

We conclude that aeolian sediment transport has significant correlation with freestream wind direction. When intersection angle exceeds 45°, solar PV arrays can effectively play a role in sand-fixation and shelter efficacy. This effect was very limited when intersection angle was less than 45°, resulting in easier soil loss under the surface of solar PV arrays. This information can be used to determine prevention and control technical schemes for solar PV footprints. For solar PV arrays with panels facing south and east-west arrangement, in response to wind directions of NNW, N, NNE, SSE, S, and SSW, we need to focus on near-surface sand control engineering measures for the north and south edge zones. In response to wind directions of SW, WSW, W, WNW, NW, NE, ENE, E, ESE, and SE, we need to set up sand barriers on east and west sides of solar PV arrays to reduce wind energy. This is also effective for protecting edge zones. Sand barriers should play an important role in reducing wind energy entering solar PV arrays, not only in sand fixation. Hence, sand barrier configuration can be an upright sand fence protective belt or a combination of upright sand fence and checkerboard sand barriers. Sand barriers could also be replaced by facilities with similar functions. Meanwhile, we can plan protection engineering structures for solar PV arrays in sandy areas according to wind regime. For example, our study solar PV array was located in Northwest China, where the primary harmful wind direction is W or NW; therefore, protection engineering structures on the west side of solar PV arrays should be better than those on the east side.

5 Conclusions

Utility-scale solar PV power stations in desert areas represent one of the most important growth points in clean energy development. Detailed field observations of wind-blown sediment flux under solar PV power station interference enable definition of near-surface mass flux density profiles, which help plan sand control engineering structures for solar PV footprints in sandy areas according to wind regime.

We found that the existence of solar PV arrays does not change the sediment transport rate model. The two-parameter exponential function provides an adequate description of aeolian flux density profiles under solar PV array interference. However, as intersection angle increases, saltation height of sand particles for sites between and behind panels increased significantly, while saltation height decreased at the observation site before panels.

Sediment transport rate above shifting dunes was always greatest. By contrast, it reduced by 51.58% above solar PV arrays when intersection angle was less than 45° and by 82.58% when intersection angle exceeded 45°. This shows that aeolian sediment transport above solar PV arrays was significantly affected by free-stream wind direction.

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References

Adinoyi M J, Said S A M. 2013. Effect of dust accumulation on the power outputs of solar photovoltaic modules. *Renewable Energy*, 60: 633–636.

Al-hasan A, Ghoneim A. 2005. A new correlation between photovoltaic panel' s efficiency and amount of sand dust accumulated on their surface. *International Journal of Sustainable Energy*, 24(4): 187–197.

Appels R, Lefevre B, Herteleer B, et al. 2013. Effect of soiling on photovoltaic modules. *Solar Energy*, 96: 283–291.

Bechtel National, Inc. 1980. *Wind design of flat panel photovoltaic array structures*. SAND 79-7057. Springfield: National Technical Information Service, U.S. Department of Commerce.

Boyle L, Flinchpaugh H, Hannigan M P. 2015. Natural soiling of photovoltaic cover plates and the impact on transmission. *Renewable Energy*, 77: 166–173.

Cabanillas R E, Munguia H. 2011. Dust accumulation effect on efficiency of Si photovoltaic modules. *Journal of Renewable and Sustainable Energy*, 3(4), doi: 10.1063/1.3622609.

Dong Z, Liu X, Wang H, et al. 2002. The flux profile of a blowing sand cloud: a wind tunnel investigation. *Geomorphology*, 49(3–4): 219–230.

Dong Z, Lu J, Man D, et al. 2011. Equations for the near-surface mass flux density profile of wind-blown sediments. *Earth Surface Processes and Landforms*, 36(10): 1292–1299.

Dong Z, Lü P, Zhang Z, et al. 2012. Aeolian transport in the field: A comparison of the effects of different surface treatments. *Journal of Geophysical Research: Atmospheres*, 117(D9). doi.org/10.1029/2012JD017538.

Ellis J T, Li B, Farrell E J, et al. 2009. Protocols for characterizing aeolian mass-flux profiles. *Aeolian Research*, 1(1–2): 19–26.

Elminir H K, Ghitas A E, Hamid R H, et al. 2006. Effect of dust on the transparent cover of solar collectors. *Energy Conversion and Management*, 47(18–19): 3192–3203.

Etyemezian V, Nikolich G, Gillies J A. 2017. Mean flow through utility scale solar facilities and preliminary insights on dust impacts. *Journal of Wind Engineering and Industrial Aerodynamics*, 162: 45–56.

Garcia E T, Ogueta-Gutierrez M, Avila S, et al. 2014. On the effects of windbreaks on the aerodynamic loads over parabolic solar troughs. *Applied Energy*, 115: 293–300.

Guo C, Han Z, Li A, et al. 2018. Dynamic mechanism research on the secondary blown sand disaster in the 110-MW photovoltaic arrays of the Hobq Desert. *Journal of Desert Research*, 38: 225–232.

Houser C A, Nickling W G. 2001. The emission and vertical flux of particulate matter <10 mm from a disturbed clay-crusted surface. *Sedimentology*, 48(2): 255–267.

Huang B, Li Z, Zhao Z, et al. 2018. Near-ground impurity-free wind and wind-driven sand of photovoltaic power stations in a desert area. *Journal of Wind Engineering and Industrial Aerodynamics*, 179: 483–502.

Jackson P S, Hunt J C R. 1975. Turbulent wind flow over a low hill. *Quarterly Journal of the Royal Meteorological Society*, 101(430): 929–955.

Jubayer C M, Hangan H. 2014. Numerical simulation of wind effects on a stand-alone ground mounted photovoltaic (PV) system. *Journal of Wind Engineering and Industrial Aerodynamics*, 134: 56–64.

Jubayer C M, Hangan H. 2016. A numerical approach to the investigation of wind loading on an array of ground mounted solar photovoltaic (PV) panels. *Journal of Wind Engineering and Industrial Aerodynamics*, 153: 60–70.

Kopp G A, Farquhar S, Morrison M J. 2012. Aerodynamic mechanisms for wind loads on tilted, roof-mounted, solar arrays. *Journal of Wind Engineering and Industrial Aerodynamics*, 111: 40–52.

Kopp G A, Surry D. 2002. Wind loads on a solar array. *Wind and Structures*, 5(5): 393–406.

Li K, He F. 2010. Analysis on mainland China' s solar energy distribution and potential to utilize solar energy as an alternative energy source. *Progress in Geography*, 29: 1049–1054.

Li S, Li C, Yao D, et al. 2020. Feasibility of microbially induced carbonate precipitation and straw checkerboard barriers on desertification control and ecological restoration. *Ecological Engineering*, 105883, doi: 10.1016/j.ecoleng.2020.105883.

Li X R, Xiao H L, He M Z, et al. 2006. Sand barriers of straw checkerboards for habitat restoration in extremely arid desert regions. *Ecological Engineering*, 28(2): 149–157.

Lü P, Dong Z, Ma X. 2016. Aeolian sand transport above three desert surfaces in northern China with different characteristics (shifting sand, straw checkerboard, and gravel): field observations. *Environmental Earth Sciences*, 577, doi: 10.1007/s12665-016-6180-3.

Macpherson T, Nickling W G, Gillies J A, et al. 2008. Dust emissions from undisturbed and disturbed supply-limited desert surfaces. *Journal of Geophysical Research*, 113(F2), doi: 10.1029/2007JF000800.

Mani M, Pillai R. 2010. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. *Renewable and Sustainable Energy Reviews*, 14(9): 3124–3131.

Mertia R S, Santra P, Kandpal B K, et al. 2010. Mass-height profile and total mass transport of wind eroded aeolian sediments from rangelands of the Indian Thar Desert. *Aeolian Research*, 2(2-3): 135-142.

Nahar N M, Gupta J P. 1990. Effect of dust on transmittance of glazing materials for solar collectors under arid zone conditions of India. *Solar & Wind Technology*, 7(2-3): 237-243.

Namikas S L. 2003. Field measurement and numerical modelling of aeolian mass flux distributions on a sandy beach. *Sedimentology*, 50(2): 303-326.

Ni J R, Li Z S, Mendoza C. 2002. Vertical profiles of aeolian sand mass flux. *Geomorphology*, 49(3-4): 205-218.

Said S A M. 1990. Effects of dust accumulation on performances of thermal and photovoltaic flat-plate collectors. *Applied Energy*, 37(1): 73-84.

Schellenberg A, Maffei J, Telleen K, et al. 2013. Structural analysis and application of wind loads to solar arrays. *Journal of Wind Engineering and Industrial Aerodynamics*, 123: 261-272.

Shademan M, Barron R M, Balachandar R, et al. 2014. Numerical simulation of wind loading on ground-mounted solar panels at different flow configurations. *Canadian Journal of Civil Engineering*, 41(8): 728-738.

Shen Y, Wang X, Cong R, et al. 2013. Eco-geographical zoning of deserts and gobi in China. *Journal of Arid Land Resources and Environment*, 27(1): 1-13.

Warsido W P, Bitsuamlak G T, Barata J, et al. 2014. Influence of spacing parameters on the wind loading of solar array. *Journal of Fluids and Structures*, 48: 295-315.

Zhang C, Li Q, Zhou N, et al. 2016. Field observations of wind profiles and sand fluxes above the windward slope of a sand dune before and after the establishment of semi-buried straw checkerboard barriers. *Aeolian Research*, 20: 59-70.

Zhang Z, Dong Z. 2013. Field Observation of Aeolian Sediment Flux in the Southeast Tengger Desert. *Journal of Desert Research*, 23(4): 973-980.

Zhang Z, Dong Z. 2014. Characteristics of aeolian sediment transport over different land surfaces in northern China. *Soil and Tillage Research*, 143: 106-115.

Zhang Z, Dong Z, Li C. 2015. Wind regime and sand transport in China' s Badain Jaran Desert. *Aeolian Research*, 17: 1-13.

Zhang Z, Dong Z, Wu G. 2017. Field observations of sand transport over the crest of a transverse dune in northwestern China Tengger Desert. *Soil and Tillage Research*, 166: 67-75.

Zingg A W. 1953. Some characteristics of aeolian sand movement by saltation process. *Edition du Centre National de la Recherche Scientifique*, 7: 197-208.

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Zorrilla-Casanova J, Piliougine M, Carretero J, et al. 2013. Losses produced by soiling in the incoming radiation to photovoltaic modules. *Progress in Photovoltaics*, 21(4): 790-796.

Note: Figure translations are in progress. See original paper for figures.

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